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# Performance analysis and routing in nanosatellite constellations : models and applications for remote regions

Maria-Mihaela Burlacu

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UNIVERSITE DE HAUTE ALSACE  
Faculté de Sciences et Techniques

**Thèse de Doctorat**  
Spécialité INFORMATIQUE

Présenté par :  
**Maria-Mihaela BURLACU**

Sujet de thèse :

***Analyse des Performances et Routage dans les Constellations  
de Nano-satellites : Modèles et Applications pour les Régions  
Eloignées***

**Performance Analysis and Routing in Nanosatellite  
Constellations: Models and Applications for Remote Regions**

**Soutenue le 3 décembre 2010 devant le jury :**

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## Résumé

La réduction des budgets du domaine spatial et les missions scientifiques traditionnelles ayant des coûts et une complexité croissants a amené la communauté scientifique à se concentrer sur les petits satellites qui fournissent non seulement des résultats scientifiques de valeur, mais permettent aussi de nouvelles applications dans le domaine de la télédétection, de la surveillance environnementale et des télécommunications. De plus, le concept de vol en formation de petits satellites est une technologie-clé pour beaucoup de missions spatiales futures, en améliorant la capacité de survie et réduisant le coût des missions.

Ce travail de recherche a un double but : la proposition de modèles innovants de constellations de nano-satellites et de nouvelles approches de routage pour les réseaux de nano-satellites.

Cette thèse propose et analyse trois modèles de constellations de nano-satellites dénommés NanoDREAM, NanoICE et NanoSPHERE, qui fournissent des services de télécommunications aux régions éloignées. Le modèle NanoDREAM est conçu pour le Désert Salar de Uyuni en Bolivie, une région qui détient 70% de la réserve mondiale de lithium. Le modèle NanoICE est destiné aux Régions Polaires, pour satisfaire les besoins de télécommunications de la communauté scientifique. Le modèle NanoSPHERE est conçu pour fournir une couverture globale de la Terre pour un marché de télécommunications concurrentiel. De plus, nous avons proposé une architecture pour le segment terrestre basée sur la technologie sans fil. Cette architecture a été déployée sur la zone d'exploitation du Désert Salar de Uyuni. Ces modèles ont été développés analytiquement et mis ensuite en œuvre dans le simulateur SaVi afin d'identifier la meilleure constellation satisfaisant les requis de la mission en termes de couverture et en réduisant au minimum le nombre de nano-satellites de la constellation.

Aussi, cette thèse propose une méthode pour estimer le nombre de nano-satellites nécessaires pour couvrir une certaine zone. De plus, une méthode basée sur le modèle de Markov est proposée afin d'évaluer les performances de constellations de nano-satellites.

La Qualité de Service (QoS) dans les réseaux de nano-satellites sera un grand défi pour la communauté scientifique, en considérant l'évolution de la technologie multimédia et l'intérêt commercial des futurs opérateurs nano-satellites pour fournir des services de télécommunications de haute qualité au grand public. Pour cette raison, nous avons proposé plusieurs approches pour intégrer l'aspect QoS dans les réseaux de nano-satellites.

En outre, les défis uniques imposés par les réseaux nano-satellites exigent que nous révisions la conception des protocoles de communication, la gestion de réseau et que nous proposons des nouveaux mécanismes de routage qui prennent en considération les ressources limitées des nano-satellites. Ce travail de recherche propose de nouvelles approches de routage pour les constellations de nano-satellites, basées sur une étude faite sur le routage dans les réseaux de satellites traditionnels, les réseaux Ad hoc et les réseaux de capteurs. De plus, cette étude a montré que le protocole XSTP (*eXtended Satellite Transport Protocol*) pourrait être un candidat ciblé pour les constellations nano-satellites. Une méthodologie pour évaluer les performances du protocole XSTP sur des réseaux de satellites traditionnels et des constellations de nano-satellites a été mise en œuvre dans le simulateur NS2. Les scénarios de test et les approches de simulation sont présentés en détail avec leurs résultats respectifs. La partie finale de ce travail de recherche propose plusieurs perspectives d'études complémentaires dans le domaine des nano-satellites.

## Abstract

The growth in cost and complexity of traditional scientific missions along with the reduction in space budgets have determined space community to focus on small satellites that not only provide valuable scientific returns, but also allow completely new applications in remote sensing, environmental monitoring and communications.

Furthermore, small satellite flying in formation is a key technology for many future space science missions, by improving mission survivability and reducing mission costs, and offering multi-mission capabilities, achieved through reconfiguration of formations.

The main goal of this thesis is two-fold: proposing innovative nanosatellite constellation models and new routing approaches for nanosatellite network telecommunications.

Therefore, this research work proposes and analyzes three models of nanosatellite constellations, named NanoDREAM, NanoICE, NanoSPHERE, that provide telecommunication services to remote regions of the Earth. NanoDREAM model is designed for Bolivia's Salar de Uyuni Desert, a region which detains 70% of the global lithium reserve. NanoICE model is intended for Polar Regions, in order to meet the voice and data transfer needs of the entire Antarctic and Arctic scientific community. NanoSPHERE is aimed to provide global coverage in the context of a robust telecommunications market. Additionally, a ground segment architecture based on wireless technology and deployed over the exploitation area of Salar de Uyuni Desert was proposed.

Moreover, two new methodologies were proposed: the first one is a method for estimating the number of nano-satellites needed to cover a specific region was, and the second one is a Markov modeling-based method for evaluating the performance of nanosatellite constellations.

These models were developed analytically and then implemented in SaVi modeler in order to identify the best constellation which meets mission coverage requirements while minimizing the number of nanosatellites within the constellation.

Since the evolution of multimedia technology and the commercial interest of future small satellite operators to reach widely public applications will make QoS in nanosatellite networks an area of great interest, several approaches for QoS provisioning in nanosatellite networks were proposed.

Furthermore, the unique challenges imposed by nanosatellite networks require us to revise communication protocols design, network management, and to consider novel routing mechanisms to accomplish "more with less". New routing approaches for nanosatellite constellations were proposed based on a survey of routing mechanisms in traditional satellite network, Ad Hoc network and sensor networks. Moreover, this study showed that XSTP (eXtended Satellite Transport Protocol) might be a candidate protocol targeted for nanosatellite constellations.

A methodology for evaluating technical performance of XSTP protocol over traditional satellite networks and nanosatellite networks was implemented in NS2 simulator. The specific scenarios, implementations aspects and simulation approaches are presented in detail along with the respective simulation results. A special emphasis is placed on the comparison between satellite network and nanosatellite network in terms of XSTP performance. Finally, several guidelines for future work within nanosatellite domain are proposed in the last part of this research work.

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## Abbreviations

ABR	Associativity Based Routing
AFOSR	Air Force Office of Scientific Research
AODV	Ad hoc On Demand Distance Vector
AP	Access Point
ARQ	Automatic Repeat Request
ASAP	Ariane Structure for Auxiliary Payloads
BER	Bit Error Rate
BGP-S	Border Gateway Protocol – Satellite Version
bps	bit per second
CanX	Canadian Advanced Nanospace eXperiment
CBRP	Cluster Based Routing Protocol
CNES	Centre National d’Etudes Spatiales
CRC	Cyclic Redundancy Check
DMC	Disaster Monitoring Constellation
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source Routing
e-CORCE	e – Constellation d'observation récurrente cellulaire
ECG	Electrocardiography
ESA	European Space Agency
EXPRESSO	EXpérimentations et PROjets Etudiants dans le domaine des Systèmes Orbitaux et ballons stratosphériques
FTP	File Transfer Protocol
GENSO	Global Educational Network for Satellite Operations
GEO	Geostationary Earth Orbit
GSR	Global State Routing
HSR	Hierarchical State Routing
HTTP	Hypertext Transfer Protocol
IAA	International Academy of Astronautics
ION-F	Ionospheric Observation Nanosatellite Formation
IP	Internet Protocol
IPY	International Polar Year
ISL	Inter-satellite link
ITU	International Telecommunication Union
ITU-T	Telecommunication Standardization Sector
Kbps	Kilo bit per second
LAR	Location-Aided Routing
LEO	Low Earth Orbit
LLC	Logical Link Control
MAC	Media Access Control
Mbps	Mega bit per second
MEO	Medium Earth Orbit
MGS	Mobile Ground Station
MUT	Mobile User Terminal

NACK	Negative Acknowledgements
NanoDREAM	Nanosatellite Constellation for Desert Region ExploitAtion and Monitoring
NanoICE	Nanosatellite Innovative Constellation
NASA	National Aeronautics and Space Administration
NS	Network Simulator
OTcl	Object Tool command language
PERSEUS	Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique
PIX	Protocol Implementation framework for Linux
PROBA	Project for On-Board Autonomy
RISTRETTO	Réseau International de Satellites de Systèmes oRbitaux ETudiants basés sur une Technique de développement en Open source
RF	Radio frequency
R&D	Research and Development
ROV	Remotely Operated Vehicles
RTT	Round-Trip Time
QoS	Quality of Service
SaVi	Satellite Visualization
SCPS	Space Communications Protocol Standards
SHAR	Satish Dhawan Space Centre
SOHO	Solar and Heliospheric Observatory
SSID	Service Set Identifier
SSP	Sub-Satellite Point
STEM	Sparse Topology and Energy Management
SSCOP	Service Specific Connection Oriented Protocol
SSR	Scalable Source Routing
STP	Satellite Transport Protocol
SSTL	Surrey Satellite Technology Ltd
Tcl/Tk	Tool command language/Toolkit
TCP	Transmission Control Protocol
TORA	Temporally Ordered Routing Algorithm
TRAMA	Traffic-Adaptive Medium Access
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking and Control
UN	United Nations
UTIAS	University of Toronto Institute for Aerospace Studies
VHF	Very High Frequency
ZHLS	Zone-Based Hierarchical Link State Routing
ZRP	Zone Routing Protocol
XSTP	eXtended Satellite Transport Protocol
XTP	Xpress Transport Protocol
WLAN	Wireless Local Area Network
WRP	Wireless Routing Protocol

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# CHAPTER 1

## Chapitre 1. INTRODUCTION

### Le cadre et les objectifs de la thèse

Les satellites traditionnels sont extrêmement chers à concevoir, construire, lancer et faire fonctionner. En conséquence, les entreprises du domaine spatial et la communauté de recherche ont concentré leur attention sur des missions impliquant plusieurs petits satellites, peu coûteux, travaillant ensemble pour atteindre les mêmes performances qu'un grand satellite. Le concept de vol en formation est devenu populaire ces dernières années grâce à son potentiel pour réaliser des mesures coordonnées dans les missions de télédétection et grâce à sa flexibilité pour des missions spatiales à long terme. Beaucoup de missions spatiales futures (par exemple, l'interférométrie, la radar-graphie ou la cartographie de la Terre) exigeront des constellations de petits satellites pour accomplir leurs objectifs scientifiques complexes.

En outre, beaucoup de projets spatiaux développés dans les laboratoires universitaires sont concentrés sur le développement de micro-, nano- et pico-satellites. Le nombre de pays participants activement aux programmes de nano-satellites grandit considérablement chaque année.

Le standard CubeSat, développé par le Professeur Bob Twiggs de l'Université de Stanford et le Professeur Jordi Puig-Suari de *California Polytechnic State University*, est devenu la norme de référence dans le domaine des nano-satellites. Le standard CubeSat a augmenté le développement de nano-satellites vers la fin du vingtième siècle et le total de projets a grandi à une centaine de projets dans le monde entier jusqu'à août 2009.

En France, le Centre National d'Etudes Spatiales (CNES) a lancé trois projets dénommés EXPRESSO, PERSEUS et RISTRETTO – pour monter l'intérêt pour l'espace parmi des étudiants et offrir à chaque étudiant une occasion unique de participer à toutes les phases d'un projet spatial concret incluant des créations expérimentales (par exemple, des petites fusées pour le lancement de nano-satellites, des systèmes orbitaux et des ballons stratosphérique).

De plus, le programme canadien CanX (*Canadian Advanced Nanospace eXperiment*) développé au sein du *Space Flight Laboratory* de l'Université de Toronto fournit un accès à l'espace peu coûteux pour la communauté de recherche à l'aide de nano- et pico-satellites. Les nano-satellites CanX sont conçus par les étudiants du Master de l'Université de Toronto, sous la coordination du personnel professionnel du Laboratoire.

Le Bureau d'Armée de l'Air Américain (AFOSR) avec la Direction de Véhicules Spatiaux (AFRL/RV) a annoncé le Programme *2011 University Nanosatellite Program* pour promouvoir la recherche au niveau des universités et soutenir l'éducation dans le domaine spatial, en se concentrant sur les nano-satellites. La NASA a lancé le Programme *Nano-Satellite Launch Challenge* avec les objectifs suivants :

- concevoir un système de lancement peu coûteux, avec un grand niveau de sécurité et qui permet des lancements fréquents de petites charges utiles (i.e., pico-satellites, nano-satellites);

- proposer des innovations dans le domaine de la propulsion et d'autres technologies pour les systèmes de lancement futurs;

- le nouveau système de lancement commercial de nano-satellites doit offrir une capacité de lancement à un coût comparable avec les actuels lancements de charges utiles secondaires. Ainsi, un nouveau marché potentiel avec le Gouvernement, les entreprises commerciales et les universitaires sera mis en place.

La technologie des petits satellites a ouvert une nouvelle ère dans l'ingénierie des satellites, en diminuant le coût des missions spatiales, mais sans réduire les performances.

Cependant, le plus grand défi à long terme pour la communauté des petits satellites est de développer un marché commercial robuste étant capable de produire des petits satellites à échelle industrielle.

La fabrication de petits satellites plus rentables exige de nouvelles technologies qui doivent être certifiées pour le vol spatial. Ainsi, une mission avec des petits satellites sera la meilleure façon d'exécuter une première vérification du fonctionnement dans l'espace.

À l'état actuel de la technologie, les micro-satellites pourraient fournir les mêmes fonctionnalités que les satellites conventionnels, bien qu'ils ne soient pas capables d'avoir la même résolution que les télescopes Planck, Herschel ou Hubble. Ils sont néanmoins capables de fonctionner aussi bien pour des communications ou des missions d'observation de la Terre.

Cette thèse se concentre sur un concept relativement nouveau – les constellations de nano-satellites – qui exigent toujours une recherche significative au niveau de la conception de la mission spatiale. Au moment de la rédaction de ce mémoire, il n'y a encore aucune mission spatiale active utilisant des constellations de nano-satellites. Les avantages principaux des nano-satellites sont la réduction du temps de production et la réduction du coût. Peut-être l'aspect le plus important pour le vol en formation est sa capacité à exécuter des mesures coordonnées et distribuées. Cependant, les constellations de nano-satellites ont des défis spécifiques, y compris des ressources très limitées en termes de CPU, mémoire, énergie, bande passante, adaptabilité, redondance des systèmes, navigation, contrôle, autonomie et robustesse par rapport aux missions spatiales avec des satellites conventionnels.

Une configuration de nano-satellites doit être capable d'atteindre les exigences et les contraintes de la mission spatiale pour laquelle elle a été conçue. Actuellement, il y a peu d'études de performances pour évaluer l'efficacité des télécommunications des constellations de nano-satellites.

Dans l'histoire des communications par satellite, il y a toujours eu une haute priorité pour développer des techniques plus efficaces pour la transmission et la réception de données. Il y a beaucoup de défis à résoudre avant que les objectifs ambitieux de communications efficaces dans les constellations de nano-satellites puissent être réalisés, y compris la conception de protocoles spécifiques prenant en considération les ressources limitées des nano-satellites, les types d'erreurs dans les constellations de nano-satellites à orbite basse, l'adaptabilité et les problèmes de synchronisation. Tous ces défis exigent que nous révisions les stratégies de gestion de réseau et que nous considérions de nouveaux mécanismes de routage pour accomplir "plus avec moins".

Cette thèse a un double but : la proposition de modèles innovants de constellations de nano-satellites et de nouvelles approches de routage pour assurer les télécommunications

dans les réseaux de nano-satellites. Pour réaliser cet objectif, nous avons considéré l'approche de recherche suivante.

Dans la première partie de ce mémoire, nous introduirons le domaine des petits satellites, en définissant des concepts comme le nano-satellite, le vol en formation, le "cluster" et la constellation.

Nous identifierons les défis des systèmes nano-satellitaires ainsi que des complémentarités entre les satellites conventionnels et les petits satellites. Une fois les défis des petits satellites identifiés, des approches de routage pour des réseaux de nano-satellites seront proposées, basées sur une étude de routage dans les réseaux de satellites classiques, les réseaux Ad hoc et les réseaux de capteurs. Nous nous concentrerons sur des réseaux de capteurs parce qu'ils partagent des caractéristiques communes avec les réseaux de nano-satellites : dispositifs très petits, bon marché, faible consommation et avec des capacités de calculs et de communications très limitées. Nous tournerons ensuite notre attention vers le domaine des réseaux Ad hoc pour trouver des approches de routage qui peuvent être utilisées ou adaptées pour les réseaux nano-satellitaires. Nous identifierons des défis communs tant pour les réseaux Ad hoc que pour les réseaux de nano-satellites. Finalement, notre étude sur le routage dans les réseaux de satellites conventionnels montrera que le protocole XSTP (*eXtended Satellite Transport Protocol*) pourrait être un candidat idéal pour les constellations nano-satellitaires.

Dans la deuxième partie de cette thèse, le cadre des télécommunications des réseaux nano-satellitaires sera présenté et discuté avec les défis en termes de Qualité de Service que nous trouvons dans ce type de réseau. L'évolution de la technologie multimédia et l'intérêt commercial des opérateurs nano-satellitaires futurs pour pénétrer le marché de télécommunications, en offrant au grand public des services de télécommunications de haute qualité et bon marché, feront que l'aspect Qualité de Service sera très important dans les futures constellations de nano-satellites. Pour cette raison, nous proposerons plusieurs approches pour implémenter la Qualité de Service dans les réseaux de nano-satellites.

Dans la troisième partie de ce travail de recherche, l'actuel intérêt considérable pour les constellations de nano-satellites à orbite basse, capables de fournir une grande gamme d'applications comme la surveillance de l'environnement et des désastres (par exemple, des inondations, des incendies, des glissements de terre, des déversements accidentels de pétrole), la topographie de la Terre ou encore les communications et l'astronomie, sera présenté. Dans ce contexte, nous proposerons trois modèles de constellations de nano-satellites pour fournir des services de télécommunications aux régions isolées :

- Le modèle NanoDREAM conçu pour le Désert Salar de Uyuni de la Bolivie, une région qui détient 70% de la réserve mondiale de lithium. La mission d'exploitation du lithium en Bolivie a reçu une attention spéciale car les futures applications envisagées pour la réduction des émissions de CO<sub>2</sub> au niveau mondial nécessitent ce métal.
- Le modèle NanoICE destiné pour les Régions Polaires, pour satisfaire les besoins de télécommunications de la communauté scientifique de l'Antarctique et de l'Arctique.
- Le modèle NanoSPHERE conçu pour fournir une couverture globale de la Terre dans le contexte d'un marché de télécommunications concurrentiel.

Pour assurer les exigences d'une mission impliquant une constellation nano-satellitaire avec un minimum de ressources, des configurations spatiales optimales de nano-satellites doivent être conçus. Ainsi, des techniques numériques et des simulations seront employées pour déterminer la meilleure constellation de nano-satellites qui répond à deux objectifs : la minimisation du nombre de nano-satellites dans la constellation et la maximisation de la zone de couverture, étant donné les ressources minimales qui sont disponibles. Pour assurer une constellation cohérente, nous considérerons aussi des contraintes sur le type d'orbite.

Ces modèles seront développés analytiquement et mis ensuite en œuvre dans le simulateur SaVi afin d'identifier la meilleure constellation satisfaisant les requis de la mission en termes de couverture et en réduisant au minimum le nombre de nano-satellites de la constellation.

De plus, nous proposerons une architecture pour le segment terrestre déployé sur la zone d'exploitation du Désert Salar de Uyuni. Ce réseau est un réseau maillé sans fil qui permet d'interconnecter facilement et efficacement tous les bâtiments, en utilisant une technologie peu coûteuse. Notre choix pour cette technologie est basé sur les capacités des réseaux maillés sans fil qui sont compatibles avec notre proposition de mission. Le simulateur OPNET sera utilisé pour exécuter des simulations afin d'évaluer ses performances pour les communications via une constellation de nano-satellites.

Finalement, le protocole de transport XSTP, identifié comme un candidat possible pour les réseaux de nano-satellites, sera implémenté dans le simulateur NS2. Plusieurs études de simulations seront conduites, en considérant un scénario de communication unidirectionnel et un scénario de communication bidirectionnel. Les performances du protocole XSTP sur le réseau de satellites traditionnels et la constellation de nano-satellites seront évaluées utilisant quatre paramètres de performances de la QoS : la bande passante effective, l'overhead, l'efficacité du canal et la bande passante nécessaire pour le canal inverse. Nous détaillerons la comparaison entre un réseau de satellites conventionnels et un réseau nano-satellitaire en termes de performances du protocole XSTP.

Pour conclure, ce travail de recherche propose de nouveaux modèles de constellations de nano-satellites et des missions scientifiques innovatrices, implémente des topologies de réseaux satellitaires et nano-satellitaires ainsi qu'une architecture d'un segment terrestre dans des simulateurs divers (i.e., NS2, SaVi, OPNET) et développe de nouveaux modules logiciel pour les protocoles de transport STP and XSTP afin d'évaluer leur performances sur les réseaux de satellites traditionnels et de nano-satellites.

## **Le plan de la thèse**

Une fois que l'approche de recherche utilisée et le cadre de cette thèse ont été présentés, nous décrivons rapidement la structure de ce mémoire. Ainsi, cette thèse est divisée en cinq chapitres, brièvement résumés ci-dessous.

Le [Chapitre 1](#) présente le cadre de la thèse, les objectifs de ce travail de recherche et la structure de ce document.

Le [Chapitre 2](#) présente un état de l'art sur le domaine des petits satellites. Dans un premier temps, les défis des petits satellites sont examinés et les aspects complémentaires des grands et des petits satellites sont discutés. Dans un deuxième temps, les applications des petits satellites sont décrits et de nouveaux concepts (i.e., le vol en formation, la constellation, le *cluster*, le *trailing*) sont définis. En outre, de nouvelles approches de routage dans les réseaux de nano-satellites sont proposées, en se basant sur une étude sur le routage dans les réseaux Ad hoc, les réseaux de capteurs et les réseaux de satellites conventionnels. De plus, deux protocoles de transport (STP – Satellite Transport Protocol et sa version améliorée, XSTP) sont brièvement présentés.

Le [Chapitre 3](#) décrit trois modèles de constellations de nano-satellites (i.e., NanoDREAM, NanoICE et NanoSPHERE) conçus pour fournir des services de télécommunications aux régions éloignées. Pour chaque modèle, une mission spécifique a été proposée. La définition du modèle mathématique est décrite, avec des paramètres de couverture et des indicateurs de performances utilisés pour l'évaluation de chaque type de constellation. Nous proposons une architecture pour le segment terrestre, basée sur la technologie sans fil, afin de fournir des services de télécommunications à la zone d'exploitation de lithium. Nous proposons aussi deux méthodes innovantes : la première est une méthodologie pour évaluer le nombre de nano-satellites dans la constellation, tandis que la deuxième est une méthode basée sur le modèle de Markov, conçue pour évaluer les performances des constellations nano-satellites.

Le [Chapitre 4](#) décrit et discute les résultats de simulations. Dans un premier temps, les trois modèles de constellations proposés dans le Chapitre 3 ont été évalués en termes de couverture, utilisant le simulateur SaVi. Des calculs numériques sont utilisés pour évaluer les performances des constellations de nano-satellites en ce qui concerne les paramètres suivants : le nombre de nano-satellites, le temps maximal en vue, des paramètres de couverture (i.e., la zone de couverture, le taux de couverture, la zone d'accès, le taux d'accès), le délai de propagation et la quantité de données transmises sur chaque passage du nano-satellite au-dessus d'une station terrestre. Cette analyse permet de déterminer la constellation nano-satellitaire optimale qui répond aux objectifs de mission. La méthode basée sur le modèle de Markov, décrite dans le chapitre précédent, est appliquée à la constellation NanoDREAM. Dans un deuxième temps, nous avons évalué les performances du protocole de transport XSTP sur un réseau de satellites classiques et un réseau de nano-satellites, en utilisant des analyses et des simulations dans le simulateur NS2. De plus, nous présentons l'environnement de simulation, les paramètres de performances de la Qualité de Service et les scénarios envisagés pour des simulations NS2. Une étude intéressante est la comparaison entre les performances du protocole XSTP sur le réseau de satellites classiques et les performances du XSTP à travers le réseau de nano-satellites.

Le [Chapitre 5](#) montre un résumé de cette thèse, ses conclusions principales, les contributions apportées par ce travail de recherche et les perspectives pour de futurs travaux de recherche.



# 1 INTRODUCTION

## 1.1 Research framework and objectives

Traditional satellites are extremely expensive to design, build, launch and operate. Consequently, both the aerospace companies and the research community have started directing their attention to missions involving many, small, inexpensive satellites, working in formation flying to achieve the same performance as a large, expensive, single satellite. The formation flying concept has recently become popular due to its potential in coordinated measurements for remote sensing missions and flexible long-term mission capabilities. Many future space missions (e.g., interferometry, space-based radar, Earth mapping) will require small satellite formation flying to achieve their complex scientific objectives.

Furthermore, many space projects in universities laboratories are focused on the development of micro-, nano- and pico-satellites for both scientific and educational purposes. The number of countries actively participating to nanosatellite programs grows substantially every year.

The CubeSat standard, developed by Prof. Bob Twiggs of Stanford University and Prof. Jordi Puig-Suari of California Polytechnic State University [1], has become the reference standard in the nanosatellite domain. CubeSat standard [2], [3], [4] has boosted the development of nanosatellites by the end of the twentieth century and the total amount of projects has grown to about a hundred projects worldwide until August 2009.

In France, the French Space Agency (CNES – Centre National d’Etudes Spatiales) has launched three projects – EXPRESSO, PERSEUS and RISTRETTO – in order to rise the interest for space among students and to offer each student a unique opportunity to participate to all phases of a concrete space project including experimental creations (e.g., very small launch vehicles for nanosatellite launching, orbital systems and stratospheric balloons).

Moreover, the Canadian Advanced Nanospace eXperiment (CanX) program [5], [6], [7], [8], [9], [10] at the UTIAS Space Flight Laboratory provides cost-effective access to space for the research and development community at home and abroad through the use of nanosatellites and picosatellites. CanX spacecrafts are designed and built by Master students at the University of Toronto, under the close supervision of professional staff.

The U.S. Air Force Office of Scientific Research (AFOSR), in conjunction with the AFRL Space Vehicles Directorate (AFRL/RV) announces the 2011 University Nanosatellite Program to promote and sustain university research and education focused on nanosatellites and related technologies. Also, NASA has launched the Nano-Satellite Launch Challenge [11] with the following objectives:

- ✓ Safe, low-cost, small payload delivery system for frequent access to Earth orbit;
- ✓ Innovations in propulsion and other technologies as well as operations and management for broader applications in future launch systems;
- ✓ A commercial capability for dedicated launches of small satellites at a cost comparable to secondary payload launches – a potential new market with Government, commercial, and academic customers.

The small satellite technology has opened a new era of satellite engineering by decreasing space mission cost, without reducing the performance. However, the biggest long-term challenge for the small satellite community is to develop a robust commercial market being able to produce small satellites.

Making small satellites more cost-effective demands new technologies that must be certified for spaceflight. Certainly, there is a higher risk associated with uncertified technology. Thus, a small satellite mission is the best way to perform a first flight verification.

At the current state of technology, micro-satellites could provide roughly the same functionalities as conventional satellites. Although they will not be able to have the same resolution as the Planck, Herschel or Hubble telescopes, they are thought to work well enough for communications and Earth observation missions.

This thesis focuses on a relatively new concept – nanosatellite constellations – which still requires significant research in many areas of space mission architecture. Actually, at the time of writing this research study, there are no active missions using nanosatellite constellations. The main advantages of nanosatellites are decreasing cost and production times. Perhaps the most significant driver for formation flying is the ability to perform coordinated yet distributed measurements. However, missions that employ a nanosatellite constellation have specific challenges, including severely constrained onboard resources, limited bandwidth, scalability, redundancy, power availability, navigation, control, autonomy, and robustness, as compared to single-spacecraft missions. A nanosatellite configuration must be capable of meeting demanding mission requirements and constraints. Yet there are little studies in the literature on performance measures for evaluating the effectiveness of communications in nanosatellite constellations.

Throughout the history of satellite communications, there has always been of high priority to find more efficient techniques of transmitting and receiving data. There are many challenges to be resolved before the ambitious objectives of efficient communications within nanosatellite constellations can be achieved, including design of specific protocols that take into consideration the limited onboard resources, the types of errors founded in LEO nanosatellite environment, scalability and synchronization issues. All these challenges require us to revise network management strategies and consider novel routing mechanisms to accomplish “more with less”.

The multidisciplinary aspect of this research study is obvious, since it requires notions of orbital mechanics, astrodynamics, constellation design, cost modeling, launch modeling and so forth. Addressing any of them in-depth would be a complete project on its own.

This research work is based on the assumption that nanosatellite constellation design is a complex problem that must balance objectives and constraints. We believe that nanosatellite constellation architectures resulted from the application of our own dimensioning technique prove that the nanosatellite constellation conceptual design problem can be properly modeled mathematically. This type of design problem involves the selection of a large number of design variables and parameters in order to minimize or maximize an objective(s) under a set of constraints.

The main goal of this thesis is two-fold: proposing innovative nanosatellite constellation models and new routing approaches for nanosatellite network

telecommunications. To achieve this overall objective, the following research approach was considered.

Firstly, an introduction into small satellite field is made, by defining concepts such as nanosatellite, formation flying, cluster, and constellation. Also, the challenges of nanosatellite systems were identified along with some complementary aspects of large and small satellites. Then, the small satellite challenges were identified and routing approaches for nanosatellite networks were suggested, based on a study of routing in conventional satellite network, Ad hoc network, and sensor networks. We focus on sensor networks because they share common features such as: small, low-power, and low-cost devices with limited computational and communication capabilities. We have also turned our attention to Ad hoc network domain to find routing approaches that can be used in nanosatellites networks. Thus, we identified common challenges for both Ad hoc and nanosatellite networks. Lastly, our survey on routing in satellite network showed that XSTP (eXtended Satellite Transport Protocol) might be a candidate transport protocol targeted for nanosatellite constellations.

Secondly, the telecommunication framework of nanosatellite networks is presented and discussed along with QoS challenges. The evolution of multimedia technology and the commercial interest of future small satellite operators to reach widely public applications will make QoS in nanosatellite networks an area of great interest. For this reason, several approaches for provisioning QoS in nanosatellite networks were proposed.

Nowadays, there is a considerable interest in LEO nanosatellite constellations capable of providing a large range of applications such as: environment and disaster monitoring (e.g., floods, fires, landslides, oil spill), Earth topographic mapping as well as communications and astronomy. Therefore, three nanosatellite constellation models were proposed for providing telecommunications services to remote regions.

NanoDREAM model is designed for Bolivia's Salar de Uyuni Desert, a region which detains 70% of the global lithium reserve. Bolivia's lithium exploitation mission has received significant attention considering the new energy policies and the low-carbon technology's applications. NanoICE model is intended for Polar Regions, in order to meet the voice and data transfer needs of the entire Antarctic and Arctic scientific community. NanoSPHERE is aimed to provide global coverage in the context of a robust telecommunications market.

To ensure that the mission requirements for nanosatellite constellations are met with the least amount of resources, optimal configurations must be determined. Thus, numerical techniques and simulations are employed to determine the best nanosatellite constellation which responds to two objectives: minimizing the number of nanosatellite within the constellation and maximizing the coverage area, given the minimal resources that are available. To ensure a cohesive constellation, we also consider constraints on the orbits as well as some simplifying assumptions.

These models were developed analytically and then implemented in SaVi modeler in order to evaluate nanosatellite constellations in terms of coverage.

Additionally, a ground segment architecture deployed over the exploitation area of Salar de Uyuni Desert was proposed. This ground segment network is a wireless mesh network that allows an easily, effectively and wirelessly connection of all the buildings using inexpensive technology. Our choice for this technology is based on the capabilities of

wireless mesh networks that are consistent with our mission proposal. OPNET modeler was used to perform simulations on this ground wireless-based network.

Finally, XSTP transport protocol, identified as a possible candidate for nanosatellite networks, was implemented in NS2 simulator and simulations studies were conducted, by considering one-way communication scenario and bidirectional communication scenario. The performance of XSTP over traditional satellite network and nanosatellite constellation was evaluated using four QoS metrics: effective throughput, transmission overhead, channel efficiency and reverse channel utilization. A special emphasis is placed on the comparison between satellite network and nanosatellite network in terms of XSTP performance.

In conclusion, this research has advanced the field of nanosatellite constellations by proposing new nanosatellite constellation models and innovative scientific missions, implementing nanosatellite network models and ground segment architecture in various modelers (i.e., NS2, SaVi, OPNET) and creating software implementations of STP and XSTP transport protocols to evaluate their performance over traditional satellite network and nanosatellite constellations respectively.

## 1.2 Thesis outline

This research work is divided into five chapters that are briefly presented below.

[Chapter 1](#) presents thesis framework, along with the research goals and an outline of this document.

[Chapter 2](#) presents a comprehensive literature review on small satellite domain. Firstly, the challenges of small satellites are examined and complementary aspects of large and small satellites are discussed. Secondly, the potential applications of small satellites are described and new concepts (i.e., formation flying, constellation, cluster) are explained. Then, important ongoing and future research directions for small satellites routing are highlighted based on a study concerning routing mechanisms and topologies in sensor networks, Ad hoc networks and conventional satellite networks. Also, two transport protocols (Satellite Transport Protocol and its extended version, XSTP), that are the main focus of our simulation studies, are briefly presented.

[Chapter 3](#) describes three nanosatellite constellation models (i.e., NanoDREAM, NanoICE, and NanoSPHERE) designed to provide telecommunications services to remote regions. For every model, a dedicated mission was proposed. The formal mathematical problem definition is described along with coverage parameters and the performance indicators used to assess the performance of each type of constellation. We propose a ground segment architecture, based on wireless technology, in order to provide communication services to the lithium exploitation area. Also, we propose two innovative methods: the first one is a methodology for estimating the number of nanosatellite in the constellation, while the second one is a Markov-based method for estimating the performance of nanosatellite constellations.

[Chapter 4](#) describes and discusses the results of simulations. Firstly, the three models of constellations proposed in Chapter 3 were evaluated with respect to coverage criterion, using SaVi simulator. Numerical calculations are employed to evaluate the performance of

nanosatellite constellations with respect to the following parameters: number of nanosatellites, maximum time in view, coverage parameters (i.e., antenna footprint, coverage rate, access area, access rate), propagation delay and the amount of data transmitted on each nanosatellite pass over a ground station. This analysis allows determining the optimal nanosatellite constellation which responds to the mission objectives. Also, the Markov modeling-based method described in the previous chapter is applied to NanoDREAM constellation.

Secondly, we assessed the XSTP transport protocol performance over conventional satellite network and nanosatellite network, by using analysis and simulations in NS2 modeler. There are also presented the simulation environment, the QoS performance metrics and the scenarios envisaged for NS2 simulations. An interesting comparison study of satellite network and nanosatellite network in terms of XSTP performance concludes this chapter.

[Chapter 5](#) shows a summary of this work, its main conclusions and contributions, and indicates potential areas for further study.



# CHAPTER 2

## Chapitre 2. ETAT DE L'ART SUR LE DOMAINE DE PETITS SATELLITES

Ce chapitre présente une vue d'ensemble sur le domaine des petits satellites. La première partie de ce chapitre introduit des concepts comme les nano-satellite, le vol en formation, la constellation, le *cluster*, et présente aussi leur avantages et leur inconvénients par rapport aux satellites classiques ainsi que leur domaines d'application. Ensuite, les avantages et les inconvénients des formations de petits satellites sont soulignés. Les défis de petits satellites sont également présentés.

Le terme nano-satellite est utilisé pour dénommer un satellite avec une masse comprise entre 1 et 10 kg.

Les principaux avantages de petits satellites par rapport aux satellites conventionnels sont :

- ✓ la conception plus simple ;
- ✓ la construction plus rapide ;
- ✓ le coût réduit de fabrication et de lancement ;
- ✓ la facilité de fabrication en série ;
- ✓ des opportunités de lancement plus fréquentes ;
- ✓ la capacité d'être lancé en groupes ("*piggyback*" ou charge utile secondaire) avec de plus grands satellites ;
- ✓ la perte financière minimale en cas d'échec.

Parmi les inconvénients de petits satellites par rapport aux satellites traditionnels, nous pouvons citer :

- ✓ la durée de vie plus courte ;
- ✓ la capacité d'équipement réduite ;
- ✓ l'impossibilité d'avoir des équipements puissants ;
- ✓ la décroissance orbitale plus rapide.

Les principaux domaines d'applications de petits satellites sont : les télécommunications, l'observation de la Terre, la recherche scientifique, les démonstrations de technologie, le domaine militaire et la formation dans le domaine universitaire.

Le concept de vol en formation est défini comme une formation de deux ou plusieurs satellites qui utilisent un mécanisme de contrôle actif pour maintenir leurs positions relatives et leurs vitesses.

Plutôt qu'utiliser un seul satellite grand et coûteux d'effectuer une certaine mission, de nombreux petits satellites, peu coûteux, peuvent être mis dans une constellation, de manière plus efficace, pour accomplir les mêmes objectifs qu'un satellite conventionnel. Par contre, remplacer un satellite traditionnel avec un groupe de petits satellites placés en formation pourrait être bénéfique pour certaines missions, mais pas rentable pour d'autres.

Il y a trois classes de vol en formation : *Leader-Follower*, *cluster* et constellation. La première classe est constituée d'un groupe de deux ou plusieurs satellites placés sur la même orbite, ayant des niveaux hiérarchiques et d'autonomie, en maintenant une distance fixe entre eux afin d'attendre des multiples capacités d'observation d'une cible. Le *cluster* est une



formation de plusieurs satellites qui fonctionnent de manière interdépendante et en coopération pour accomplir une mission spatiale complexe. Le concept de constellation désigne un groupe de satellites similaires, assurant une couverture coordonnée de la Terre, fonctionnant ensemble sous contrôle partagé, synchronisés pour qu'ils se chevauchent bien dans la zone de couverture et n'aient pas interféré avec la couverture d'autres satellites.

Les principaux avantages de vol en formation sont :

- ✓ reconfiguration sur orbite qui offre la capacité d'accomplir des missions multiples et une flexibilité de conception ;
- ✓ temps de conception et développement réduits en raison de la fabrication en série ;
- ✓ plus bas coût de fabrication pour la même raison ;
- ✓ taille et complexité de satellites réduites ;
- ✓ redondance plus haute dans la formation et une tolérance aux pannes améliorée ;
- ✓ amélioration des missions grâce à la capacité de voir des cibles sous angles multiples ou à des instants multiples ;
- ✓ masse individuelle et volume réduisent le coût de lancement et offrent une flexibilité de lancement accrue ;
- ✓ perte financière minimale en cas d'échec ;
- ✓ avantages spécifiques :
  - possibilité de créer des synthèses d'ouvertures pour les missions à interféromètres ;
  - augmentation de la portée des mesures pour les missions de surveillance.

Bien sûr que les formations de petits satellites ont aussi des inconvénients comme :

- chaque satellite exige ses propres sous-systèmes ;
- l'initialisation et la maintenance de l'emplacement relatif de chaque satellite dans la formation (particulièrement, si les satellites sont lancés séparément) ;
- des conditions sévères pour l'alignement de satellites (par exemple, pour une mission interférométrique, un mauvais alignement des détecteurs des télescopes peut introduire des erreurs de mesure, s'ils sont montés sur des satellites différentes) ;
- le coût de développement d'une formation de petits satellites peut être égal au coût d'un grand satellite si les petits satellites doivent réaliser des missions scientifiques très exigeantes ;
- complexité accrue des opérations pour les stations au sol ;
- grande quantité de débris à la fin de la durée de vie de la formation.

Les constellations de nano-satellites ont un double défi. Le nano-satellite a des ressources très limitées en termes de puissance de calcul, mémoire, énergie, capacité de communications. En même temps, le concept de constellation exige le traitement simultanément d'un grand nombre de petits satellites et la transmission de données aux utilisateurs dans un format compréhensible.

Un problème-clé dans le domaine de petits satellites est la gestion des risques. Puisqu'aucun système complexe ne peut être conçu et évalué contre tous les modes de

défaillance, la première expérience de vol est souvent la meilleure et la seule façon de tester des différentes technologies et les validées pour des missions spatiales plus complexes.

Le plus important défi, à long terme, pour la communauté de petits satellites est de développer un marché commercial robuste capable de fournir des services et des petits satellites fiables à bas coût.

Actuellement, nous ne pouvons pas parler de l'existence d'un marché commercial solide pour de petits satellites. Les organismes publics et les agences spatiales continuent à être le support financier principal de la communauté de petits satellites. Cette communauté est toujours liée avec l'éducation et aux activités de recherche. A notre avis, cette situation restera en place jusqu'à l'apparition sur le marché de satellites d'un grand nombre des entreprises qui investissent dans le domaine de petits satellites afin de pouvoir produire des petits satellites à l'échelle industrielle. Le premier pas a été déjà fait par deux entreprises : SSTL et RapidEye. Dans l'avenir, nous pourrions nous attendre à l'apparition de beaucoup de vendeurs commerciaux de petits satellites.

La deuxième partie de ce chapitre introductif présente les résultats d'une analyse de lancement de nano-satellites dans la période 2004 - mi 2007. Sachant que le domaine des petits satellites s'est imposé comme un domaine particulier dans les deux dernières décennies, nous avons mené une étude sur le lancement de nano-satellites dans la période 2004 – mi 2007 afin d'identifier la tendance future dans ce domaine. Le manque d'information et les sources dispersées de documentation quant aux systèmes nano-satellites a imposé un défi significatif à notre étude. Notre analyse montre que dans la période 2004 – mi 2007, 55 nano-satellites ont été lancés. L'année 2006 est le *leader* en termes de lancements de nano-satellites, avec presque 50% du nombre total de lancements. Aussi, en 2006 a eu lieu le premier événement impliquant 16 nano-satellites lancés simultanément. Ce lancement montre que les futures constellations de nano-satellites peuvent être rapidement déployées pour assurer des services immédiats. La plupart des charges utiles ont été conçues pour conduire des missions technologiques (67%); cela signifie que les nano-satellites sont utilisés principalement comme des démonstrateurs technologiques, pour évaluer les équipements différents qui peuvent être utilisés pour des missions spatiales plus complexes. Ainsi, la perte financière en cas d'échec est réduite au minimum. Presque 75% de nano-satellites ont été conçus par des étudiants dans des laboratoires de recherche universitaires. Dans le monde entier, des programmes de petits satellites permettent de monter l'intérêt pour le domaine spatial parmi les étudiants et offrir à chaque étudiant une occasion unique de participer à un projet spatial concret incluant des réalisations expérimentales.

Pour conclure, dans les années suivantes, les nano-satellites accéléreront l'exploration spatiale pour des besoins tant civils que militaires. Donc, les scientifiques seront capables d'obtenir des vols plus fréquents pour leurs expériences et à plus bas coût.

La dernière partie de ce chapitre introductif présente le cadre de télécommunications pour les réseaux de nano-satellites, en expliquant les raisons pour lesquelles nous nous sommes concentrés sur l'aspect de télécommunications dans les réseaux de nano-satellites. Les défis en termes de QoS de réseaux de nano-satellites sont également présentés.

De plus, des nouvelles approches de routage dans les réseaux de nano-satellites ont été proposées, en se basant sur une étude que nous avons faite sur le routage dans les réseaux de capteurs, les réseaux Ad hoc et les réseaux de satellites traditionnels. Ainsi, le protocole de

transport XSTP (*eXtended Satellite Transport Protocol*) a été identifié comme un candidat possible pour les réseaux nano-satellites.

Comme mentionné dans le premier chapitre, nous considérons que cette thèse est une fusion de deux domaines : le premier est le domaine des télécommunications, en traitant la problématique de routage dans les réseaux nano-satellites et l'évaluation des performances de protocoles de transport conçus pour ce type de réseau. Le deuxième est le domaine de la conception de constellations, en proposant et analysant des modèles de constellations de nano-satellites.

La source de notre intérêt pour le routage dans les réseaux de nano-satellites se trouve dans quelques questions que nous avons posées :

- *Quels sont les défis du routage dans les réseaux nano-satellites ?*
- *Est-ce que les protocoles des réseaux de satellites classiques peuvent être utilisés avec succès dans les réseaux de nano-satellites ou une approche différente est-elle nécessaire ?*
- *Quels types de topologies sont les plus appropriées pour les réseaux de nano-satellites ?*
- *Peuvent d'autres types de réseaux (e.g., les réseaux de capteurs, les réseaux Ad hoc, les réseaux de satellites conventionnels) nous fournir de nouvelles idées pour la communication dans les réseaux de nano-satellites ?*
- *Avons-nous besoin d'outils de simulation dédiés pour évaluer les performances des réseaux de nano-satellites en termes de communications ? Les simulateurs de réseaux actuels peuvent-ils être adaptés pour supporter ce nouveau type de réseau ?*
- *Quels types de protocoles assureront une communication fiable dans les réseaux de nano-satellites ?*
- *Existe-t-il des protocoles développés pour les réseaux de nano-satellites ?*
- *Existe-t-il des protocoles testés sur les nano-satellites déjà présents en orbite ?*
- *Comment pouvons-nous mettre en œuvre des stratégies de QoS dans les réseaux nano-satellites pour fournir des services de télécommunication efficaces ? Les stratégies actuelles de QoS sont-elles adéquates aux nano-satellites ou de nouveaux mécanismes de QoS doivent-ils être développés ?*

Répondre à toutes ces questions implique un travail considérable et complexe en termes d'études et des simulations. Certains de ces sujets peuvent être un projet complet tout seul. En considérant cette complexité, cette thèse se propose de répondre à une partie de ces questions, le reste étant traité comme des perspectives pour le travail futur.

La Qualité de Service (QoS) dans les réseaux de nano-satellites sera un grand défi pour la communauté scientifique, en considérant l'évolution de la technologie multimédia et l'intérêt commercial des futurs opérateurs nano-satellites pour fournir des services de télécommunications de haute qualité au grand public.

De plus, il devrait être souligné qu'à la meilleure connaissance des auteurs, il n'y a eu aucune recherche précédente examinant l'aspect QoS de réseaux nano-satellites. C'est une raison de plus pour prendre l'initiative et nous avons proposé dans ce chapitre plusieurs approches pour intégrer l'aspect QoS dans les réseaux de nano-satellites.

Dans un premier temps, nous avons étudié les réseaux de capteurs et nous avons fait une comparaison entre les capteurs et les nano-satellites. Ainsi, nous avons observé que les réseaux de capteurs et les réseaux de nano-satellites ont des caractéristiques communes comme :

- des dispositifs très petits, à faible consommation d'énergie, avec des capacités de communication limitées et des ressources très restreintes;
- fréquent changement de topologie du réseau à cause de la mobilité de nœuds ;
- des problèmes de sociabilité à cause du grand nombre de nœuds.

Plusieurs approches de routage ont été proposées en s'inspirant du routage dans les réseaux de capteurs.

Nous avons aussi concentré notre attention sur le domaine des réseaux Ad hoc pour trouver des approches de routage qui peuvent être utilisées ou adaptées aux réseaux de nano-satellites. Nous avons identifié que les deux types de réseaux partagent des défis communs comme :

- des problèmes d'adaptabilité en raison du grand nombre de nœuds;
- la topologie dynamique;
- des liaisons de réseau variables en temps;
- des ressources sévèrement limitées en termes de puissance de calcul, mémoire, énergie, capacité de stockage;
- la bande passante variable;
- maintenance de la topologie : mise à jour d'information de liaisons dynamiques parmi les nœuds mobiles.

En étudiant les trois types de routage Ad hoc (i.e, le routage actif, le routage réactif et le routage hybride), nous avons identifié que le routage réactif est recommandé pour les réseaux de nano-satellites avec des ressources restrictives.

Finalement, le routage dans les réseaux de satellites classiques a été investigué pour trouver des nouvelles approches de routage pour les réseaux de nano-satellites. Ainsi, le protocole XSTP a été identifié comme possible candidat pour les réseaux de petits satellites ; sachant qu'il est spécifiquement optimisé pour des liaisons satellitaires asymétriques, caractérisées par des haut taux d'erreurs et des RTT (*Round Trip Time*) variables. De nombreux types de conditions d'erreurs existent et varient dans leur nature. L'incapacité de différencier entre ces conditions d'erreurs pour réagir efficacement, est l'un des problèmes classiques des protocoles de transport standard. En conséquence, les protocoles de transports actuels imposent l'hypothèse que la congestion du réseau est la seule cause de toutes les erreurs. Dans les réseaux de satellites, il y a d'autres types d'erreurs, y compris la corruption bits, le transfert et la connectivité limitée. Ces erreurs sont interprétées et liés directement à la congestion par les protocoles de transport. L'application du contrôle de congestion sur ces erreurs implique la dégradation inutile du débit.

Le protocole XSTP utilise une nouvelle stratégie pour résoudre ce problème. Ainsi, grâce à son mécanisme de *probing*, le protocole XSTP permet de s'adapter aux différents types d'erreurs trouvées dans les réseaux de satellites à orbite base. L'objectif principal du mécanisme *XSTP-probing* est d'adapter le taux de transmission de l'émetteur aux différentes conditions d'erreur dans le réseau. En général, lors d'une détection d'une perte, le mécanisme suspend la nouvelle transmission de données et lance un cycle de *probing* pour rassembler

des statistiques de RTT sur la connexion. Le mécanisme compare ces statistiques de RTT à l'estimation RTT disponible lorsque la perte a été découverte. Après la finalisation du "*probing cycle*" et si la congestion est détectée par la comparaison des RTTs, un contrôle de congestion est immédiatement appelé. Sinon, les niveaux de transmission sont restaurés sans faire aucune action. Enfin, les segments sont immédiatement rapportés disparus et retransmis.

## 2 STATE OF THE ART OF SMALL SATELLITES DOMAIN

### 2.1 Introduction

Chapter 2 presents an overview of small satellite domain. The first part of this chapter introduces the concept of nanosatellite, discusses small satellite challenges and shows some complementary aspects of large and small satellites. Then, the advantages and disadvantages of small satellites over conventional satellites are underlined. We also reviewed the literature to determine nanosatellite applications that need more attention. The launching opportunities for small satellites are discussed in Chapter 2.2.6. The general architecture of a nanosatellite is described in Chapter 2.2.7, along with a brief explanation of each sub-system.

The second part of this chapter describes the formation flying concept. We identified three types of formation (i.e., Leader-Follower, Cluster and Constellation). Theirs features are described along with some relevant examples. Since nanosatellite constellations is the main focus of this research, we found important to point out the main advantages and disadvantages of formation flying. Thus, we show the huge potential of future nanosatellite constellations.

Considering that small satellite domain has imposed itself as a particular field in the last two decades, we found important to make an analysis of nanosatellite launches in the period 2004-mid 2007 in order to identify the trend in nanosatellite launching. This survey allows us to see if a small satellite market takes shape in the near future.

The last part of this chapter presents the telecommunications framework of nanosatellite networks. The design of efficient communication mechanisms for nanosatellite networks is a challenging task, considering all the limited resources of nanosatellites. For these reason, we have investigated other types of networks (i.e, sensor networks, Ad hoc networks, satellite networks) in search of new ideas that might be used or adapted for nanosatellite networks. The new routing approaches resulted from this survey are described. Moreover, QoS is a full featured technology that can control or reduce costs and improve nanosatellite network performance. It should be stressed out that to the best knowledge of the authors, there has been no previous research work investigating the QoS aspect of nanosatellite networks. Therefore, we proposed several approaches for QoS provisioning in nanosatellite networks.

Finally, the XSTP (eXtended Satellite Transport Protocol), identified as candidate for nanosatellite networks, along with its basic version (i.e., STP - Satellite Transport Protocol) are briefly presented.

### 2.2 Nanosatellite survey

#### 2.2.1 Introduction

The term "nanosatellite" or "nanosat" is usually applied to the name of an artificial satellite with a mass between 1 and 10 kg. Compact and lightweight, the nanosatellites have a great potential – they are easier and less expensive to launch into orbit than traditional satellites.

The small satellite technology has opened a new era of satellite engineering that minimizes costs by risk management.

Table 2.1 presents a classification of satellites, with specifications of mass, cost and time of development.

<i>Category</i>	<i>Mass (kg)</i>	<i>Cost</i>	<i>Time (years)</i>
<b>Large</b>	<b>≥ 1000</b>	<b>≥ \$500M</b>	<b>≥ 15</b>
<b>Small</b>	<b>500 - 1000</b>	<b>\$100M</b>	<b>5</b>
<b>Mini</b>	<b>100 - 500</b>	<b>\$20M</b>	<b>2-3</b>
<b>Micro</b>	<b>10 - 100</b>	<b>\$10M</b>	<b>1.5</b>
<b>Nano</b>	<b>1 - 10</b>	<b>\$350K – 1M</b>	<b>≈ 1</b>
<b>Pico</b>	<b>0.1 - 1</b>	<b>≥ \$100K</b>	<b>≥ 1</b>
<b>Femto</b>	<b>&lt; 0.1</b>	<b>-</b>	<b>-</b>

*Table 2.1 – Satellite classification*

Nowadays, many universities laboratories over the world have developed nanosatellites programs in order to design and build low-cost nanosatellites for education and research experiments. Appendix 1 [12] presents a list of various nanosatellites programs developed worldwide. Also, paper [13] provides the results of a global survey of publicly known pico- and nanosatellite projects.

During the documentation phase of this research work, we have studied several microsatellite projects [14], [15], nanosatellite projects, as shown by papers [16], [17], [18], [19], [20], [21], [22], picosatellite projects [23], [24], [25], [26], all developed by various universities worldwide.

In Europe, Surrey Satellite Technology Ltd (SSTL), a spin-off company of the University of Surrey, now fully owned by EADS Astrium, is an important actor in the small satellites domain. Its small satellite program is described in papers [27], [28], [29]. Also, the researchers have gone even further in the process of satellite miniaturization by developing femtosatellites [30] that are satellite with a mass of 100 g.

Moreover, the Technical University of Denmark developed its own small satellite program, described in papers [31], [32], [33].

The French Space Agency (CNES) has launched three projects in the nanosatellite domain: PERSEUS, EXPRESSO and RISTRETTO.

EXPRESSO (*EXpérimentations et PROJets Etudiants dans le domaine des Systèmes Orbitaux et ballons stratosphériques*) project [34], [35], led by Toulouse Space Center, is a request for ideas in the field of orbital systems and balloons.

This project has two major goals:

- ✓ to rise the interest for aerospace among students and to offer each student a unique opportunity to take part in a concrete project including experimental creations.
- ✓ to allow students to participate in the evolution of the technological knowledge of the CNES.

PERSEUS (*Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique*) project [36], [37], [38], [39] has three major objectives:

- ✓ to develop a very small launch vehicle for nanosatellite launches;

- ✓ to serve as an educational tool;
- ✓ to act as a research and innovation program.

RISTRETTO (*Réseau International de Satellites de SysTèmes oRbitaux ETudiants basés sur une Technique de développement en Open source*), launched in 2009, is part of a CNES initiative to assist the emergence and development of small satellites in universities. The RISTRETTO concept is based on the development of a generic platform for the study of satellites in the range (30kg, 30W, 30L). This platform shall be developed within the context of international cooperation between universities with support offered by interested organizations (agencies, industrial companies, laboratories, etc.). Another feature of this concept is to make the platform available as an open source (technical documents, development drawings, databases, software, etc.) following the example of open source software.

According to IAA study [40], small satellite missions are supported by four contemporary trends:

- Advances in electronic miniaturization and associated performance capability;
- The recent appearance on the market of new small launchers (e.g. using modified military missiles to launch small satellites);
- The possibility of ‘independence’ in space (small satellites can provide an affordable way for many countries to achieve Earth Observation and/or defense capability, without relying on inputs from the major space-faring nations);
- Ongoing reduction in mission complexity as well as in those costs associated with management.

As a general conclusion, small satellites, through exploiting advanced technology provide an attractive solution in terms of serving the needs of developing countries.

### 2.2.2 Small satellite challenges

For information systems, nanosatellite constellations are a double-barreled challenge. The nanosatellite constrains the on-board resources for on-board processing and communications to the ground, but the constellations also require that the information systems simultaneously handle a large number of spacecraft and provide information to the users in an understandable format.

The small mass (1-10 kg) of nanosatellites limits the amount of energy provided by solar arrays as well; therefore, power availability is a constraint on both the spacecraft processor and the communications systems.

RF systems of nanosatellites typically radiate only about 0.5 watts of power. In addition to this, nanosatellites mostly use omni-directional antennas without gain because no tracking is needed for these antennas.

Depending on the orbit used, the nanosatellite may be out of contact with the ground for over a week. The limited communications opportunities and limited bandwidth impose constraints on data handling, fault detection and correction and instrument commanding in general. Because of this, the nanosatellite needs to operate autonomously and handle any anomalies or opportunities that occur. This autonomy must be accomplished within a



processing capability that is less powerful than on a bigger satellite. Because of the limited resources, use of redundant systems is not possible.

The most important long-term challenge for small satellite community is to develop a robust commercial market capable of providing low-cost, effective services.

For certain countries, small satellites are a mean to enhance the industrial domain and to provide to students a first experience by participating to all the phases of design and conception of a space project. The latter represents only a finite market.

For developing a robust market for small satellites, the manufacturers must remain relevant and cost-effective. A new trend has been observed for many space companies - the era of diminishing returns. For example, if we can reach space imaging with a spatial resolution of 1 meter, do we gain anything, in term of market, by using a resolution of 10 cm? In consequence, more companies will try to offer the same imaging product. This implies that more vendors might aspire to provide the same imagery product. Considering that the key driver is revisit time, the future small satellite market could support more suppliers of imagery products.

IAA Committee acknowledges in paper [40] that the vertical integration of the industry, to provide instruments, data and integrated data products, is likely to spur significant growth.

Nowadays, we cannot speak of the existence of a solid commercial market for small satellites. The government continues to be the main financial support of the small satellite community. This community is still linked to education and research activities – activities that rely on government support. This situation will remain in force until some economies of scale can be achieved. Two notable examples of commercial ventures are SSTL and RapidEye. In the future, we could expect many small satellite commercial vendors to come to live.

A key issue in small satellite domain is managing risk. Since no complex system can be designed and tested against all failure modes, the first fly experience is often the best and only way to make trades.

Large organizations, such as space agencies, impose a high level of restrictions on space systems. For example, NASA uses the notion of Technology Readiness Level or TRL of a system. A system has a significant flight experience if it has higher TRLs. Considering this, small satellites can be effective platforms to raise the TRL of various sub-systems that can be used in a latter design for more complex space missions. As mentioned in paper [15], IAA Committee considers that the main challenge faced by the small satellite community is to gain a broader acceptance of the notion that TRLs can be raised as an integral part of a mission rather than by implementing a dedicated mission.

Making small satellites more cost-effective demands new technologies that must be certified for spaceflight. Certainly, there is a higher risk associated with uncertified technology. A small satellite mission is the best way to perform a first flight verification. Thus, many university small satellite programs are real examples because from an educational point of view, even a failure to operate on orbit, or to achieve the orbit, can still be a successful demonstration.

### 2.2.3 Advantages and disadvantages of small satellites over conventional satellites

The main advantages of small satellite missions are:

- more frequent mission opportunities that implies faster return of science and for application data;
- larger variety of missions and therefore a greater diversification of potential users;
- more rapid expansion of the technical and/or scientific knowledge base;
- greater involvement of local and small industry.

Miniaturized satellites have several advantages over conventional satellites, such as:

- ✓ Lower cost of manufacture;
- ✓ Easiness of mass production;
- ✓ Lower cost of launch;
- ✓ Ability to be launched in groups or "piggyback" along with larger satellites;
- ✓ Ideal test bed for new technologies;
- ✓ Minimal financial loss in case of failure;
- ✓ Faster building times.

Among the small satellites disadvantages over conventional satellites are:

- Generally shorter working life;
- Reduced hardware-carrying capacity;
- Lower transmitter output power capability;
- More rapid orbital decay.

### 2.2.4 Complementary aspects of large and small satellites

The new technologies such as, formation flying algorithms, constellation self-reconfiguration, accurate precision algorithms, developed for small satellites are often later used on major missions, involving large spacecrafts (e.g., space telescope missions: ESA's Darwin, NASA's Constellation-X).

Some applications can be better solved by using distributed systems (e.g. employing constellations of micro-satellites or nanosatellites optimally configured to achieve global cover). Yet, other space mission need centralized systems (e.g., employing large optical instruments, using high power, direct broadcast, communications systems etc.).

On the other hand, for particular missions with stringent requirements, the cost of developing a small satellite constellation could be equal or even greater than a large satellite.

Through the eyes of NASA philosophy "*faster, better, cheaper*", we tend to think that small satellites is the "graal" for reducing space mission cost. Generally, space missions are design so as to obtain the lowest cost design consistent with the mission requirements and constraints. Nearly all missions to date have been "cost effective." Certainly, not all missions have been low-cost and nowadays, many organizations over the world demand reduction of mission cost.

The questions that rise here are:

*Can we get the same product, with the same performance for less money?*

*Can we achieve reliability throughout simple designing?*

*Can we meet the mission objectives with a low-cost, small satellite with respect to a traditional mission?*

*Can a small satellites constellation accomplish more complex mission than a conventional satellite?*

It is a known fact that, by dramatically reducing mission cost, the resulting system will be fundamentally different in at least some features.

In the literature, there are many methods for reducing the cost of space missions. It is important to note that there is no single, broad method for reducing mission cost. Even though many techniques may be effective, they are not all equally applicable to different programs. Each low-cost program need to find a set of solutions to fill its particular requirements. Table 2.2 summarizes cost reduction methods which are selectively used by the builders of low-cost missions.

In addition, the main aim of most space agencies, in long term, is to reduce the cost of space missions without reducing the performance.

Considering all these aspects, we cannot state that, in the future, small satellites will replace large satellites. Certainly, every type of satellite (i.e., large or small), has its own advantages and limitations. Therefore, the choice between small satellites and large satellites will depend in large measure on the goals and objectives of the mission, its requirements and design. For the purpose of this study, we consider large satellite missions and small satellite missions being complementary rather than competitive.

Method	Mechanism	Comments
<b>Programmatic</b>		
<b>Schedule Compression</b>	Reduces overhead of standing army; forcing program to move rapidly does drive down cost	- it often results in a poor design due to lack of up-front mission engineering; - it must reduce work required to be consistent with schedule
<b>Reduce Cost of Failure</b>	Allows both ambitious goals and calculated risk in order to make major progress	- fear of failure feeds cost-growth spiral; - major breakthroughs require accepting the possibility of failure, particularly in test
<b>Continuous, Stable Funding</b>	Maintains program continuity and maintains team together	Program delay will be funding break + 2 – 4 months
<b>Minimize Documentation</b>	Reduces programmatic overhead for creating, reviewing and maintaining	Critical to document reasons for key decisions and as-built design
<b>Personnel</b>		
<b>Improved Interpersonal Communications</b>	Dramatically reduces errors and omissions; it conveys understanding as well as data.	Large programs use formal, structured communications through specified channels
<b>Small Team</b>	Clear, nearly instantaneous communications; high morale; strong sense of personal responsibility	Could be a problem if a key person drops out – but in practice it rarely happens.
<b>Co-located Team</b>	Improves communications	Best communications are face-to-face, but AMSAT and others don't seem to need it
<b>Empowered Project Team</b>	Rapid decision making; strong sense of personal responsibility; can make “sensible” decisions	Eliminates a major function of the management structure
<b>Systems Engineering</b>		
<b>Trading on Requirements</b>	Eliminates non-critical requirements; it allows the use of low-cost technology	Makes traditional competition difficult
<b>Concurrent Engineering</b>	Allows schedule compression; reduces mistakes; increases design feedback	High non-recurring cost relative to lowest cost programs
<b>Design-to-Cost</b>	Adjusts requirements and approach until cost goal has been achieved	Spacecraft has rarely used it
<b>Large Margins</b>	Reduces testing; better flexibility; reduces cost of engineering, manufacturing and operations	Margins traditionally kept small for best performance – it drives up development cost
<b>Technology</b>		
<b>Use COTS Software</b>	Immediate availability; very low cost	May need modification and thorough testing; typically not optimal
<b>Use COTS Hardware</b>	Same as software	Same as software
<b>Use Existing Spares</b>	Reduced cost; rapid availability; meant for space	Only works so long as spares exist – not applicable for operational programs
<b>Use of Non-Space Equipment</b>	Takes advantage of existing designs and potential for mass production	Typically not optimal; it must be space qualified
<b>Autonomy</b>	Reduces operations costs	Can increase non-recurring cost
<b>Standardized Components and Interfaces</b>	Reduces cost and risk by reusing hardware; standardization is a major requirement for other types of manufacturing	Has been remarkably unsuccessful in space; sub-optimal in terms of weight and power
<b>Extensive Use of Microprocessors</b>	Minimizes weight; provides high capability in a small package; allows on-orbit reprogramming	Problem of single-event upsets; high cost of flight software; very difficult to manage software development
<b>Common S/W for Test and Ops</b>	Reduces both cost and schedule; avoids reinventing the wheel	May be less efficient, user-friendly than ops group would prefer

Table 2.2 – Cost reduction methods overview [40]

## 2.2.5 Small satellite applications

This chapter presents some small satellite applications drawn from UN Documents. Our comments are based on IAA study “*Cost Effective Earth Observation Missions*” [40].

### **a) Telecommunications**

Telecommunications activity potentially involves many applications. Remote and mobile communications (including messaging, electronic mail and localization) could be established using small satellites in LEO orbit. This solution can be attractive to users in remote areas/regions lacking communications infrastructure.

In the last two decades, various constellations of small satellites in LEO have been proposed to provide worldwide communications using only hand-held portable terminals for real-time voice/data services (e.g. Iridium, Globalstar) and non-real-time data transfer (e.g. Orbcom, VITASat, GEMStar, E-SAT).

Telemedicine is an application that allows the transmission of information obtained by cheap, simple sensors sited in remote areas to complex processing units in large medical centers - where these data can be interpreted by specialists.

An example is provided by the HEALTHNET project which employs a 60 kg micro-satellite (HealthSat) flown in LEO to relay medical data recorded in a number of African countries to North America.

Also, Colombian Space Agency works on the implementation of a telemedicine pilot project for transmission and reception of ECG signals. The main objective of this project is to evaluate the performance of a tele-cardiology system on Internet. The principal interest is to bring medical services to isolated communities through small satellite networks

Mobile satellite communications can play an important role in large natural disasters, by providing rescue teams with important logistical support. An example is Disaster Monitoring Constellation, a network of seven small satellites, which provides emergency Earth imaging for disaster situations.

### **b) Earth Observations**

Earth Observation applications cover activities related to data collection and to imagery. Remote sensing using low-cost small satellites which allow direct data downlink to various, small, ground stations, eliminates the need for a centralized processing and distribution system while yet providing the advantages of:

- ✓ real-time access to the observations concerned;
- ✓ small size databases and,
- ✓ easy information distribution within areas not well served by communications systems.

Furthermore, in the area of disaster prevention, demands exist for earthquake forecasts, early detection of tropical storms and predictions of volcanic activity.

### **c) Scientific Research**

As mentioned by Prof. Martin Sweeting in the lecture [41], nanosatellites can offer a very quick turn-around and inexpensive means of exploring well-focused, small-scale science

objectives (e.g.: monitoring the space radiation environment, updating the international geomagnetic reference field, etc.) or providing an early proof-of-concept prior to the development of large-scale instrumentation. Therefore, scientists could have more opportunities to gain 'real-life' experience of satellite and payload engineering and to be able to initiate a research program.

During the last decade of the 20<sup>th</sup> century, considerable progress was made in the northern hemisphere in the matter of studying both the global behavior of the upper terrestrial atmospheric regions and in establishing how these regions respond to changes in the interplanetary medium.

Many ongoing co-operative scientific programs in the area of solar and space-plasma physics illustrate the advantage of using a coordinated group of satellites to obtain multi-point measurements of various phenomena.

A particular case is provided by the International Solar-Terrestrial Physics program, which involves the co-ordination of data from the Solar and Heliospheric Observatory (SOHO) spacecraft of ESA, the WIND and POLAR spacecraft of NASA and the Geotail spacecraft of ISAS.

Further, the southern hemisphere is an important region for mounting studies of significant celestial objects not visible to astronomers in the northern hemisphere. In this respect, satellite observations could usefully complement those ground based studies of the southern sky already carried out over many years.

#### **d) Technology Demonstrations**

Nanosatellites can provide an attractive and low-cost means of testing, verifying and evaluating new technologies or services on a real orbital environment and within acceptable risks prior to a commitment to a full-scale, expensive mission. Paper [42] illustrates the nanosatellites developed in a two-year project, Delfi-C3, of Delft University of Technology in the Netherlands.

Such technology demonstrations were mounted on Japan's Hypersat Class [43] spacecraft and on ESA's Project for On-Board Autonomy (PROBA) [64].

#### **e) Military Applications**

A military version of the SSTL microsatellite platform with deployable solar panels has been developed to support various military payloads.

The main differences between the 'commercial' and 'military' versions relies on are in the specification of components and in the amount of paperwork for hardware and procedures. This involves also an increase factor for cost and timescale of approximately 1.5 when compared to the 'commercial' microsatellite procurement process.

#### **f) Academic Training**

Small satellites programs provide means for the education and training of scientists and engineers in space related skills, by allowing them direct, hands-on, experience at all stages (technical and managerial) of a particular mission (including design, production, test, launch and orbital operations). Development of a low-cost, rapid time-scale, mission within

an academic setting provides an approach attractive to countries wishing to establish expertise in space technology.

At present, many universities and schools of engineering in several countries in Europe, Japan, U.S.A, etc, had already developed, launched and operated their own small satellites.

### **g) Ground Segment**

The ground segment has three distinct functions:

- 1) operations which include status and health monitoring of the satellite, as well as necessary command preparation and validation;
- 2) tracking telemetry and commanding which are realized by the telecommunications station, possibly in association with the operations centre;
- 3) data reception and the transmission of data to the user(s) for processing and further distribution.

Generally, the ground station can be based on a simple, very high frequency (VHF), antenna (e.g., University of Surrey's UoSAT satellite series). The complexity of the ground station depends on the mission type. For example, an Earth Observation mission can require more complex support for collecting a large volume of data. Paper [44] presents a modular ground station, specifically designed for nano- and picosatellites.

Generally, small satellites rely on on-board autonomy and safe modes. This reduces their need for continuous ground monitoring, thus simplifying and reducing the cost of the ground segment. It was recommended that, although a ground system for a small satellite program should feature low cost, its reliability should remain sufficient to ensure that satellite data transmissions are not missed. The system should further offer a fast return of critical data, as well as a rapid response to critical commanding.

GENSO (Global Educational Network for Satellite Operations) [45] is an ambitious project launched and coordinated by ESA's Education Office. The main aim is to increase the return from educational space missions by forming a worldwide network of ground stations and spacecraft which can interact via a software standard.

### **h) Economic Benefits**

The main benefits within a country from using small satellites include:

- ✓ Improvement of agricultural and animal productivity in medium to large-size farms due to better weather predictions, identification of soil characteristics, improvements in communications and transportation;
- ✓ Reducing transportation costs, by optimizing truck, bus and ship routing, location and early robbery detection, with favorable impact on the price of goods;
- ✓ Communication provision for the basic needs of rural settlements in remote areas;
- ✓ Improvements in natural disaster detection, by using systems that integrate scientific communications and remote-sensing satellite networks;
- ✓ Educational programs for populations in remote areas.

The investments in the space sector determine a significant growth of gross national product (by a multiplication factor of the order of seven). Additionally, developing small and micro-satellite systems provides a powerful means to acquire national expertise in space

domain. When setting up any commercial contract for acquiring a new space system, technology transfer, through education programs and formal training, should be built in.

Figure 2.1 depicts taxonomy of satellite applications, as presented by Thomas Estier in paper [46]. A satellite application lies on the exploitation of the characteristics conferred by the orbital state. This classification is established on a mission type basis: data manipulation (or more generally, energy manipulation) and matter manipulation. In some cases, it is not the mission itself that matters, but the deployment of this mission. For this reason, the “Essence” category has been defined. The traditional satellite applications (in exploitation phase) are represented in black, while the innovative applications (in development phase) are in blue and the new concepts are marked in red.

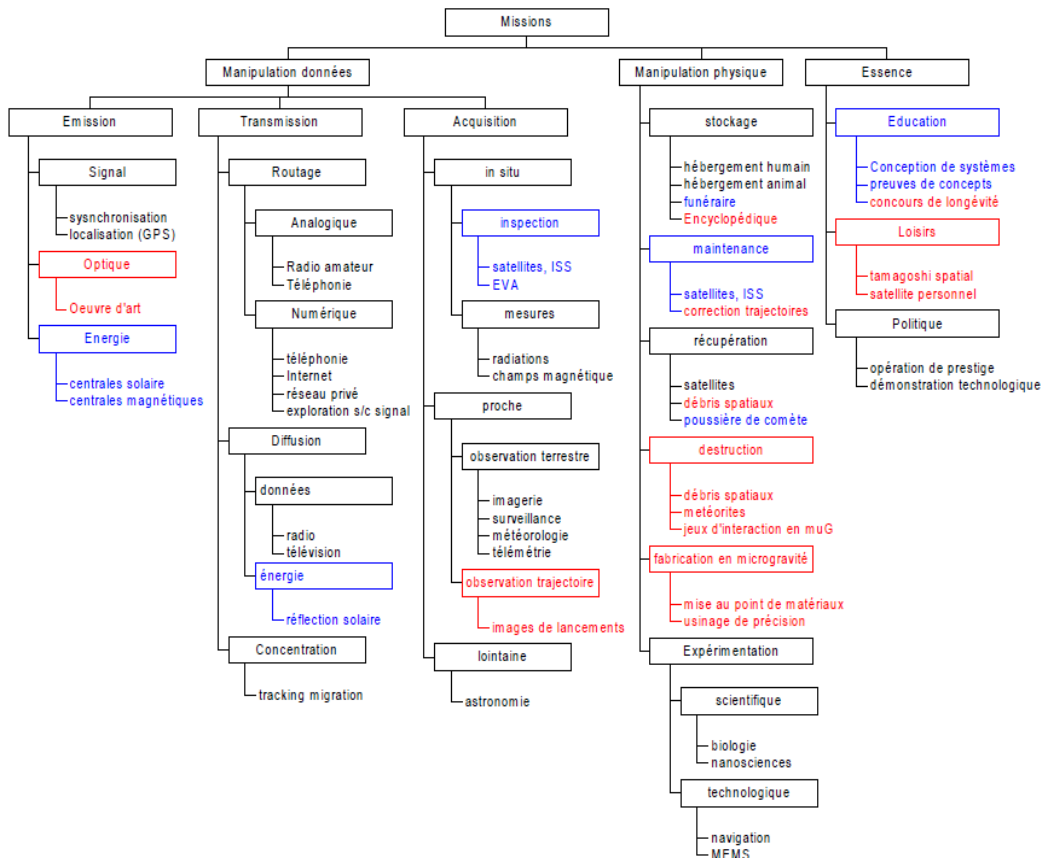


Figure 2.1 - Taxonomy of satellite applications [46]

## 2.2.6 Launching opportunities for small satellites

There are two opportunities for small satellites to access space:

- ✓ launch on a dedicated, expendable launch vehicle;
- ✓ launch as a secondary (piggyback) satellite. Typically, they are launched inert (not powered) and are activated on deployment using a separation switch.

Choosing between different launch opportunities involves weighing up the requirements of a desired mission against the capabilities, costs and constraints characterizing a particular option.



Two important considerations must be mentioned here:

- the first one refers to a shared launch: flexibility with regard to the date of launch/orbit attainment and the value of the spacecraft itself should be carefully taken into account by the secondary partner.
- the reliability record of the potential launch vehicle (those launching a series of low-cost payloads might be willing to risk using a relatively low-cost vehicle with an unproven record).

Access to a launch may be achieved in three ways:

- ✓ on a purely commercial basis;
- ✓ on an international agreement basis; or
- ✓ using national launch capability.

The present experiences in terms of small satellite projects shows that the utilization of launch services provided by an international commercial company can be preferable, especially for countries preparing for a first launch.

For microsattellites (10-100 kg), it is more economical to launch them on the larger launchers, where the prime payload has procured the launch, and employing the spare capacity does not incur significant additional costs.

Over the past decades, many countries have developed indigenous launch capabilities. The small class of expendable launch vehicles can deliver payloads weighing between 25 kg and 1500 kg to LEO. The launch of two or more small satellites on the same launcher (“dual manifesting”) is also feasible. Long-range and intercontinental missiles from military arsenals of the cold-war rival super powers are, in addition, presently available for civilian space launches.

It is important to note that the specific cost per kilogram into orbit of small launchers is higher than for larger launch vehicles. However, their absolute cost is much lower.

Manufacturers of large expendable launch vehicles are interested in offering the option of flying secondary (piggyback) payloads on missions where the primary payload does not fully utilize the capability of the launcher. For example, United States Delta launcher, Russian Federation Soyuz, the European launcher Vega. Also, the Ariane 4 launcher disposes of a special supporting structure (the Ariane Structure for Auxiliary Payloads ASAP), which is specifically designed to support the simultaneous launch of several small satellites. The mass of an individual participating satellite (up to seven per launch can be lofted together) is limited to 50 kg. The more powerful Ariane 5 is designed to launch several 50-100 kg piggyback satellites into geo-stationary transfer, as well as into low polar orbits. Also, a Korean research team proposed in paper [47] a hybrid air-launching rocket for nanosatellites.

Table 2.3 and Figure 2.2 illustrate the launching cost/kg for various launching vehicles.

Launch vehicle	LEO kg	Cost \$M	Cost/kg (\$)
Pegasus XL	443	13.5	30474
Rokot	1850	13.5	7297
Start	632	7.5	11867
Taurus	1380	19	13768
Delta 2	5144	55	10692
Dnepr	4400	15	3409
CZ 2E	9200	50	5435
Soyuz	7000	37.5	5357
Ariane 5	18000	165	9167
Proton	19780	85	4297
STS	28803	300	10416

Table 2.3 – Launching cost for various small launchers (Source: Futron, 2002)

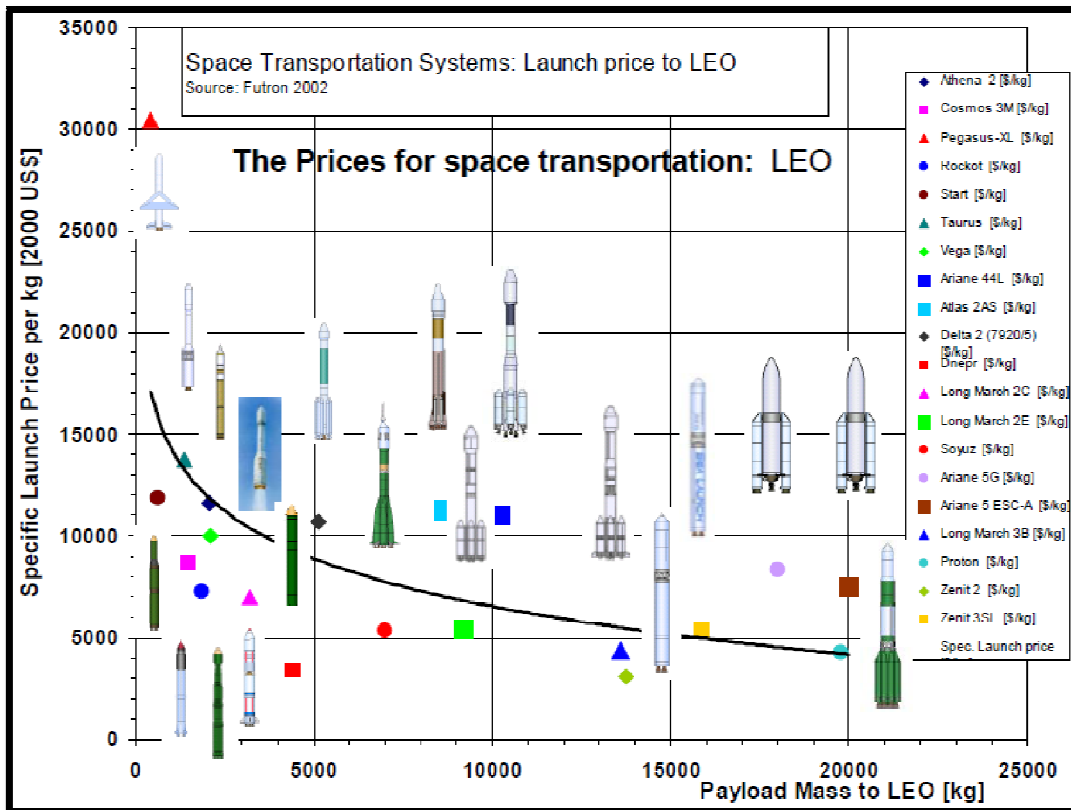


Figure 2.2 – Space transportation cost for LEO orbit [48]

Figure 2.3 presents some examples of small satellite launchers used worldwide.



Figure 2.3 – Examples of small satellite launchers: a – first commercial flight of PSLV (credit: ISRO); b – Athena 2 (credit: Lockheed Martin); c – DNEPR; d – Taurus I (credit: Orbital); e – Rockot; f – Delta II (credit: NASA/MSFC); g – Pegasus launcher carried by Lockheed L-1011 “Stargaze”; h – Pegasus XL launching from Lockheed L-1011

## 2.2.7 Nanosatellite general architecture

A nanosatellite has the same sub-systems as a conventional satellite, such as:

- ✓ Science Payload is represented by different types of instruments according to mission type.
- ✓ Structural Subsystem: most nanosatellites have the mechanical structure made from either aluminum or magnesium alloys, depending on the mass requirements of the mission.
- ✓ Attitude Determination and Control (ADAC) Subsystem is responsible for handling the orbit control and position determination.
- ✓ Communication Subsystem allows the communication within the constellation and between ground segment and nanosatellites.
- ✓ Propulsion Subsystem is used in order to perform thrusting maneuvers required for formation flying.
- ✓ Command & Data Handling Subsystem coordinates all activities of the nanosatellite. Generally, it communicates with subsystems through an I<sup>2</sup>C bus. It is able to turn off/on each subsystem in order to manage its power absorption, and to communicate with ground station.
- ✓ Power Subsystem has the following main functions: to generate and distribute the power supply to all subsystems and, to assure the energy storage.
- ✓ Thermal Control Subsystem is charge of assuring the optimal temperature conditions for the good functionality of all sub-systems.

Figure 2.4 presents the architecture of CanX-3 nanosatellite [49].

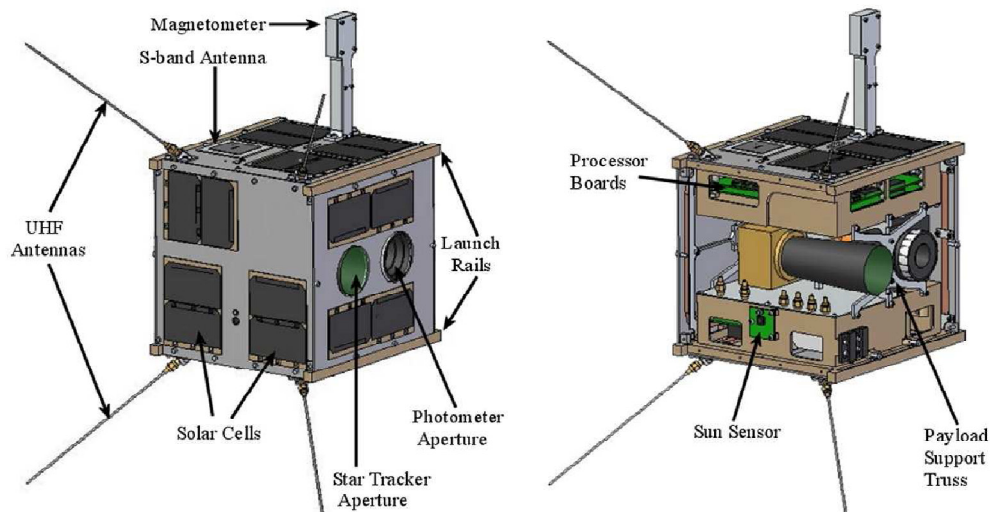


Figure 2.4 – External and internal views of one of the four BRITE-Constellation satellites [49]

In order to show the present level of nanosatellite development, we analyzed in paper [50], various nanosatellites systems/programs such as, CanX program, ION-F program, Munin and QuakeSat nanosatellites. Appendix 2 [51] presents a comparison of the nanosatellites described in paper [50]. Appendix 4 [52] summarizes the nanosatellite sub-systems, showing real examples of electronic components.

## 2.3 Formation flying survey

### 2.3.1 Introduction

Across the Formation Flying research community there are a wide range of definitions for formation flying and related terms. We will consider some representative definitions that are generally consistent with most elements of the community.

From the perspective of engineering definition, according to Jesse Leitner [53], “*formation flying involves the control of relative distances or geometric configuration between spacecraft.*”

Another definition is presented by *F. Bauer et Al.* in paper [54] as “*the on-orbit position maintenance of multiple spacecraft relative to measured separation errors*”.

Also, *Nicholas M. Short* mentions in [55] a more detailed definition: “*groupings of duplicate or similar satellites, having sensors in common or are complementary (related), that talk to each other and share data processing (onboard and/or by means of utilizing comparable ground stations and facilities), payloads, and mission functions.*”

The concept of formation flying mission is to replace a large satellite with a “virtual satellite” – a cluster of smaller satellites, flying in very precise relative positions. Rather than using a single, large, expensive satellite to perform a given mission, many small, inexpensive satellites can be flown in a constellation more effectively.

According to paper [56], the key issues that need to be addressed regarding communications in a formation-flying constellation include:

- The overall architecture and distribution of processing;
- The type of communication that needs to take place among the sensor spacecraft;
- Timing and synchronization issues;
- Whether or not a separate communication channel should be allocated for positioning or if positioning can be performed in-band with other communication;
- The media access required between the Hub and sensor spacecraft.

Some applications for satellite formations flying are:

- ✓ Large sensor apertures in order to obtain an increased resolution;
- ✓ Servicing, by replacing failed formation elements individually;
- ✓ Upgrade and Maintenance: working on individual components without removing whole mission;
- ✓ Change formation geometry: evolving mission sensing requirements.

Replacing a single satellite with a formation flying system could be beneficial for some missions, but uneconomical for others. Many opinions exist in scientific research community, and some of the advantages and disadvantages of multiple-satellite systems are discussed in Chapter 2.2.2.

Appendix 5 [57] presents a survey of formation flying missions and reveals the numerous applications of formation flying research that would contribute to scientific, military and communications mission operations.

### 2.3.2 Types of formations

There are different terms used to describe spacecraft formations. Those encountered during the literature survey are listed in Table 2.4. The formation types are illustrated in Figure 2.5.

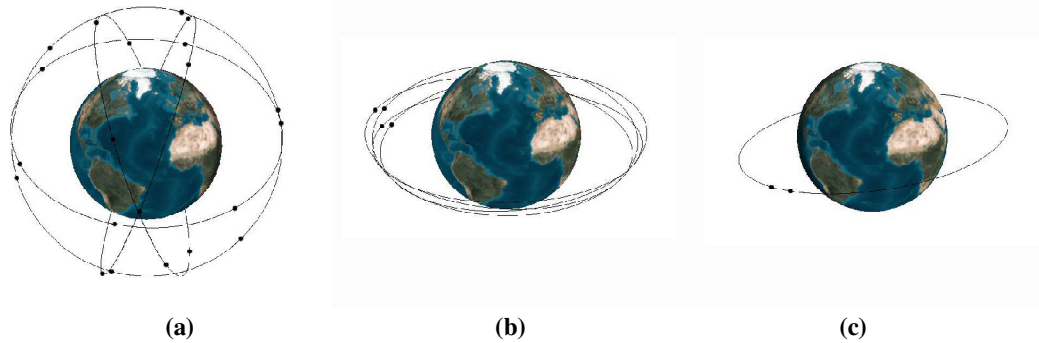


Figure 2.5 – Types of spacecraft formations:  
 (a) Constellation (b) Cluster (c) Leader-Follower [58]

<i>Formation flying type</i>	<i>Description</i>	<i>Examples</i>
<b>Trailing (Leader-Follower)</b>	<ul style="list-style-type: none"> <li>✓ multiple satellites orbiting on the same path</li> <li>✓ satellites are displaced from each other at a specific distance to produce either varied viewing angles of one target or to view a target at different times</li> <li>✓ satellites with a hierarchy of authority</li> </ul>	<ul style="list-style-type: none"> <li>▪ Landsat 7 with EO-1</li> <li>▪ CALIPSO with CloudSat</li> <li>▪ Terra with Aqua</li> </ul>
<b>Cluster</b>	<ul style="list-style-type: none"> <li>✓ large numbers of satellite randomly distributed in their orbit planes</li> <li>✓ satellites operating interdependently and cooperatively</li> <li>✓ no propulsion to maintain relative position</li> </ul>	<ul style="list-style-type: none"> <li>▪ TechSat-21</li> <li>▪ Constellation-X (NASA)</li> <li>▪ Darwin (ESA)</li> <li>▪ F6</li> </ul>
<b>Constellation</b>	<ul style="list-style-type: none"> <li>✓ group of similar satellites, operating together under shared control, synchronized so that they overlap well in coverage and complement rather than interfere with other satellites' coverage</li> <li>✓ coordinated ground coverage</li> </ul>	<ul style="list-style-type: none"> <li>▪ GPS</li> <li>▪ Globalstar</li> <li>▪ Iridium</li> <li>▪ Glonass</li> <li>▪ Orbcmm</li> <li>▪ Disaster Monitoring Constellation</li> <li>▪ RapidEye</li> <li>▪ Galileo</li> </ul>

Table 2.4 – Types of spacecraft formations

Depending on the application field, there are three formations possible:

➤ **Trailing (Leader-Follower)**

The *Leader-Follower* (Figure 2.6) is suited for meteorological and environmental applications, such as viewing the progress of a fire, cloud formations, and making 3D views of hurricanes.

In this type of formation, the satellites have the same orbits and are only separated in true anomaly. Thus, they will roughly experience the same perturbations.

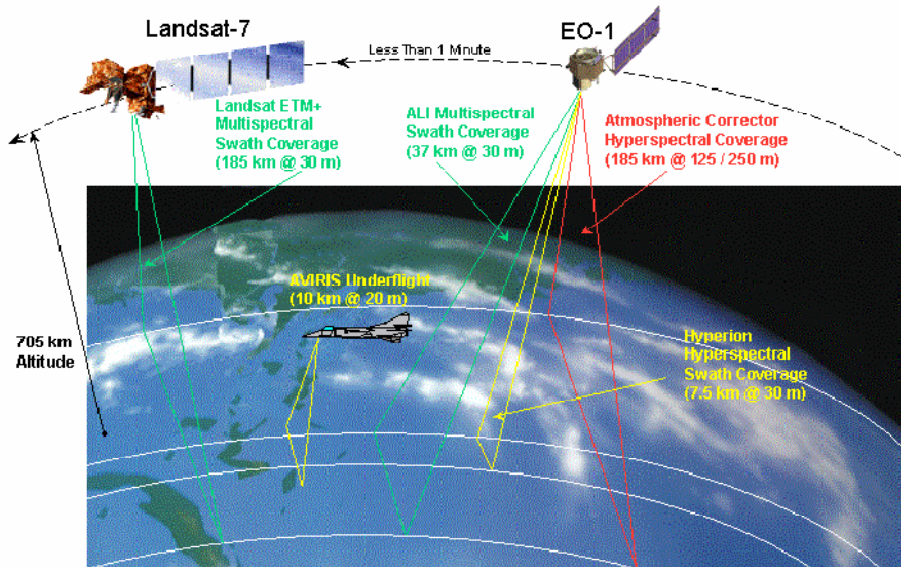


Figure 2.6 – EO-1 and Landsat-7 formation flying parameters [59]

➤ **Cluster**

A *cluster* (Figure 2.7) is constituted of any group of two or more spacecraft whose cooperation and knowledge of relative position is essential for completion of the mission. A level of spacecraft inter-dependency is demanded, but it doesn't required precision formation keeping.

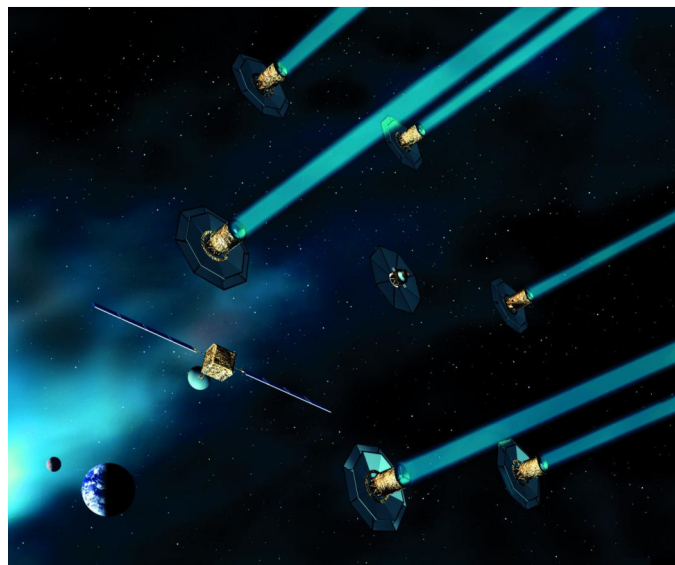
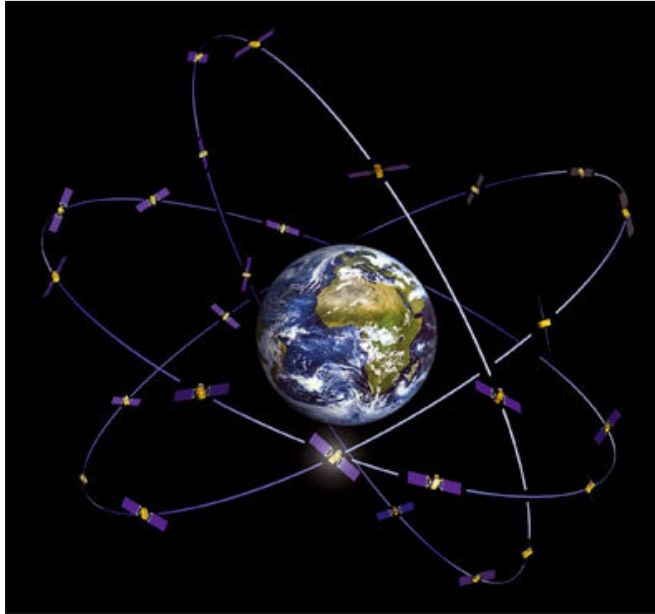


Figure 2.7 – Darwin's six telescopes look at light from space and analyze the atmospheres of Earth-like planets (ESA Illustration by Medialab)

➤ **Constellation**

A *constellation* (Figure 2.8) is a group of similar satellites with coordinated ground coverage, operating together under shared control, synchronized so that they overlap well in coverage and complement rather than interfere with other satellites' coverage.



*Figure 2.8 – An artist's concept depicts the Galileo satellite constellation  
(credit: ESA, J. Huart)*

The missions involving formations of satellites can be categorized into three primary application areas: communications, military and science. Appendix 3 [60] presents a summary of current and planned small satellite formations flying missions, including formation type, launch year, and the number of satellites in each formation.

Appendix 6 [61] includes a short description of various small satellites missions such as:

- e-CORCE project described in papers [62], [63], [64], [65] is an innovative satellite remote-sensing system envisaged by French Space Agency (CNES), capable of generating a high-resolution picture of Earth on the Web, refreshed every week;
- RapidEye constellation presented by papers [66], [67], [68], [69] is a German geospatial information provider focused on assisting in management decision-making through services based on their own Earth observation imagery.
- Prisma [70], [71], [72] is a satellite project led by the Swedish Space Corporation (SSC) which consist of two satellites that fly in formation to test and qualify novel technologies for autonomy, guidance, navigation and control.

Other examples of formation flying systems are presented in papers [73], [74], [75], [76], [77], [121], [122].



### 2.3.3 Advantages and disadvantages of formation flying

Table 2.5 summarizes the advantages and disadvantages of using multiple satellites, based on information from paper [58].

<b>Advantages</b>
<ul style="list-style-type: none"> <li>✓ On-orbit reconfiguration within the formations offers multi-mission capability, by integrating new technology during mission, and design flexibility</li> <li>✓ Inherent adaptability afforded by the ability to add incrementally new or upgrade older elements of the formation;</li> <li>✓ Reduced design and development work time due to mass production;</li> <li>✓ Reduced size and complexity of satellites within the formation;</li> <li>✓ Higher redundancy across the formation and improved fault tolerance;</li> <li>✓ Mission improvements through the ability to view research targets from multiple angles or at multiple times;</li> <li>✓ Lower individual launch mass and smaller spacecraft volume translates into a reduced launch cost and an increased launch flexibility;</li> <li>✓ Minimal financial lost in case of failure;</li> <li>✓ Separating scientific payloads onto several simpler single-string satellites can accomplish the same complex missions without the added design and operational overhead, while risking only one payload at a time.</li> <li>✓ Lower cost of manufacturing due to mass production techniques;</li> <li>✓ In terms of specific application benefits, the opportunity to create synthetic apertures for interferometry or radar surveillance missions and to increase the scope of field measurements for survey missions.</li> </ul>
<b>Disadvantages</b>
<ul style="list-style-type: none"> <li>• Each cluster satellite requires its own core systems (i.e. there is a minimum overhead associated with each small satellite which may in total be more than that of a single large spacecraft);</li> <li>• Initialization and maintenance of the relative location of formation (especially if component satellites are launched separately);</li> <li>• Severe conditions for satellite alignment (for example, in case of an interferometry mission, a misalignment of telescopes' sensors may introduce additional measurement errors if they are mounted on different platforms);</li> <li>• Increased complexity of ground system operations;</li> <li>• Small satellite development costs can be equally high compared to large satellites when they retain the complexity needed to achieve demanding scientific requirements. A possible solution to counter this is the use of commercial off the shelf (COTS) components;</li> <li>• Increased quantity of orbital debris at the end of formation's lifetime, and the introduction of potentially complex and expensive de-orbiting systems.</li> </ul>

Table 2.5 – Advantages and limitations of formation flying with respect to single satellite

## 2.4 Analysis of nanosatellite launches in the period 2004 – mid2007

Knowing that small satellite domain has imposed itself as a particular field in the last two decades, we found important to make an analysis of nanosatellite launches in the period 2004-mid 2007 for two reasons:

- it allows us to see the evolution of nanosatellites launches and the future trend in this domain. The main questions that can be addressed are:

- ✓ *Can we speak about a nanosatellite market that is shaping as a niche market?*
- ✓ *Can we envisage commercial applications for small satellites and when there will be available for the public?*
- we think that this period is probative for nanosatellite launches, by showing future trends in nanosatellite launching activity.

For a more detailed analysis of nanosatellite launches, the interest reader could consult papers [78] and [79] and Appendix 6 [61].

The results of this survey are presented in details in

Nowadays, there is no database application which gathers the small satellite systems. As a consequence, it is very difficult to make analyses concerning the technologies used in these systems and to obtain different statistics. The main sources of information existing on the nanosatellite systems developed until now are: different Web sites, articles and PowerPoint presentations. In other words, the information is spread on different sites and there is no centralized application that gathers all information concerning nanosatellite systems. Also, some nanosatellite projects are not documented or the information is not available for the public.

The lack of information and the scattered sources of documentation regarding nanosatellite systems imposed a significant challenge to our survey. Thus, we tried to collect data from different launch logs [80], [81] and the resulting list of nanosatellites is complete to the best of the author's ability. Therefore, we included only the nanosatellites launched between 2004 and mid2007 and we analyzed them regarding:

- ✓ owner country of the payload;
- ✓ mission type;
- ✓ mass category;
- ✓ orbit type;
- ✓ launcher type;
- ✓ spaceport;
- ✓ type of activity;
- ✓ mission status.

According to our analysis, some important ideas can be retained:

- ✓ in the period 2004 – mid 2007, there were recorded 55 nanosatellites launches.
- ✓ 2006 is the leader in terms of nanosatellites launches, accounting almost 50% of the total number of launches; 2006 recorded also the first event involving 16 nanosatellites launched simultaneously. This event shows that future nanosatellite constellations can be rapidly deployed in order to assure immediate services.
- ✓ most payloads were designed to conduct Technological missions (67%); this means that nanosatellites are used mainly as technological demonstrators, for testing different equipments that can be used for much complex space missions. In this way, the financial loss in case of failure is minimized.
- ✓ almost 75% of nanosatellite campaigns had an Institutional purpose, which explains the great involvement of university's laboratories in small satellite projects. Worldwide small satellite programs allow to rise the interest for

aerospace among students and to offer each student a unique opportunity to take part in a concrete project including experimental creations.

In conclusion, in the years to come, nanosatellites will accelerate the space exploration for both civil and military needs. Therefore, scientists will be able to obtain more frequent flights for their experiments at lower cost. The low cost unit of the small satellites will make commercial constellations a practical commercial proposition.

## 2.5 Telecommunications framework of nanosatellite networks

### 2.5.1 Introduction

As mentioned in Chapter 1, the goal of this thesis is two-fold: proposing innovative nanosatellite constellation models and, new routing approaches for telecommunications in nanosatellite networks. Therefore, we consider that this research work is a merging of two fields: the first one is telecommunications, by treating routing problematic in nanosatellite networks and evaluating, through simulations, the performance of transport protocols designed for this type of network. The second one is constellation design domain, by proposing and analyzing nanosatellite constellation models.

The source of our interest in nanosatellite networks routing is founded in some questions that we are asking ourselves, such as:

*Which are the routing challenges of nanosatellite networks?*

*Can the conventional satellite network protocols be used with success in nanosatellite networks or a different approach is needed?*

*What kind of protocols will assure a reliable communication throughout a nanosatellite constellation?*

*What types of topologies are most suited for nanosatellite networks?*

*Can other types of networks (e.g., sensor networks, Ad hoc networks) provide us new ideas for nanosatellite communications?*

*Do we need dedicated simulation tools for evaluating the performance of nanosatellite networks in terms of communications? Can the present network simulators be adapted in order to support this new type of network?*

*Are there any protocols already developed for nanosatellite networks?*

*Is there any communication protocol tested in real, on-orbit nanosatellites?*

*How can we implement QoS strategies in nanosatellite networks in order to provide efficient telecommunication services? Are the present QoS strategies appropriate for nanosatellites or new QoS mechanisms need to be developed?*

Finding answers to all these questions involves a significant and complex work in terms of studies and simulations. We also believe that some of this rising topics can be a complete project on its own. Considering this complexity, only some of these questions are answered in this thesis, the rest being treated as future work directions.

Furthermore, the context of future small satellite networks communications needs to be considered. Internet development and an ever-increasing demand for bandwidth will spur the market for small satellite solutions. In the scenario of a robust nanosatellite telecommunications market, these networks have to be capable of providing bandwidth at

lower cost and a guaranteed level of QoS, which is a fundamental requirement for a large range of services (e.g., conversational voice, video conferencing, voice and video messaging, audio and video streaming, etc).

The design of efficient communication mechanisms for nanosatellite networks is a challenging task, requiring the definition and implementations of specific protocols and architectures appropriate to space critical conditions. New emerging protocols might deliver new and interesting ways for interconnecting nanosatellites networks and sensor/or Ad hoc networks. But several different problems are usually encountered on these networks that require us to revise communication protocol design, network management, and to consider novel routing mechanisms to accomplish “more with less”. For instance, common problems of nanosatellite networks are onboard resources, limited communications opportunities, limited bandwidth, scalability, redundancy, power availability, high-speed node mobility, the type of communication among satellites, assigning or not a separate communication channel for positioning, timing and synchronization issues. Finally, a lot of new services via small satellite will come into service once small satellite operator comes to live.

Moreover, the present sub-chapter includes a state-of-the-art of protocols that can be used in small satellite networks. In order to identify candidate protocols and network topologies that can be used or adapted for small satellite networks, we conducted a study of routing mechanisms in traditional satellite network, Ad Hoc network and sensor networks [82]. This study is part of PERSEUS (*Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique*) program, launched by CNES (Centre National d'Etudes Spatiales) in June 2005. Based on this study, some routing approaches have been identified for nanosatellite networks. Additionally, XSTP transport protocol performance over conventional satellite networks and nanosatellite constellations is evaluated, through simulations and analysis, in Chapter 4.

### 2.5.2 QoS challenges in nanosatellite networks

The evolution of multimedia technology and the commercial interest of future small satellite operators to reach widely public applications will make QoS in nanosatellite networks an area of great interest. Moreover, QoS is a full featured technology that can control or reduce costs and improve nanosatellite network performance. It should be stressed out that to the best knowledge of the authors, there has been no previous research work investigating the QoS aspect of nanosatellite networks. According to our inquiry, the existing literature does not record any paper that discusses this topic. This is a further reason for us to take initiative and point out some interesting ideas that could be a solid base for future work.

Cisco defines Quality of Service (QoS) in the Internetworking Technology Handbook [83] as: “*the capability of a network to provide better service to selected network traffic over various technologies*”.

The primary goal of QoS is to provide priority, including dedicated bandwidth, controlled jitter and latency and improved loss characteristics. Moreover, it is important to assure that providing priority for one or more flows does not cause the failure of other flows. On intuitive level, QoS represents a certain type of requirements to be guaranteed to the users

(e.g., how fast data can be transferred, how much the receiver has to wait, how correct the received data is likely to be, how much data is likely to be lost, etc.).

A nanosatellite network, on the other hand, can be seen as an autonomous system, having its own routing protocols and network management mechanisms, and most important, having specific limitations.

To support QoS, the link state information such as delay, bandwidth, cost, loss rate, and error rate in the network should be available and manageable. However, getting and managing these in nanosatellite networks is very difficult because of the resource limitations and the complexity associated with the mobility of nanosatellites.

Although QoS and complexity are terms that usually go together, we must keep complexity as low as possible since this may also lead to excessive power consumption which is a stringent limitation of nanosatellite networks. Maintaining a low level of complexity and providing efficient QoS services is a real challenge of nanosatellite networks.

Based on our studies, we identified three main constraints in terms of QoS for nanosatellite networks are:

- 1) the limited bandwidth, since a nanosatellite has usually poor bandwidth resources (e.g., 9.6 kbps for uplink and 32-256 kbps for downlink);
- 2) the dynamic topology, since nanosatellites are continually moving on their orbit, connecting and disconnecting from the network making connections many times unreliable;
- 3) the limited processing and storing capabilities of nanosatellites, as compared to Internet routers.

Furthermore, all satellite communications systems generate a noticeable delay which is known as the main source of communications quality. Nanosatellite network make no exception of this rule. The round trip propagation delay for a LEO nanosatellite is comparable to the round trip communication time in terrestrial networks due to the low altitude of the satellites. This delay is important for two-way, real-time applications such as voice or videoconferencing, since these applications are very sensitive to short-term delay variation. Numerical calculations in Chapter 4 sustain this observation. For example, if we consider a communication between two user terminals by passing through a nanosatellite placed at 1500 km of altitude, the propagation delay varies between 20 and 44 ms, not counting additional sources of delay. We think that this delay range may be acceptable for LEO nanosatellite systems that could provide telecommunication services to remote places.

One of the most significant challenges of future nanosatellite network telecommunications will be provide some type of service guarantees for different types of traffic. This will be a particular challenge for streaming video applications, which often require a significant amount of reserved bandwidth to be useful.

For an efficient QoS provisioning in nanosatellite environment, we propose the following approaches:

- 1) Developing tools that allow an efficient use of nanosatellite network resources; also, these tools can show the resources used by nanosatellite network at a certain moment and the priority of each type of traffic.
- 2) Implementing QoS technologies in nanosatellite networks in order to accommodate multimedia services needed in the near future.

- 3) Developing specific methods for identifying the type of traffic carried by nanosatellite network. Classification is the first step for providing preferential service to a certain type of flow.
- 4) Developing congestion-avoidance techniques in order to monitor nanosatellite network traffic loads at certain points in the network, in an effort to anticipate and avoid congestion before it becomes a problem. If the congestion begins to increase, packets are discarded, leading to a slowing down of data transmission at the source node, as a result of the early dropped traffic detection.
- 5) Developing congestion-management techniques that operate to control congestion after it occurs. Congestion-management tools allow raising the priority of a flow by queuing and servicing queues in different ways. Congestion-avoidance and congestion-management are opposed mechanisms.
- 6) Developing traffic shaping and policing techniques for nanosatellite networks. As mentioned earlier, fundamentally, QoS provides priority either by raising the priority of one flow or by limiting the priority of another. Policing and shaping provide priority to a flow by limiting the throughput of other flows.
- 7) Defining End-to-End QoS levels that refer to the capability of the nanosatellite network to deliver service needed by specific traffic from edge to edge. Every service delivered by nanosatellite network has a certain level of QoS strictness which describes how tightly the service can be bound by specific bandwidth, delay, jitter, and loss characteristics. In terrestrial IP networks, there are three common levels of end-to-end QoS:
  - Best-effort service, which means basic connectivity with no guarantees;
  - Differentiated service, where certain traffic is treated better than the rest (e.g., faster handling, more average bandwidth);
  - Guaranteed service, which is an absolute reservation of network resources for specific traffic.

Since these QoS levels are relevant only to terrestrial networks, other QoS levels need to be developed for nanosatellite networks. We think that a good starting point is to investigate if these End-to-End QoS levels can be applied or adapted to nanosatellite networks and how can these levels could be implemented. If they are not suited for nanosatellite networks, other types of levels need to be defined.

In conclusion, we consider that QoS techniques can provide powerful value added service for nanosatellite networks. By using those mechanisms, we hope that the user traffic can be controlled and the nanosatellite network resources could be used efficiently.

### 2.5.3 Routing approaches for nanosatellite constellations

Firstly, we surveyed sensor networks and we made an analogy between sensors and nanosatellites. A sensor network is constituted of small, low-power, and low-cost devices with limited computational and wireless communication capabilities. Table 2.6 presents the common features of sensor networks and nanosatellite networks.

Sensor network features	Nanosatellite network features
Small-scale devices: grams	Small satellites: 1 – 10 kg
Limited resources: <ul style="list-style-type: none"> <li>• CPU</li> <li>• memory</li> <li>• range</li> <li>• wireless comms bandwidth</li> </ul>	Limited resources: <ul style="list-style-type: none"> <li>• CPU</li> <li>• memory</li> <li>• bandwidth (e.g., 4 kbps – <i>uplink</i>; 32 - 256 kbps – <i>downlink</i>, 1Mbps theoretically)</li> <li>• radiated power (0.5 - 1 W)</li> <li>• payload</li> <li>• propulsion</li> <li>• batteries, etc</li> </ul>
High degree of dynamics → frequent network topology changes and network partitions	Topology changes (e.g., nanosatellite reconfiguration in order to compensate a lost satellite)
High level of redundancy	Only critical sub-systems are backed up
Sensor nodes: <ul style="list-style-type: none"> <li>- very limited in the amount of energy they can store or harvest from the environment;</li> <li>- subject to failures due to depleted batteries or to environmental influences.</li> </ul>	Electronic sub-systems placed on an extreme environment
Scalability issues due to the large number of sensor nodes	High level of cooperation between nanosatellites (inter-satellite links)

Table 2.6 – Sensor networks vs. nanosatellite networks

By studying sensor network routing, we identified the following approaches for nanosatellites:

- Sensor networks could be integrated with nanosatellite networks for space and Earth monitoring missions.
- Self-reconfiguration network after initial deployment. Once placed in the orbit, the nanosatellite constellation could reconfigure itself in order to compensate for a lost nanosatellite without loss of the mission. For doing this, a certain level of artificial intelligence is integrated on every spacecraft. Self-reconfiguration is also a way of maximizing system’s flexibility.
- A certain level of redundancy is needed in order to achieve a higher level of efficiency. Generally, small satellites have only their critical sub-system backed up.
- One of the main challenges of sensor network is traffic minimization. This principle applies also to nanosatellite networks. Traffic should be minimized so that the network won’t be overloaded with unnecessary information.
- Using MAC routing protocols:
  - TRAMA (Traffic-Adaptive Medium Access) is greatly reducing the energy loss caused by packet collisions;
  - STEM (Sparse Topology and Energy Management) allows nodes activation only when traffic is generated, thus allowing an energy efficient routing mechanism.

- Using routing-based on resources.  
Two types of routing strategies have been identified: energy-aware routing and fidelity-aware routing. Routing decisions are made based on the power consumption level. Thus, the route which cost less power will have more possibility to be chosen.
- Using data-centric protocols.  
Query-based protocols depend on the naming of desired data, eliminating this way many redundant transmissions.
- Using location-based protocols.  
By using position information, the data is relayed to the desired regions rather than to the whole network;
- Other sensor network concepts that might be interesting for nanosatellite networks are: Intelligent Sensor and Web Sensor.

Paper [84] presents a retrospective on the use of wireless sensor networks for planetary exploration.

We have also turned our attention to Ad hoc network domain to find routing approaches that can be used in nanosatellites networks. We identified common challenges for both Ad hoc and nanosatellite networks, such as:

- scalability issues due to large number of nodes;
- dynamic topology;
- time-varying network links;
- severely limited resources in terms of power, storage capacity, memory;
- time-varying achievable channel bit rate;
- topology maintenance: updating information of dynamic links among mobile nodes.

By studying the three types of Ad Hoc routing (i.e., proactive routing, reactive routing and hybrid routing), we can state that reactive routing approach is preferred for high-mobility small satellite networks with restrictive resources.

The main benefits of adapting reactive routing to small satellites networks are:

- Proactive calculation of nanosatellites position reduces delay and control overhead.
- Passive listening allows listening to neighbor's routing packages in a passively manner and updating their local routing table. Thus, broken links can be detected easily.
- Suspend mode allows to a node to suspend and notify its neighbors not to communicate with it even though its communication channels are in good condition. This mode is a good way of energy saving, a critical aspect in nanosatellite networks.

Paper [85] presents XLP protocol which is a cross-layer protocol for efficient communication in wireless sensor networks. We recommend a detailed study of this protocol to identify if it can be used or adapted for nanosatellite networks.

Table 2.7 summarizes the main advantages and limitations for Ad hoc routing types.



Routing type	Advantages	Disadvantages	Examples
<b>Proactive routing (table driven)</b>	<ul style="list-style-type: none"> <li>✓ successfully combines dynamic group with hierarchical level concepts</li> <li>✓ routes are calculated independent of intended traffic</li> <li>✓ there is little delay until the route is determined</li> </ul>	<ul style="list-style-type: none"> <li>• keeping routes to all destinations up-to-date, even if they are not used</li> <li>• big routing table in order to assure the path to all network nodes</li> <li>• the periodical control traffic might delay data packets, thus reducing the effective bandwidth</li> <li>• unnecessarily consumption of energy and system resources (i.e., CPU time, memory space, bandwidth) in case of low data traffic</li> </ul>	HSR ZHLS DSDV WRP GSR
<b>Reactive routing (On Demand)</b>	<ul style="list-style-type: none"> <li>✓ acquisition of routing information on a on-demand basis → reducing the routing overhead in order to save bandwidth</li> <li>✓ higher bandwidth</li> <li>✓ no resources wasting</li> <li>✓ smaller routing table</li> </ul>	<ul style="list-style-type: none"> <li>• rapid network saturation due route request flooding mechanism → not optimal in terms of bandwidth utilization</li> <li>• increased latency for sending data packets</li> </ul>	LAR CBRP DSR AODV TORA ABR SSR
<b>Hybrid routing</b>	<ul style="list-style-type: none"> <li>✓ provides efficient and fast discovery of routes by integrating the two radically different classes of traditional routing protocols: <ul style="list-style-type: none"> <li>- pro-active discovery within a node's local neighborhood;</li> <li>- reactive mechanism for communication between neighborhoods.</li> </ul> </li> <li>✓ reduced control overhead as compared to both proactive and reactive routing</li> </ul>	<ul style="list-style-type: none"> <li>• short latency for finding new routes</li> </ul>	ZRP

Table 2.7 – Comparison of Ad hoc routing types

Lastly, we interested on traditional satellites networks to investigate if protocols and topologies specific to large satellites can be used or adapted for small satellites. We focus our study on LEO satellite networks since low-earth orbit is the common type of orbit used by small satellites.

We start by pointing out the main advantages of LEO satellite routing:

- ✓ Predictable movement and position derived from orbit calculation; this data could be a way of reducing control overhead;
- ✓ Low propagation delay: less than 20 ms round-trip;
- ✓ No elements that could obstruct communication path as compared to ground communications.

Among the limitations of LEO satellite routing, we could mention:

- dynamic change of data rate and Bit Error Rate (BER) which makes the communication link unstable;
- significant transmission overhead;
- frequent change of network topology due to satellites movement on the orbit;
- limited resources in terms of CPU, memory, bandwidth;
- QoS issue: the LEO satellite link is characterized by frequently changes of traffic density and data packets with different QoS parameters;

- hybrid routing approach: for uplink/downlink transmissions is used an infrastructure mode while for inter-satellite communication, an Ad hoc mode.

From a networking point of view, we identified two fundamentally different approaches:

- ground-based approach, where network functionality is entirely terrestrial;
- space-based approach, where the space segment possesses network functionality.

The first one considers that each satellite is a space-based re-transmitter of traffic received from user terminals and local gateways, returning the traffic to the ground. This impose challenges in the space segment for medium access control (MAC), logical link control (LLC) and handover. Some examples of commercial satellite networks systems based on this approach are: Globalstar, the ICO Global and SkyBridge.

As Lloyd Wood mention in paper [86], the topology of such a ground-based constellation network is entirely arbitrary because the satellites are only used to provide last-hop connectivity. It can be assumed that all satellite telemetry, tracking and control (TT&C) ground stations will be networked, to share information about the state of the constellation.

However, there are a large number of networking possibilities and a number of different ways that the constellation gateways can be integrated with existing terrestrial networks, including the Internet. As a result, the design and topology of the terrestrial network component of a ground-based constellation is far more arbitrary than that of any space-based constellation whose network topology is governed by orbital geometry.

In the space-based constellation network, each satellite has on-board processing and it is considered as a network switch or router which is also able to communicate with neighboring satellites by using high-frequency radio or laser intersatellite links (ISLs). Thus, a user terminal below the satellite exchanges traffic with gateways to the terrestrial network or with users below distant satellites not visible to that terminal, without requiring a local gateway information. In this approach, the network layer is integrated into ISLs.

Furthermore, satellites in such constellations must support onboard routing as well as onboard switching. In conjunction with its ground stations, the satellite constellation forms an autonomous system.

Some examples of commercial and proposed systems utilizing ISLs includes: Motorola's LEO Iridium constellation, LEO Teledesic constellation, Hughes' GEO Spaceway, MEO Spaceway NGSO proposal and GEO Astrolink proposal.

Table 2.8 presents a parallel between satellite networking approaches, by emphasizing the main advantages and limitations of every approach.

<i>Approach</i>	<i>Advantages</i>	<i>Disadvantages</i>
<b>Space-based network approach</b>	Satellites communicate directly with each other by line of sight.	It decreases ground-space traffic across the limited available air frequencies assigned to the constellation.
	It provides ubiquitous service in regions where the locally-overhead satellites visible to a ground terminal are not simultaneously visible from a ground gateway station.	It removes any need for multiple ground-space hops required for communication between distant ground terminals for the ground-based constellation.
		It requires more complex and sophisticated processing/switching/routing onboard satellite than the ground-based approach.
		Design restricted by the constraints imposed by orbital geometry and the difficulties in implementing networking in the space segment.
	Networking and space segment issues must be considered together.	
<b>Ground-based network approach</b>	It separates network functionality from the space segment, allowing network-layer issues and space-segment issues to be considered separately.	
	It allows reuse of the satellites for different purposes by simply upgrading or replacing easy-to-access ground equipment, and of reducing system complexity.	

Table 2.8 – Advantages and disadvantages of ground- and space-based network approaches

Hereinafter, we present here a brief introduction on satellite network topologies. The highly topological dynamics characterizes the fundamental feature of satellite and nanosatellite networks as regard to terrestrial networks. This dynamic is due to the constant movement of satellites on the orbit and it determines the permanent changing of satellite network topology.

Unlike terrestrial networks, the frequent and rapid topological changes affects many aspects of LEO satellite and nanosatellite networks, such as constellation design, reliable transmission control protocols, routing issues and QoS guarantee.

As *A. Ferreira et al.* states in paper [87], the dynamic topology of a LEO satellite network is characterized by a periodical series of snapshots or fixed constellation topologies.

The topology of a satellite network can take many forms and there are variations on those. The most common satellite network topologies are: Star, Mesh and Hybrid (or Multi-Star), each one with its own advantages and limitations.

The Star topology is the simplest way to configure a satellite network. However, it has one issue that affects its performance. Star topology delay can become noticeable for voice communications. Therefore, this topology is suited when communications is primarily between a central system and remote locations in a single hop, or when communications doesn't require immediate response.

Applications that need direct communications between remote sites can employ the Mesh topology. The trade-off is the requirement for a larger antenna and a higher powered transmitter, both of which increasing costs. Some Mesh topology networks are demand-

assigned so that links are set up only when needed. This reduces the steady-state capacity requirement on the satellite, thus saving bandwidth and money.

Hybrid topology provides a mix of Star and Mesh solutions. The reason for going hybrid is a trade-off with cost. In this case, some parts of the network might need a mesh topology while other sites might only need to talk to one central site thus connecting with a Star topology.

Because of the trade-offs in price and performance, cost-benefit analysis must always be performed in order to design the appropriate network topology necessary for each site.

Nanosatellite networks might use the same types of topologies as satellite networks. However, we believe that other types of topologies might be envisioned for nanosatellite networks. This topic is not the object of this thesis and it will be considered as a future work direction. To the best of our knowledge, there is no previous significant study exploiting the topic of nanosatellite network topologies, this being a further reason to be developed in future research work.

In our survey [82], we have analyzed various satellite protocols such as: XTP (Xpress Transport Protocol), SCPS (Space Communications Protocol Standards) suite, BGP-S (Border Gateway Protocol – Satellite Version), STP (Satellite Transport Protocol) and XSTP (eXtended Satellite Transport Protocol).

According to our study, XSTP (eXtended Satellite Transport Protocol) could be a candidate for small satellites communication links, considering that it is specifically optimized for asymmetrical satellite networks, characterized by high BER and variable RTTs. The simulation results presented in paper [88] shows that XSTP attained higher effective throughput, much lower overhead, and better channel efficiency as compare to TCP clones, in case of high BER conditions.

As mention in [5] and [6], XSTP has been used as transport protocol for CanX-2 nanosatellite launched on April 28<sup>th</sup>, 2008 from the Satish Dhawan Space Centre (SHAR).

## **2.5.4 Overview of candidate protocols for small satellite networks**

This chapter briefly describes two transport protocols that are the point of interest of our research – Satellite Transport Protocol (STP) and its extended version, XSTP.

### **2.5.4.1 Satellite Transport Protocol**

The Satellite Transport Protocol (STP), proposed by Katz and Henderson [89], [90] is a transport protocol, which is specifically optimized for the unique constraints of satellite network environment. STP is found to outperform TCP in environments characterized by high BER, severe asymmetry and varying RTTs, typically characteristics of LEO satellite links.

Based on paper [91], the main features of STP can be summarized as follows:

- ✓ Enforcing the separation between data and control information in order to minimize the control overhead in smaller data segments;
- ✓ Mechanism that adapts to the amount of rate control required in the network, ranging from no rate control to explicit rate control. Unlike TCP, which uses a

self-clocking property, STP depends on a delayed send timer to pace transmissions uniformly over the estimated RTT. The main benefit of the pacing mechanism is the reduction of the risk of introducing large bursts to the network.

- ✓ Segment type overloading for supporting a fast connection start mechanism;
- ✓ Efficient acknowledgement strategy.

STP employs an automatic repeat request (ARQ) mechanism that uses selective negative acknowledgements (NACK). By using this mechanism, only segments reported missing by receivers are retransmitted. The advantage is lower reverse link traffic when the loss is negligible and a speedy recovery when the loss is severe. In contrast with TCP, there is no RTO mechanism in STP, which makes it more resilient to RTT variations.

Finally, it is important to mention that even if STP includes many of the basic principles found in TCP, it is only functionally but not semantically equivalent to it. Unfortunately, the STP protocol inherits the congestion control bias from its ancestor protocols (i.e., TCP, SSCOP [92]). Although the protocol can efficiently recover from multiple losses in the same round trip, its error recovery tactics can negatively affect its overall performance.

#### 2.5.4.2 *eXtended Satellite Transport Protocol (XSTP)*

In order to explain the reasons for which we focus on XSTP, we must first describe its features and its operating principle. Thereby, we could stress out significant characteristics that make this protocol a possible candidate transport protocol for nanosatellite networks.

XSTP is a software implementation of the STP protocol in the PIX (Protocol Implementation Framework for Linux) framework. [93] The protocol is used to host a new error control strategy, called XSTP-probing. Typically, XSTP protocol can be deployed on top of a network protocol (e.g., IP). The protocol provides a reliable connection-oriented byte streaming service to application protocols (e.g., FTP).

An XSTP session is composed of one lower and one upper session. Figure 2.9 depicts a typical configuration for a communication suite including XSTP.

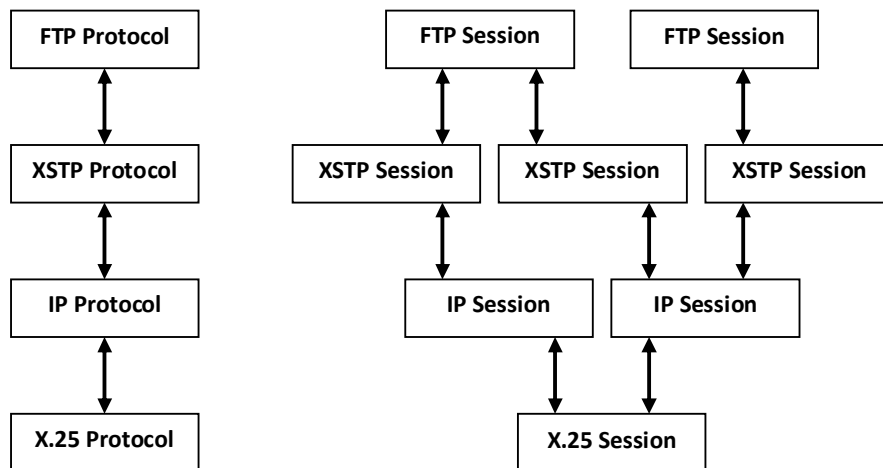


Figure 2.9 – PIX protocol and session configurations including XSTP [94]

As Maged E. Elaasar explains in paper [94], when such a suite is initialized, an instance of the XSTP protocol is created, configured and then installed in the appropriate location in the protocol hierarchy. Once there, application level protocols can use the service of the protocol to manipulate XSTP sessions.

An XSTP session plays double role (sender and receiver), which implies defining two new classes: an XSTP sender and an XSTP receiver. An instance of each of those classes is created in the private state of the session's object. As depicted in Figure 2.10, these two instances play the sending and receiving roles of the session.

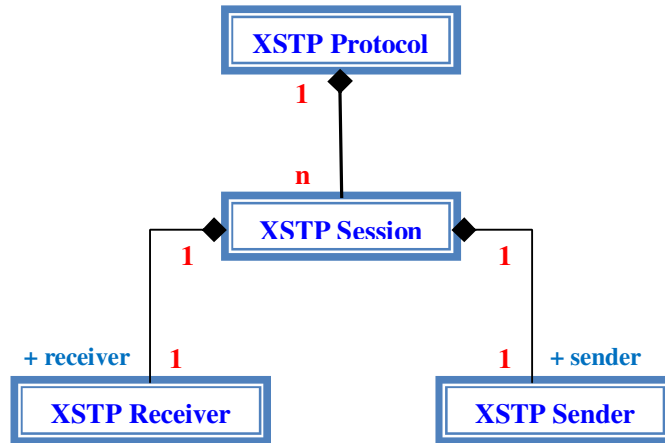


Figure 2.10 – XSTP class diagram [94]

The aim of developing the XSTP-probing mechanism was to stretch the STP protocol's ability to adapt to the different types of error found in LEO satellite networks.

There are different kinds of errors in the space channel that need to be considered and corrected in order to ensure efficient communications in nanosatellite networks. The first type is bit errors. Single and double bit errors are usually simple to correct for using CRC codes. The second type is burst errors, where many bits are corrupted at once, occur more frequently than single bit errors and cannot be corrected by CRC codes. Depending on the burst length, FEC should be able to help with recovery and avoid retransmissions when space channel experiences these errors. Another cause of errors is bit slips, where bits are lost due to variations in the respective clock rates of the transmitter and receiver.

There is also the possibility that an entire packet is lost due to incorrect addressing, or hardware error because of electrical interference or thermal noise. In this case, it is necessary to either retransmit or ignore the lost packet.

The possibility of link failure, due to a damaged or out of range nanosatellite, also must be considered. Also, channels' asymmetry (forward and return links are not symmetric) may generate significant errors.

Other potential cause of errors resides in space link designs that have to consider variable RTTs, increased noise or bursts of noise, limited bandwidth, nanosatellite antenna obscurations, limited processing power and memory.

According to papers [91], [94], the goal of any error control strategy is to adapt the sender's transmission rate to the varying error conditions in the network. This goal is usually accomplished by taking an aggressive attitude when the error is detected to be transient and a

conservative one, when it is persistent. The XSTP-probing mechanism makes no exception to this principle. It is implemented as a configurable option on the XSTP session and it is modeled as a class called *XSTPProbing*.

The probing-mechanism is triggered (Figure 2.11) upon detecting a segment loss to assess the level of congestion in the network. If congestion is detected, the mechanism responds by invoking congestion control; otherwise, it resumes with *Immediate Recovery* (restoring congestion window to the same level as before probing).

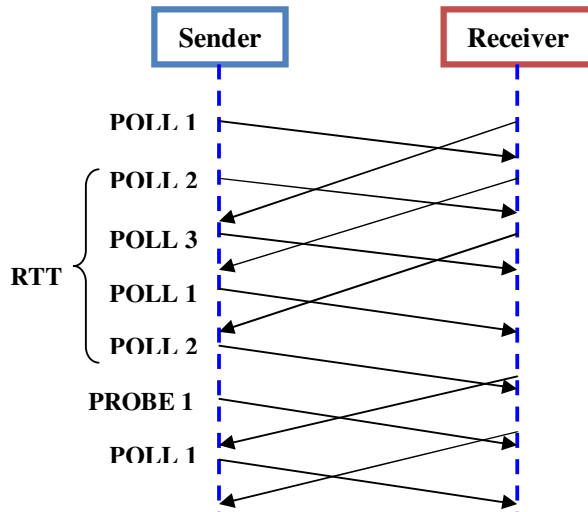


Figure 2.11 – Triggering probing mechanism by a false early timeout event [94]

Additionally, this mechanism evaluates the connection for possible error free conditions and only transmitting in those windows. As described in paper [91], it suspends new data transmission upon detecting a loss and initiates a probing cycle to collect RTT statistics on the connection. Then, it compares these RTT statistics to the RTT estimate available when the loss was discovered. It is interesting to observe that the duration of that probing cycle is proportional to the level of error in the network, which helps the connection sit out the error conditions. After the cycle is finished and if congestion is detected by proliferating RTTs, congestion control is immediately invoked. Otherwise, transmission levels are restored without taking any action. Finally, the missing segments are immediately retransmitted. Figure 2.12 illustrates different phases of a typical probing cycle as they occur in the network.

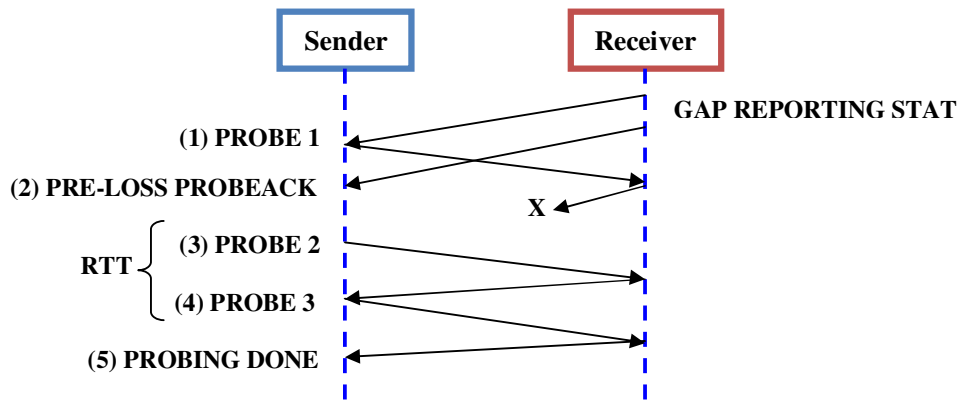


Figure 2.12 – Probing cycle phases [94]

We found important for our research to make a comparison of TCP-probing mechanism and XSTP-probing mechanism in order to outline the benefits of XSTP protocol (Table 2.9).

TCP-probing mechanism	XSTP-probing mechanism	Advantages for XSTP-probing
Changes are introduced to both sending and receiving ends of the connection	Sender-only mechanism	Simple implementation deployment of the mechanism to a network with nodes running an older version of the protocol
It adds a few new segment types and their associated states	It doesn't introduce any new segment types	XSTP's polling cycle reusing
It introduce states for tracking the progress of probing cycle	It does not introduce several states to track the progress of the probing cycle	Scalability in terms of the ability of configuring the probing cycle with different numbers of probing exchanges
the probing cycle = a number of consecutive exchanges of probes and their acknowledgements		
A version number is stored and reflected by all segments of the cycle (two probes and two probe acknowledgments) <ul style="list-style-type: none"> <li>✓ if the first probe exchange is successfully completed, the other exchange start.</li> <li>✓ if any segment gets dropped:               <ul style="list-style-type: none"> <li>- the whole cycle is abandoned;</li> <li>- a new one cycle is initiated with a new version number.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>✓ the previous exchange is not ignored but is rather given more time (up to one more RTT) to complete.</li> <li>✓ if after that time it is still not completed, a new exchange begins and the old exchange becomes obsolete.</li> </ul>	
Segment loss detected by means of a timeout	✓ sending a probe segment every RTT	Clear advantage in case of RTT extension (common phenomenon in LEO satellite networks)

Table 2.9 – Comparison of TCP-probing mechanism and XSTP-probing mechanism

Figure 2.13 presents the basic algorithm of XSTP-probing mechanism. As described in paper [33], the XSTP-probing mechanism implements this strategy by defining an ordered map between the sent probe's (POLL) timestamp and its corresponding acknowledgment's (STAT) RTT measurement. Whenever a probe is sent, its timestamp is reordered in the next empty entry in the probing map. Also, whenever a valid probe acknowledgment is received, its RTT measurement is saved in the corresponding entry in the map. The probing cycle does not complete until two consecutive entries in the map get filled with RTT measurements.

The probing map has a constant size set as a configuration parameter and it has also a policy of deleting the oldest entry to make room for new probe entries; hence the map size should be set in proportion to the expected error levels in the network.

For a more comprehensive overview of STP, XSTP and its probing mechanism, the interested reader is directed to papers [91] and [94].



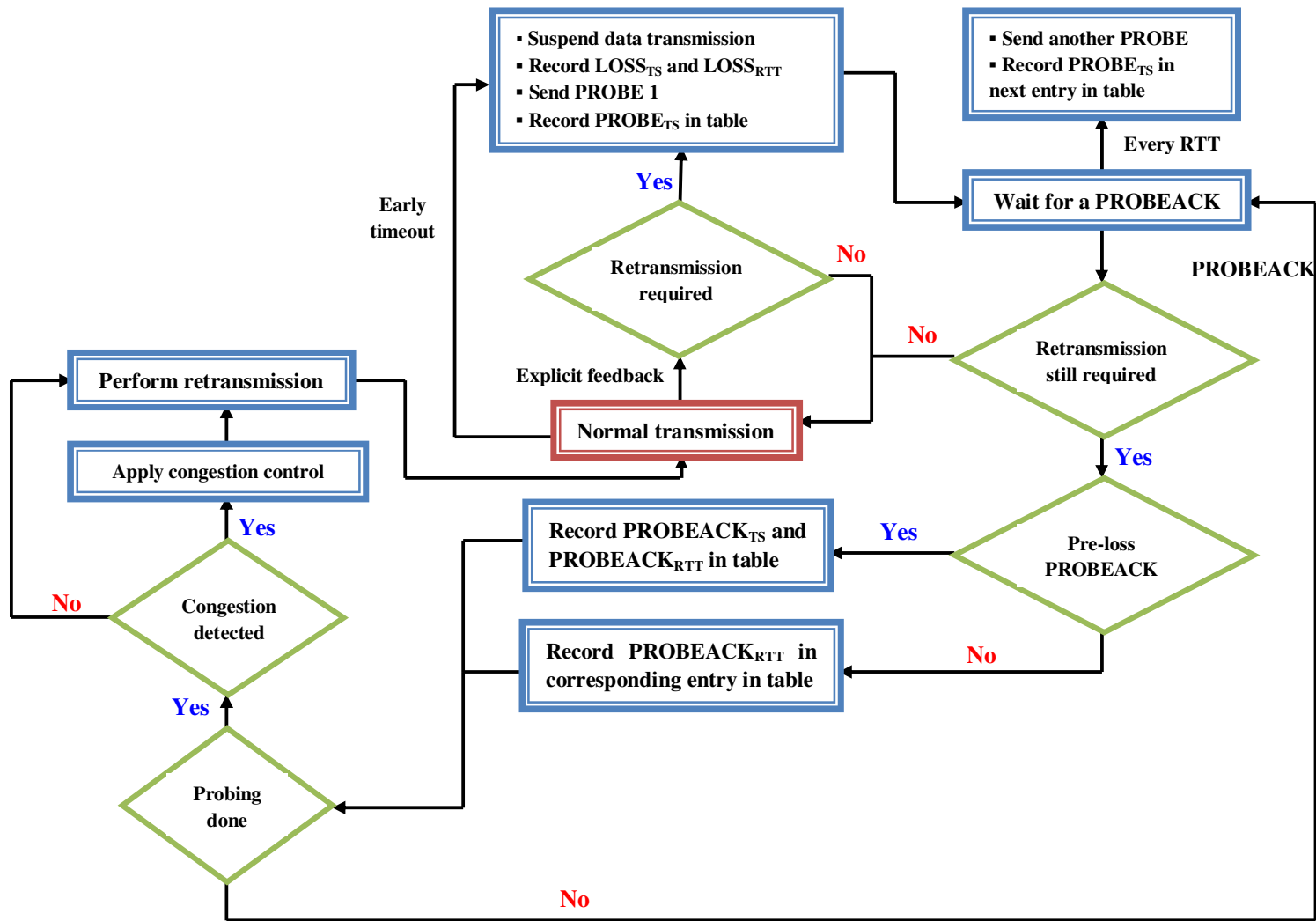


Figure 2.13 – XSTP-probing mechanism [94]

## 2.6 Summary

Chapter 2 presented an overview of small satellite domain, by describing its main concepts (i.e., nanosatellite, formation flying, constellation) and their applications. Also, an analysis of nanosatellite launches in the period 2004-mid 2007 was presented in order to identify the trend in nanosatellite launching. Then, the telecommunications framework of nanosatellite networks was described along with new approaches for routing and QoS provisioning in nanosatellite networks. Chapter 2 ended with a detailed presentation of XSTP protocol, identified as a good candidate for nanosatellite network communications, and its basic version, STP protocol.

In the next chapter, we propose three nanosatellite constellation models, named NanoDREAM, NanoICE and NanoSPHERE. For each model, a novel mission is envisaged. We adopted a simple constellation design approach which gives us a general idea of the constellation's behavior. For this reason, we consider it as a good starting concept for planning remote region exploitation missions.

NanoDREAM is a nanosatellite constellation deployed over Bolivia's Salar de Uyuni Desert in order to assure telecommunication services for an industrial company in charge of lithium resources exploitation. Also, a wireless mesh network aimed to provide efficient communications over the exploitation area of Salar de Uyuni Desert is proposed. NanoICE is a polar nanosatellite constellation designed for providing telecommunication services for Polar Regions scientific community. The last model, NanoSPHERE, is aimed to offer global coverage in the context of a robust nanosatellite telecommunications market. For each model, the development framework is set up, by pointing out the objectives and the assumptions considered for simplifying numerical calculations.

Moreover, a new method for estimating the number of nanosatellites needed to cover a specific area is proposed. Since the coverage is a key element in our nanosatellite constellation design, we defined several parameters for Earth coverage assessment.

Since one of the objectives of this thesis is to study the telecommunication framework of nanosatellite networks, we define in Chapter 3, some parameters (i.e., propagation delay and its relative variation, latency and the amount of data transmitted at each nanosatellite pass) that allow us to evaluate the communication performance of nanosatellite constellations. Finally, a novel Markov modeling-based method for assessing nanosatellite constellations' performance is presented along with the reasons for focusing on Markov methods.



# CHAPTER 3

### Chapitre 3. LES MODELES DE CONSTELLATIONS DE NANO-SATELLITES

Dans ce chapitre, nous présentons plusieurs principes généraux de conception de constellations de satellites afin de développer nos propres modèles de constellations de nano-satellites. La taille de la constellation et sa structure ont un impact significatif sur le coût du système et ses performances, donc il est nécessaire d'évaluer plusieurs configurations de constellations et justifier les raisons pour lesquelles la solution finale a été choisie.

Cette thèse propose trois modèles de constellation nano-satellitaires. Nous avons décrit, dans un premier temps, la mission de chaque modèle et ensuite nous avons présenté le modèle mathématique. Cette approche aide le lecteur à mieux comprendre le contexte dans lequel chaque modèle a été conçu et nos raisons pour se concentrer sur ces types de missions. En raison de la complexité du problème de conception de constellations, quelques hypothèses doivent être faites pour chaque modèle afin de simplifier les calculs numériques.

Le premier modèle, nommé NanoDREAM (*Nanosatellite Constellation for Desert Region Exploitation and Monitoring*) est conçu pour fournir des services de télécommunications à une société industrielle étant responsable de l'exploitation de lithium dans le Désert Salar de Uyuni en Bolivie, une région qui détient 70% de la réserve mondiale de lithium. Nous avons envisagé cette mission, en considérant la nouvelle réglementation sur la réduction des émissions de CO<sub>2</sub> au niveau mondial qui peut entraîner une exploitation massive du lithium dans l'avenir. Plusieurs études estiment que la demande mondiale du lithium, le plus léger métal utilisé pour construire des batteries très puissantes pour des téléphones portables, des ordinateurs portables et des voitures hybrides, triplera dans les 15 ans à venir. Nous avons étudié les opérateurs mobiles actuels de la Bolivie et nous avons observé qu'aucun ne fournit une couverture de ce désert. Dans ce contexte, nous avons pensé que le déploiement d'une constellation de nano-satellites peu coûteuse serait la meilleure solution. De plus, nous proposons de déployer un réseau maillé de type Ad hoc sur la région d'exploitation de lithium afin de connecter les bâtiments de façon simple et efficace, en utilisant une technologie peu coûteuse.

Le deuxième modèle, nommé NanoICE (*Nanosatellite Innovative Constellation*) est conçu pour fournir des services de télécommunication à la communauté scientifique des Régions Polaires. Notre motivation pour le concept NanoICE réside sur la croissance continue de la communauté scientifique des Régions Polaires, soutenue par des projets innovants et le progrès technologique.

Le troisième modèle, nommé NanoSPHERE, est développé dans le contexte d'une forte demande des services de télécommunications par des entreprises chargés de l'exploitation de ressources minières dans plusieurs régions de la Terre. Nous avons supposé qu'un opérateur nano-satellitaire pourrait utiliser des techniques de déploiement partiel pour assurer les requis de couverture désirables à un certain moment et progressivement étendre la zone de couverture en même temps que la demande de services augmente.

En outre, nous avons proposé une nouvelle méthode pour le dimensionnement des constellations de nano-satellites, en calculant le nombre de nano-satellites nécessaires pour couvrir une zone spécifique.

Le défi principal de la modélisation de constellations de nano-satellites est de formuler le modèle, en utilisant un ensemble d'expressions mathématiques. La formulation mathématique d'un modèle de constellation de nano-satellites consiste principalement de deux parties :

- la fonction objectif, qui est une fonction mathématique qui montre "le coût" d'une solution ;
- un ensemble de contraintes, exprimé comme un groupe d'équations mathématiques avec une ou plusieurs limitations sur la plage de solutions acceptables. Les équations de contrainte définissent la région de solution faisable.

Une fonction objectif et son ensemble de contraintes constituent un programme mathématique, qui permet de trouver une solution optimale qui minimise ou maximise la fonction objectif en satisfaisant l'ensemble des contraintes.

Nous avons montré comment nous pouvons transformer un problème de conception de constellation de nano-satellites dans un problème d'optimisation mathématique. Aussi, nous modélisons notre problème de conception de constellations de nano-satellites comme une « boîte » avec des entrées et des sorties. Donc, certains paramètres sont définis comme des données d'entrée pour un module de constellation qui fournira plusieurs données de sortie.

La couverture est un élément clé dans la conception des constellations de nano-satellites. Pour cette raison, nous avons défini un vecteur de couverture ayant quatre paramètres (i.e., le taux de couverture, le taux d'accès, la zone d'accès, la zone de couverture) afin d'évaluer les performances en termes de couverture de chaque type de constellation de nano-satellites.

Puisqu'un des objectifs de cette thèse est d'étudier le cadre des télécommunications des réseaux de nano-satellites, nous définissons dans ce chapitre, plusieurs paramètres qui nous permettent d'évaluer les performances des constellations nano-satellites (i.e., le délai de propagation et sa variation relative, le délai de bout en bout et la quantité de données transmises à chaque passage d'un nano-satellite).

Finalement, nous proposons une méthode basée sur le modèle de Markov pour évaluer les performances des constellations de nano-satellites. Nous avons choisi le modèle de Markov parce qu'il a été traditionnellement utilisé pour évaluer les performances et la fiabilité de systèmes complexes. Puisqu'une constellation de nano-satellites est un système complexe constitué de beaucoup de nano-satellites, chacun ayant plusieurs sous-systèmes, le modèle de Markov est adapté pour étudier sa fiabilité et ses performances. Par contre, l'inconvénient majeur de la méthode de Markov est la croissance accrue du nombre d'états possible du système (i.e., constellation) au fur et à mesure que la taille du système augmente. Les diagrammes d'états résultants pour de grands systèmes sont extrêmement compliqués, difficiles à construire et à calculer. Pour cette raison, nous avons appliqué cette méthode seulement au modèle NanoDREAM. Les modèles NanoICE et NanoSPHERE nécessitent une approche différente et d'autres techniques pour évaluer leur performances.

## 3 NANOSATELLITE CONSTELLATION MODELS

### 3.1 Introduction

In this chapter, we firstly introduced several constellation design principles in order to set up a base for developing our constellation models. Then, three nanosatellite constellation models are presented. We found appropriate to describe, in the first place, the mission envisaged for each model and then to introduce the mathematical model. This approach helps the interest reader to better understand the framework in which each model has been designed and our reasons of focusing on these types of missions. Due to the complexity of constellation design problem, some assumptions have to be made for each model to simplify numerical calculations.

The first model, named NanoDREAM (**N**anosatellite Constellation for **D**esert **R**egion **E**xploit**A**tion and **M**onitoring) is designed to provide telecommunications services to an industrial company in charge of lithium exploitation in Salar de Uyuni Desert. We focus on Bolivia's Salar de Uyuni Desert where more than half of lithium world's supply is founded. Also, we proposed to deploy a wireless-based network over the exploitation area of Salar de Uyuni Desert in order to provide efficient telecommunications services.

The second model, named NanoICE (**N**anosatellite **I**nnovative **C**onst**E**llation) is designed for providing telecommunication services for Polar Regions scientific community.

The third model, named NanoSPHERE, is developed in the context of a robust nanosatellite telecommunications market. A nanosatellite constellation that provides global coverage is needed in case of an increasing demand of telecommunications services by several industrial companies in charge of mineral resources exploitation in different remote regions of the Earth.

Furthermore, we proposed a new method for dimensioning nanosatellite constellation, by estimating the number of nanosatellite needed to provide coverage over a specific area.

The coverage is a key element in our nanosatellite constellation design. For this reason, we defined a coverage vector with four parameters (i.e., coverage rate, access rate, access area, footprint area) in order to evaluate the performance in terms of coverage of every type of nanosatellite constellation.

Since one of the objectives of this thesis is to study the telecommunication framework of nanosatellite networks, we define in this chapter, several parameters that allow us to evaluate nanosatellite constellations performance (i.e., propagation delay and its relative variation, latency and the amount of data transmitted at each nanosatellite pass).

Finally, a novel Markov modeling method for assessing the performance of nanosatellite constellations is proposed, explaining also the reason for choosing a Markov – based method. We focus on Markov models because they have traditionally been used to evaluate the performance and the reliability of complex systems. Since a nanosatellite constellation is a complex system constituted of many nanosatellites characterized by a high interdependency, Markov model is suited to study its reliability and performance.

### 3.2 Nanosatellite constellation design principles

The design of a nanosatellite constellation is very complex due to all the factors that need to be considered, from orbit elements to very limited resources and ending with perturbations that act on each satellite. Therefore, nanosatellite constellations are among the most challenging systems to design as a large number of variables are involved. Both the total number of nanosatellites within the constellation and the orbit drive the selection of the launch vehicle, which can be a significant contributor to the system cost. The orbit also affects the space segment size and the communication data rate. Likewise, the size of the space segment (i.e., total number of nanosatellites) also determines the complexity of the ground segment operations, and so forth. There are a lot of trades between system cost, its performance and each of the design parameters, both individually and in combination with other design parameters.

For these reasons, we considered that specifying all orbit elements for each nanosatellite of the constellation is inconvenient and overwhelming. A reasonable approach is to begin with nanosatellite constellation in circular orbits and at common inclination angle and altitude. In this case, the period, velocity and node rotation rate will be the same for all nanosatellites. The constellation size and structure has a strong impact on the overall system cost and its performance, so it is necessary to evaluate various constellation designs and to explain the reasons for final choice. The main design variables needed to be defined for a satellite constellation are listed in Table 3.1.

<i>Parameter</i>	<i>Effect</i>	<i>Selection Criteria</i>
<b>MAIN DESIGN VARIABLES</b>		
<b>Number of Satellites</b>	Principal cost and coverage driver	Minimize number consistent with meeting other criteria
<b>Constellation Pattern</b>	Determines coverage vs. latitude	Select for best coverage
<b>Minimum Elevation Angle</b>	Principal determinant of single satellite coverage	Minimum value consistent with constellation pattern
<b>Altitude</b>	It impacts the coverage, environment, launch & transfer cost	System level trade of cost vs. performance
<b>Number of Orbit Planes</b>	Determines coverage, growth and degradation	Minimize consistent with coverage needs
<b>Collision Avoidance Parameters</b>	Key element for preventing constellation self-destruction	Maximize the inter-satellite distances at plane crossings
<b>SECONDARY DESIGN VARIABLES</b>		
<b>Inclination</b>	Determines latitude distribution of coverage	Compare latitude coverage and launch costs
<b>Plane Phasing</b>	Determines coverage uniformity	Select best coverage among discrete phasing options
<b>Eccentricity</b>	Mission complexity and coverage vs. cost	Normally zero; non-zero may reduce number of satellite needed
<b>Size of Stationkeeping Box</b>	Coverage overlap needed; cross-track pointing	Minimize consistent with low-cost maintenance approach
<b>End-of-Life Strategy</b>	Eliminating orbital debris	Any mechanism that allows you to clean up the space

Table 3.1 – Main parameters needed to be defined during constellation design



For designing our nanosatellite constellation models, we followed several principles explained by James R. Wertz in paper [95] (Table 3.2).

Step
<b>1. Establish mission requirements, particularly:</b> <ul style="list-style-type: none"> <li>• Latitude-dependent coverage</li> <li>• Goals for growth and degradation plateaus</li> <li>• Requirements for different modes or sensors</li> <li>• Limits on number of satellites</li> </ul>
<b>2. Do all single satellite trades, excepting coverage</b>
<b>3. Do trades between swath width, coverage, number of satellites</b> <ul style="list-style-type: none"> <li>• Evaluate candidate constellations for: <ul style="list-style-type: none"> <li>- coverage Figures of Merit vs. latitude;</li> <li>- coverage excess;</li> <li>- growth and degradation;</li> <li>- altitude plateaus;</li> <li>- End of Life option.</li> </ul> </li> <li>• Consider the following orbit types (Walker patterns, Equatorial, Elliptical, Polar).</li> </ul>
<b>4. Evaluate ground track plots for potential coverage holes or methods to reduce the number of satellites needed.</b>
<b>5. Adjust inclination and in-plane phasing to maximize the intersatellite distances at plane crossings for collision avoidance.</b>
<b>6. Review the rules of constellation design.</b>
<b>7. Document reasons for choices.</b>

*Table 3.2 – Constellation design summary*

### 3.3 NanoDREAM model

#### 3.3.1 NanoDREAM mission description

This chapter describes the mission envisaged for NanoDREAM (Nanosatellite Constellation for Desert Region Exploitation and Monitoring) model.

Worldwide, there are a lot of unexploited regions in terms of mineral resources. Several minerals, highly significant in the global economy, are mined in deserts, where they occur not because of current aridity but rather due to geological history. Indeed, the Simpson Desert (in Australia) is rich in uranium, the Sahara Desert is rich in iron ore and salt, the Atacama Desert (Chile) is rich in iron and copper ore. Therefore, it is highly likely that in the near future, industrial companies will exploit those areas for their precious wealth.

A study of United Nations Environment Programme [96] states that 38% of the global supply of bauxite (an aluminium source) is mined in Australian drylands; 52% of the world's copper extraction in 2004 was mined from deserts in Chile, Australia and Mexico; 33% of world's diamonds were extracted in the drylands of Botswana and Namibia; and the deserts of South Africa, northwest China, Australia, Uzbekistan, and Mali accounted for at least 35% of the world's production of gold. Phosphate rock is mined in the deserts of Morocco (16% of world production), Senegal (9%), Tunisia (6%), Jordan (5%), Australia (4%), and Israel (3%), adding up to 43% of global production. Finally, half the world's uranium ores are

mined in deserts (Kazakhstan, Niger, Namibia, Uzbekistan, and South Africa). The most important contribution of deserts to mineral wealth is their deposits of evaporite minerals - soda, boron, and nitrates (e.g. Chile saltpetre), which are not found in other ecosystems.

High in the Andes, in a remote corner of Bolivia, lies more than half the world's reserves of a mineral that could radically reduce our reliance on dwindling fossil fuels. Fifty to 70 percent of the world's supply of this critical mineral is contained in Bolivia's Uyuni salt flats, shown in Figure 3.1.



Figure 3.1 – Salar de Uyuni Desert [97]

As mentioned in paper [98], the global demand for lithium, the lightweight metal used to make high-powered batteries for cell phones, laptops, and hybrid cars, is expected to triple in the next 15 years.

The geographic distribution of resources and reserves are shown in Figure 3.2 and Figure 3.3. The majority (over 50%) of the world's lithium reserves exist in Chile, Bolivia and Argentina. Other countries with important resources and reserves are: US, China, Russia, Zaire, Australia and Canada.

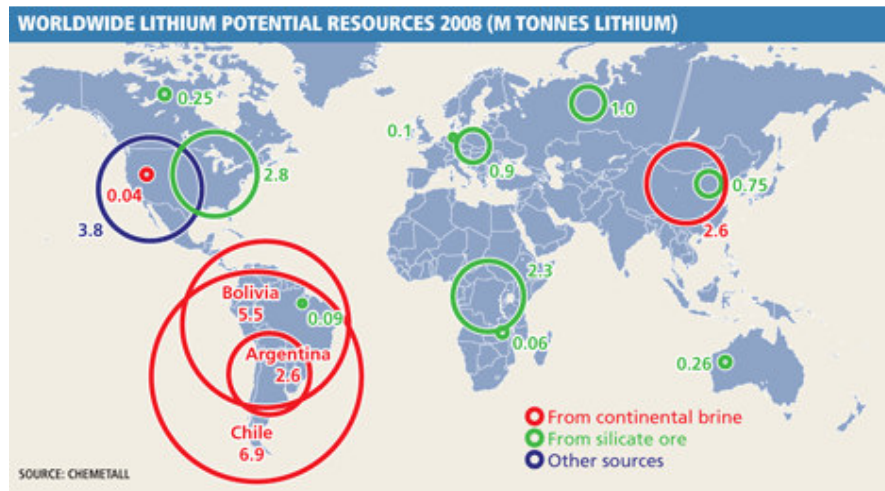
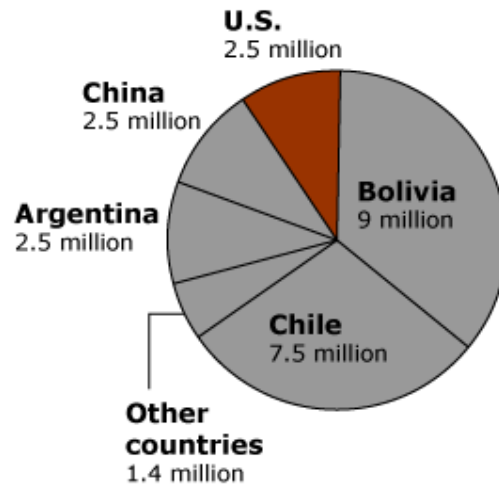


Figure 3.2 – Lithium resources over the world

### Identified Lithium Resources

In metric tons, out of a total of 25.5 million metric tons of world resources currently identified. Recent discoveries in Afghanistan have not been detailed.



SOURCE: U.S. GEOLOGICAL SURVEY  
GRAPHIC CREDIT: SOLAR HOME & BUSINESS JOURNAL

Figure 3.3 – Identified lithium resources

The United States Geological Survey [99] states that 5.4 million tons of lithium could potentially be extracted in Bolivia, compared with 3 million in Chile, 1.1 million in China and just 410,000 in the United States.



Figure 3.4 – Salar de Uyuni viewed from space, with Salar de Coipasa in the top left corner

Therefore, we focus on the Salar de Uyuni, the world's largest salt flat desert of 10,582 square kilometers. It is located in the southwest Bolivia (Figure 3.4), near the crest of the Andes, and is elevated 3,656 meters above the mean sea level.

At present, Bolivia's lithium reserves are at the centre of the attentions of several multinationals, as well as the government. The latter intends to build its own pilot plant with a modest annual production of 1,200 tons of lithium and to increase it to 30,000 tons by 2012. [100]

Comibol, the state agency that oversees mining projects, is investing about \$6 million in a small plant near the village of Río Grande on the edge of Salar de Uyuni (Figure 3.5),

where it hopes to begin Bolivia's first industrial-scale effort to mine lithium from the white, moonlike landscape and process it into carbonate for batteries. [101]



Figure 3.5 – Pilot lithium plant under construction in Uyuni [99]

Figure 3.6 shows lithium mining process at Salar de Uyuni. [97]

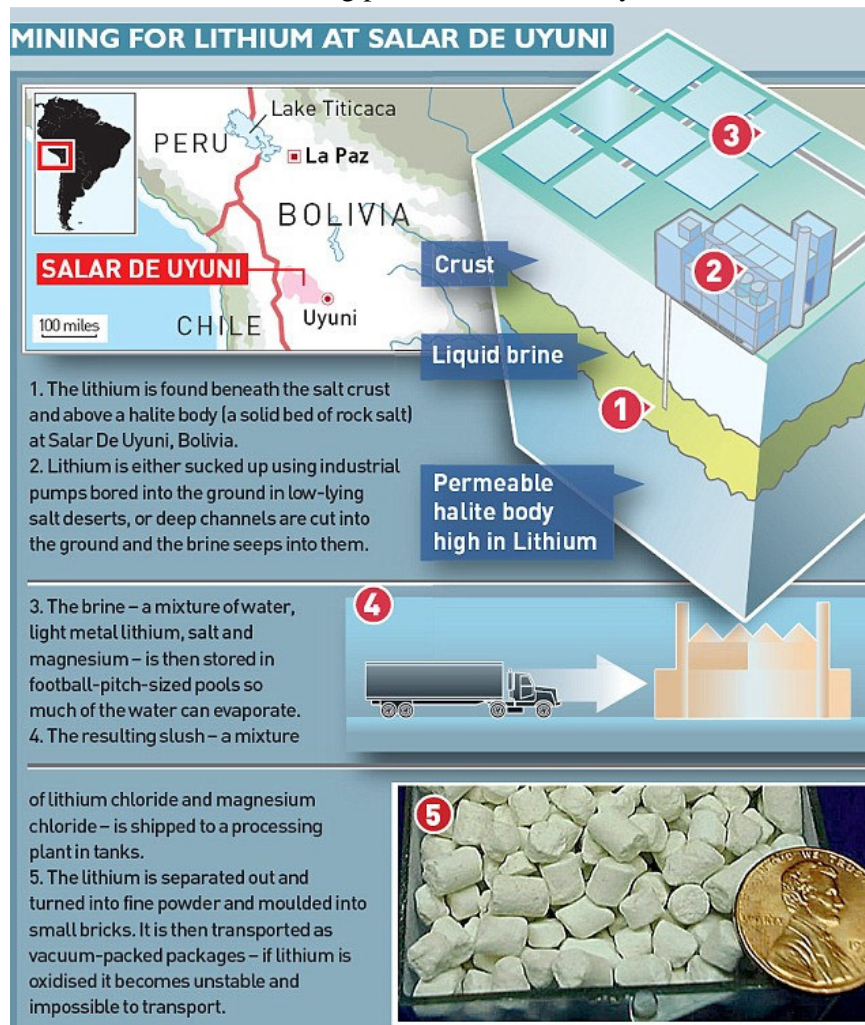


Figure 3.6 - Lithium mining process at Salar de Uyuni [97]

Considering this context, we propose to deploy a nanosatellite operator that provides communications services (voice, SMS and images) for an industrial company in charge of lithium resources exploitation in Salar de Uyuni desert. It is important to mention that this small satellites system can be applied to any similar remote area.

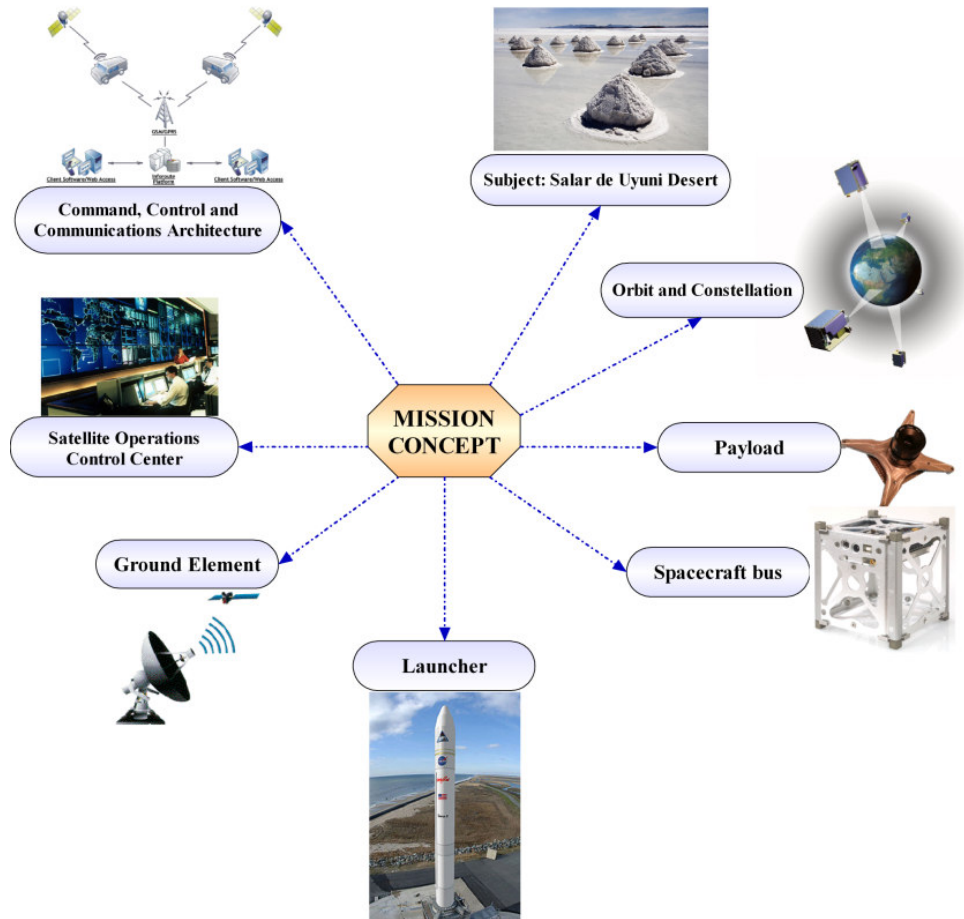


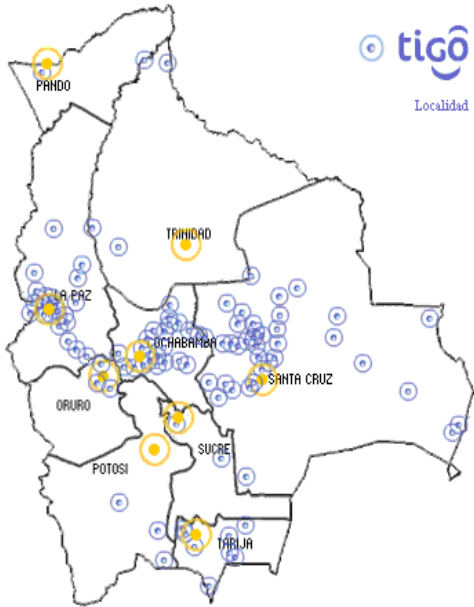
Figure 3.7 – Mission concept basic elements

Figure 3.7 presents all the elements of our mission, which implies high-level processes from mission analysis and design to cost estimation models.

Firstly, we have investigated the existing Bolivian mobile operators and their coverage areas. There are 3 mobile operators in Bolivia:

- Telefonica Celular De Bolivia S.A. (TELECEL BOLIVIA), operating within GSM850 band;
- Entel SA, operating within GSM1900 band;
- Nuevatel PCS De Bolivia SA, operating within GSM1900 band.

As seen in Figure 3.8, Figure 3.9 and Figure 3.10, none of the operators have coverage over or close to the Salar de Uyuni desert.



Seguimos creciendo para brindarte la mejor comunicación GSM Multimedia.

Figure 3.8 – TELECEL BOLIVIA coverage map



Figure 3.9 – Entel SA coverage map (Credits : 2009 GSM Association; Europa Technologies Ltd.)



Figure 3.10 – Nuevatel PCS De Bolivia SA coverage map (Credits : 2009 GSM Association; Europa Technologies Ltd.)

Secondly, an analysis of possible needs of the industrial company personnel yields the following requirements:

- Continuous coverage of the target area (24h/24).
- Mobile terminals with voice and data capabilities (e.g., voice, SMS, imaging).
- Group Voice communications among on-site personnel.

The network architecture should be “flexible”, so it has to be able to provide direct coverage to the area without having to go through a hierarchical command center.

Our system architecture is divided into three segments:

- Space segment is represented by the nanosatellite constellation;
- Ground segment is represented by Mobile Ground Station (or MGS). Based on the same principle as the i-c@r, used to provide WiFi Internet over a certain area via satellite, we can consider a similar, modified MGS, with an S-band transceiver to ensure the satellite link via a 3m wide satellite dish.
- User segment is represented by Mobile User Terminals (or MUT) with voice and data capabilities.

### 3.3.2 Ground segment architecture

Based on the lithium extraction and processing technique, we envisaged the following structure for a lithium exploitation plant (Figure 3.11):

- 1 industrial building which contains the pumps bored into the ground that will suck up the liquid brine (a mixture of water, lithium, salt and magnesium) and pump it into evaporation pools. Another technique is to cut channels into the salt soil in which liquid brine is accumulated.

- 10 solar evaporation pools;
- 1 processing building designed for transformation lithium into small bricks that will be transported in vacuum-packed packages for preventing it to become unstable.
- 5 housing buildings that will accommodate the plant's personnel;
- 1 canteen;
- 1 administration office;
- 1 service building in charge of transport vehicles maintenance.

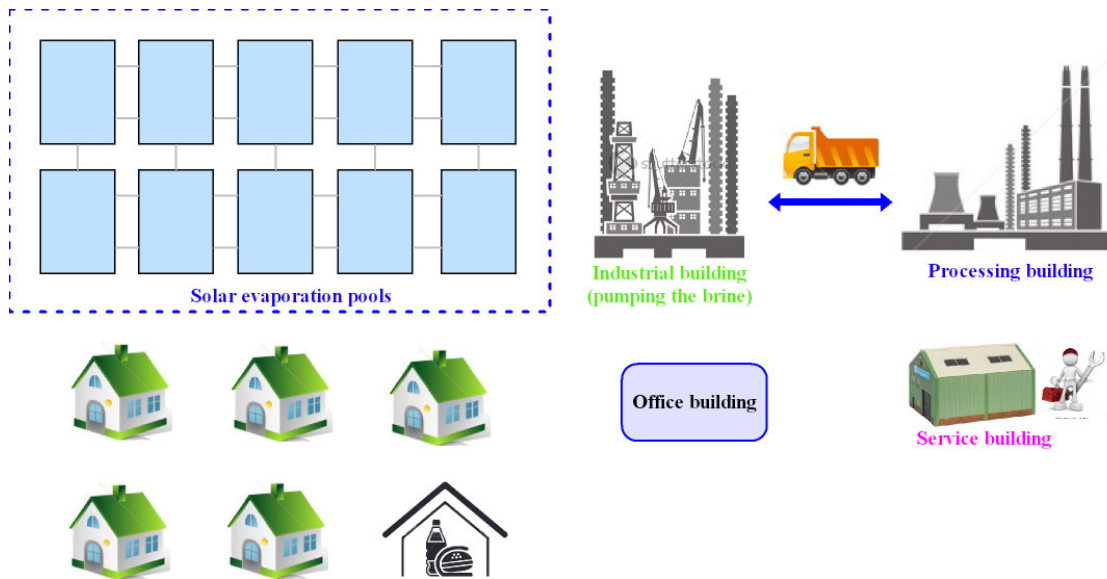


Figure 3.11 – Plant architecture

We propose to deploy a wireless mesh network over the exploitation area in order to easily, effectively and wirelessly connect all the buildings using inexpensive technology. Our choice for this technology is based on the capabilities of wireless mesh networks that are consistent with our mission proposal. In order to justify our choice, we found appropriate to enumerate here the main advantages of wireless mesh networks:

- ✓ Easiness to set up  
The cost of the equipment is lower compared to other networking solutions, and the ease of installation clearly outcores other methods, since there is no need to mount cables around an entire city to obtain a huge network.
- ✓ Good coverage  
A wireless mesh network consists of multiple nodes that communicate with each other. If for whatever reason a node is blocked and separated from the network for a while, other nodes in its vicinity cover the respective area and take the load.
- ✓ Self-Management  
Once set up, a wireless mesh network can manage its load to avoid clogging a certain network node. If one node becomes very busy, the network traffic is redirected through other nodes, maintaining a good balance of the network load. The self-management feature, which allows for the system to find the best traffic paths when congestion occurs, provides a system that may experience less failure and downtime.



✓ Speed

In a wireless mesh network, each node acts as an individual server. This allows for greater speeds for local connection, which run directly from the source to their destination, without needing to pass through a dedicated server.

✓ Interconnectivity

Since wireless mesh networks use the same protocols as regular wireless network, it is easy to establish connectivity between your own local networks and a wireless mesh network. A wireless mesh network can be a good method to connect two local networks, situated in opposite parts of a region, without using the Internet. This way, the data speeds are increased and the chances of a network drop are very low.

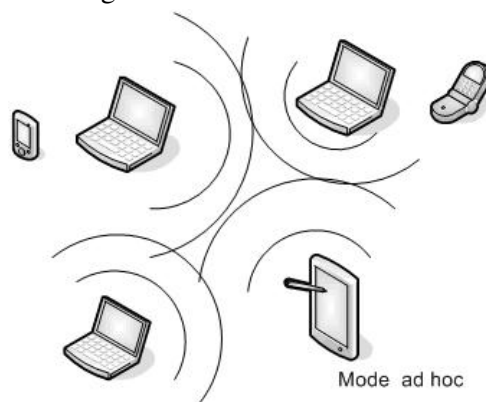
✓ Flexibility

The flexibility of the mesh network arises from its self-configuration, self-healing and scaling capabilities. Self-configuring means that network automatically incorporates a new node into the existing structure without needing any adjustments by a network administrator. Self-healing is the network capability to automatically find the fastest and most reliable paths to send data, even if nodes are blocked or lose their signal. The self-configuration and self-healing capabilities of the mesh network render it eminently scalable.

There are only two communication modes:

- Ad hoc mode, illustrated in Figure 3.12, is a method for wireless devices to directly communicate with each other. Operating in Ad hoc mode allows all wireless devices within range of each other to discover and communicate in peer-to-peer fashion without involving central access points. In addition, all wireless adapters on the ad-hoc network must use the same SSID and the same channel number.

Ad hoc networks have the advantage of working well as a temporary fallback mechanism if normally-available infrastructure mode gear (access points or routers) stop functioning.

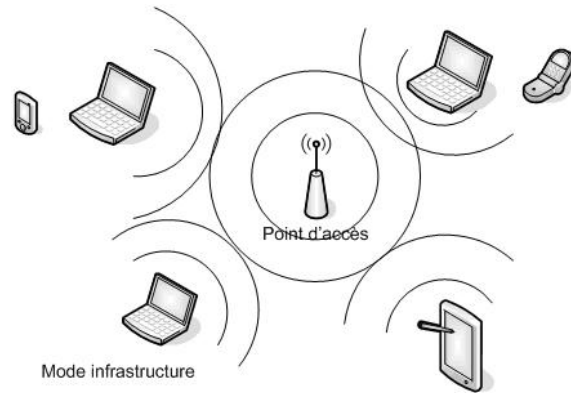


*Figure 3.12 – Ad hoc mode*

- Infrastructure mode, depicted in Figure 3.13, joins a wireless network to a wired Ethernet network. It also supports central connection points for WLAN clients. A wireless access point (AP) is required for infrastructure mode wireless

networking. To join the WLAN, the AP and all wireless clients must be configured to use the same SSID. The AP is then cabled to the wired network to allow wireless clients access to, for example, Internet connections or printers. Additional APs can be added to the WLAN to increase the reach of the infrastructure and support any number of wireless clients.

Compared to Ad hoc mode, infrastructure mode networks offer the advantage of scalability, centralized security management and improved reach. Its main disadvantage is simply the additional cost to purchase AP hardware.



*Figure 3.13 – Infrastructure mode*

As communication protocol for our ground segment architecture, we propose AODV (Ad hoc On-Demand Distance Vector) protocol, a reactive protocol, meaning that a route is established only when it is required by a source node for transmitting data packets. Thus, AODV responds to reactive routing approach that needs to be considered for nanosatellite networks, as explained in Chapter 2.4.3.

In order to justify our choice and understand the simulation results, we found interesting to briefly describe here the main features of AODV.

AODV is intended for use by mobile nodes in an Ad hoc network. It offers quick adaptation to dynamic link conditions, low processing and memory overhead, low network utilization, and determines unicast routes to destinations within the Ad hoc network. It uses destination sequence numbers to ensure loop freedom at all times, avoiding problems such as "counting to infinity" associated with classical distance vector protocols. Much of the complexity of the protocol is to lower the number of messages to conserve network capacity.

The main advantage of AODV is that it doesn't create extra traffic for communication among existing links, that's because routes are established on demand and destination sequence numbers are used to find the latest route to the destination. In addition, it doesn't require much memory or calculation.

One of AODV disadvantage is that intermediate nodes can lead to inconsistent routes if the source sequence number isn't updated for a while, hence they don't have the latest destination sequence number. For more information regarding AODV, the interest reader is invited to consult the references [102] and [103].

### 3.3.3 NanoDREAM framework development

In this sub-chapter, the NanoDREAM framework development is set up, by pointing out the objectives and the assumptions. Moreover, it describes concepts and ideas that could be applied to space segment dimensioning of nanosatellite constellations. Due to the complexity of the problem, some assumptions have to be made that simplifies numerical calculations.

We assumed that nanosatellites are placed on an equatorial, sun-synchronous LEO type orbit and they are passing over a target represented by Salar de Uyuni Desert. Also, we assume that Earth is a perfect sphere, an adequate assumption for most mission geometry applications. For precise calculation, a correction for oblateness must be applied. In our calculations, we neglected the Earth's rotation in the short period for which the nanosatellite passes over the interested area.

In paper [95], James R. Wertz states that if the regions of interest do not include the poles, then an equatorial constellation may provide all the coverage with a single orbital plane, which leads to flexibility, multiple performance plateaus and graceful degradation.

In this research work, we used this design idea to propose a nanosatellite constellation concept, named NanoDREAM. Knowing that our target area is Salar de Uyuni Desert placed on 20° S latitude, a constellation having several equatorial nanosatellites placed on a LEO, sun-synchronous orbit, with enough altitude to provide the appropriate coverage at the smallest elevation angle ( $\epsilon$ ) is the best solution for our mission.

NanoDREAM is a simple model which gives a general idea of the system's behavior. For this reason, we consider it as a good starting concept for planning remote region exploitation missions. Of course, this model has its own limitation, by not being capable of describing real on-orbit behavior of nanosatellite constellations because it does not consider all the perturbation effects that act on each nanosatellite. For these reasons, the model should be backed up by simulations with more precise and complex models.

The main goal is to find a nanosatellite constellation with a minimum number of nanosatellites, which provides continuous coverage over Salar de Uyuni Desert and maximize the data quantity transmitted over ground station on each nanosatellite pass. Providing coverage over a specific desert region means that the nanosatellite has to stay as long as possible over the target area so, the time in view needs to be maximized.

Once the objectives have been formulated and the assumptions have been described, the next step is to define NanoDREAM model and its parameters. The NanoDREAM concept definition involves a specific approach which can be summarized as follows:

- formal mathematical problem definition;
- conceptual nanosatellite constellation design problem formulation;
- design and constant vectors definition;
- methodology for estimating the number of nanosatellites in the constellation;
- geometric relationships between nanosatellite and user terminal on Earth;
- Earth coverage assessment;
- performance indicators for nanosatellite telecommunications.

### 3.3.4 Formal mathematical problem definition

The main challenge of nanosatellite constellation modeling lies in setting up the model in a clear set of mathematical expressions. The procedure for transforming a verbally formulated problem into a model includes the following steps:

- 1) Determine the object to be optimized and express it as a mathematical function (define input variables).
- 2) Identify all requirements and limitations, and express them mathematically (define constraints).

In order to understand the behavior of a mathematical model under any circumstances, an analytical solution needs to be determined. This involves calculus, trigonometry, and other math techniques to write down the solution.

The NanoDREAM model mathematical formulation mainly consists of two parts:

- The objective function, which is a mathematical function that shows the “cost” of a solution;
- A set of constraints, expressed as a set of mathematical equations with one or more limitations on the range of acceptable solutions. The constraint equations define the feasible solution region.

An objective function and its associated set of constraints is named a mathematical program, which once formulated, allows finding an optimal solution that minimizes or maximizes the objective function while satisfying the set of constraints.

A classical single objective linear optimization problem can be formulated as follows:

$$\text{Minimize(or Maximize)} \left( f(y) = q_1y_1 + q_2y_2 + q_3y_3 + \dots + q_ny_n = \sum_{j=1}^n q_j y_j \right) \quad (1)$$

Subject to:

$$a_{11}y_1 + a_{12}y_2 \dots + a_{1n}y_n \leq b_1 \quad (2)$$

$$a_{21}y_1 + a_{22}y_2 \dots + a_{2n}y_n \leq b_2 \quad (3)$$

⋮

$$a_{m1}y_1 + a_{m2}y_2 \dots + a_{mn}y_n \leq b_m \quad (4)$$

Given:

$$y_j \leq u_j \text{ for all } j \quad (5)$$

$$y_j \geq l_j \text{ for all } j \quad (6)$$

The first part is the objective function to be maximized (or minimized). The decision variables, noted as  $y_j$ ,  $j = \overline{1, n}$ , are the parameters whose values vary over a given range to minimize or maximize the objective function  $f$ . The decision variables in a nanosatellite constellation design problem can be real continuous (i.e. constellation altitude between 500 km and 1500 km), integer (i.e. minimum elevation angle), binary (i.e. whether or not to consider inter-satellite links), or any combination of these. In this research, all the decision variables are considered static variables (i.e. their values do not change dynamically over time). The cost coefficients  $q_j$ ,  $j = \overline{1, n}$  are associated with each of the decision variables.

The second part (Eq. 2 to Eq. 4) is the set of constraints, where there are  $m$  linear constraint equations for the decision variables. These constraint equations place limits  $b_m$  on

certain combinations of the decision variables. The last two inequalities (Eq. 5, Eq. 6) represent the upper  $u_j$  and lower  $l_j$  limits placed on each decision variable.

We define a feasible solution as a combination of decision variables' values  $y_j$  which satisfies all constraint equations as well as the upper and lower limits.

An optimal solution is a combination of decision variables' values which includes a feasible solution and minimizes or maximizes the objective function.

The mathematical formulation of the NanoDREAM model could be written as:

**Objectives: min  $N_n$  and max  $Cov$**

**Constraints: Subject to**

*Altitude  $500 \text{ Km} \leq h \leq 1500 \text{ Km}$*

*Minimum elevation angle  $5^\circ \leq \epsilon_{min} \leq 30^\circ$*

*Latitude  $L = 20^\circ \text{ S}$*

*Sun-synchronous, equatorial orbit  $i=0^\circ$*

*Downlink data rate  $9.6 \text{ Kbps} \leq r \leq 1024 \text{ Kbps}$*

The objective vector  $V$  is summarized in Eq. 7:

$$V = \begin{bmatrix} N_n \\ T \\ d \end{bmatrix} = \begin{bmatrix} \text{Number of nanosatellites in the constellation} \\ \text{Time in view} \\ \text{Data quantity} \end{bmatrix} \quad (7)$$

The overall objectives for NanoDREAM mission are:

- **Objective 1:** minimizing the number of nanosatellites within the constellation:  $N_n$
- **Objective 2:** maximizing the time in view ( $T$ ) spent by each nanosatellite over any point of the coverage area
- **Objective 3:** maximizing the quantity of data ( $d$ ) transmitted over each nanosatellite pass.

**3.3.5 Conceptual nanosatellite constellation design problem formulation**

As mentioned in the previous section, a classical optimization problem (Eq. 1) contains an objective function, decision variables, constraint equations, and decision variable limits. Figure 3.14 illustrates a mapping of classical optimization problem elements onto the nanosatellite constellation design problem. This diagram clearly shows the transformation of our nanosatellite constellation conceptual design problem into a mathematical optimization problem.

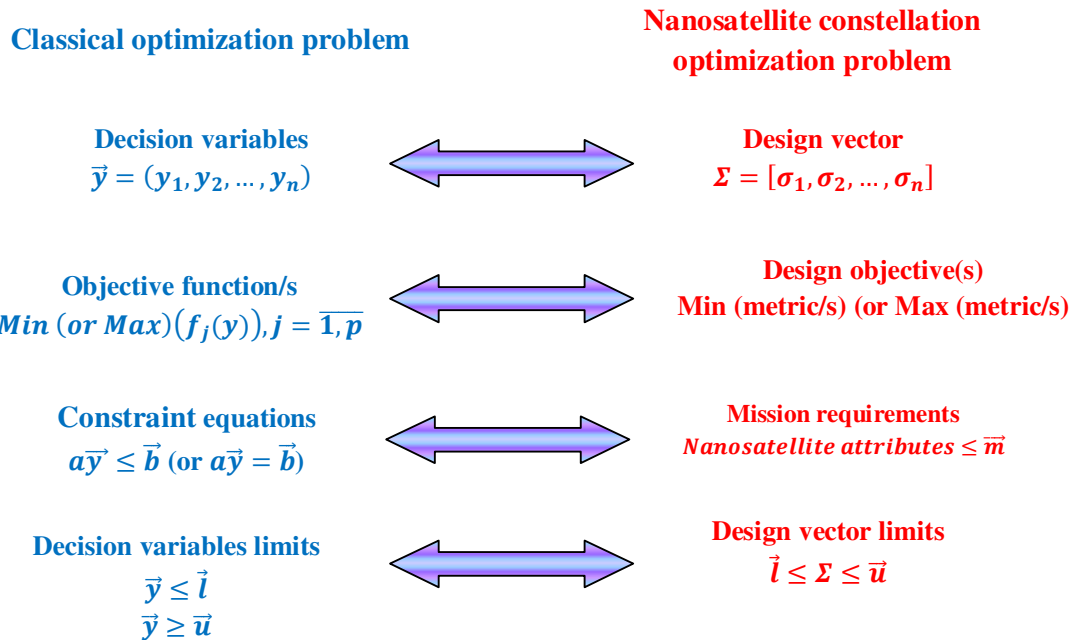


Figure 3.14 – Mapping of classical optimization problem onto the nanosatellite constellation design problem

### 3.3.6 Design vector and constant vector definition

We model our problem as a box with inputs and outputs. Therefore, some parameters are defined as input data for a constellation module (box) that will delivers several output data. Figure 3.15 illustrates key inputs and outputs of the constellation module.

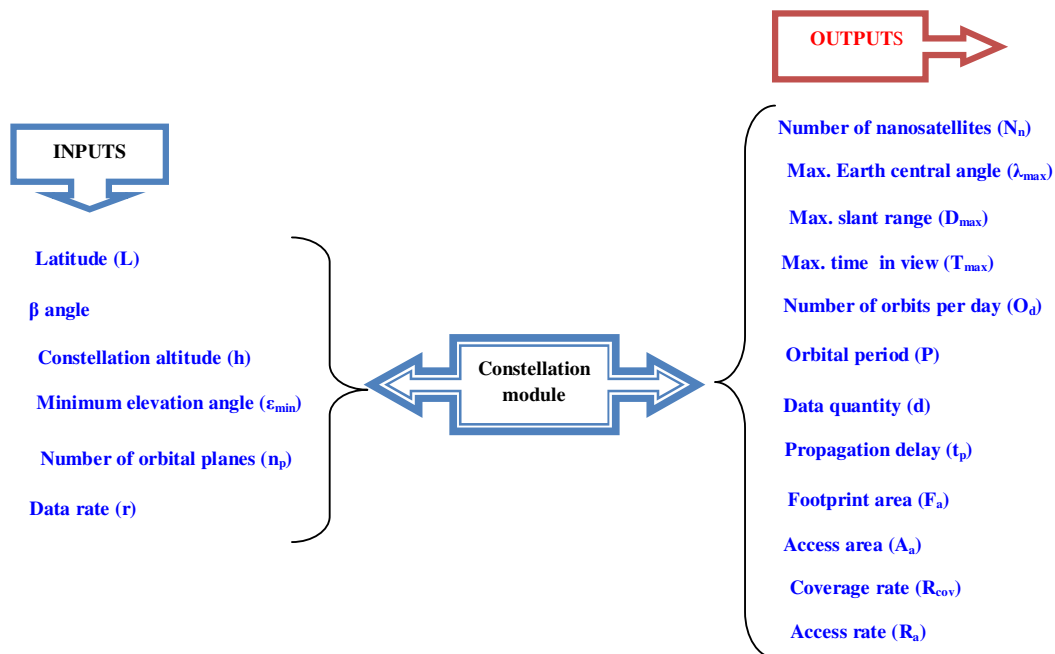


Figure 3.15 – Inputs and outputs of constellation module

Two vectors were defined: design vector and constants vector. The first one contains the attributes that will distinguish and differentiate alternative nanosatellite constellations. The latter contains attributes that will not differentiate alternative system architectures. For example, the latitude of Salar de Uyuni Desert is a constant value of 20° regardless of the other attributes of the architecture.

As Eq. 8 shows, three variables – constellation altitude, downlink data rate and minimum elevation angle – make up the design vector.

$$\Sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{bmatrix} = \begin{bmatrix} km \\ Kbps \\ degrees \end{bmatrix} \quad (8)$$

Latitude ( $L$ ), inclination angle ( $i$ ) and  $\beta$  angle are variables of constant vector, given by Eq. 9.

$$\Gamma = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix} = \begin{bmatrix} degrees \\ degrees \\ degrees \end{bmatrix} \quad (9)$$

Table 3.3 summarizes design vector variables while Table 3.4 presents the values for constant vector parameters.

Design vector variable	$\Sigma$	Range
Constellation altitude	$\sigma_1$	500 km ≤ h ≤ 1500 km
Downlink data rate	$\sigma_2$	9.6 Kbps ≤ r ≤ 1024 Kbps
Minimum elevation angle	$\sigma_3$	5° ≤ $\epsilon_{min}$ ≤ 30°

Table 3.3 – NanoDREAM design vector

Constant vector variable	$\Gamma$	Value
Latitude	$\gamma_1$	20°
Inclination angle	$\gamma_2$	0°
$\beta$ angle	$\gamma_3$	70°

Table 3.4 – NanoDREAM constant vector

### 3.3.7 Methodology for estimating the number of nanosatellites in the constellation

In this chapter, we present a method for estimating the number of nanosatellite needed to cover a specific area.

Firstly, we define the coordinates of any point on the Earth surface, by considering a 3D coordinate system. As depicted in Figure 3.16, the center of Earth is the origin of this coordinate system. The z-axis represents the North Pole, and the x-axis represents the Greenwich Meridian, or the line of 0 degrees longitude. Let  $\alpha$  be the angle between any vector and the positive x-axis (i.e., the longitude of any point on Earth). The angle  $\beta$  represents the angle between any vector and the positive z-axis (i.e., the difference between 90° and the latitude of any point on Earth).  $\beta$  is the complement angle of the latitude angle.

For example, a point of Salar de Uyuni Desert that lies at 20° S latitude and 67° E longitude can be represented by a vector whose length is the radius of Earth ( $R_E=6378$  km), whose  $\alpha$  angle is 67°, and whose  $\beta$  angle is  $90^\circ-20^\circ=70^\circ$ .

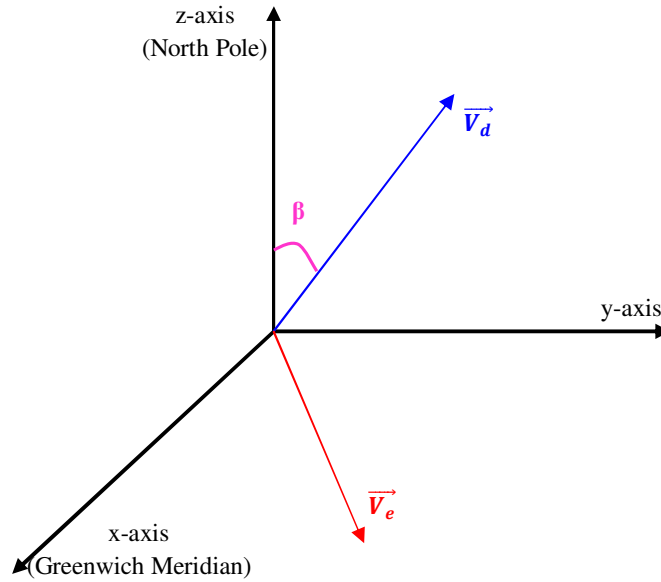


Figure 3.16 – 3D coordinate system

Thus, any point A can be described by a vector  $\vec{V} = [R_E, \alpha, \beta]$ , where  $R_E$  is the Earth radius,  $\alpha$  is the longitude angle and  $\beta$  is the complement of latitude angle.

The relationship between  $(R_E, \alpha, \beta)$  and  $(x, y, z)$  is as follows:

$$x = r \sin \beta \cos \alpha \quad (10)$$

$$y = r \sin \beta \sin \alpha \quad (11)$$

$$z = r \cos \beta \quad (12)$$

Using these relationships, the vector  $V$  could be written as follows:

$$V = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \leftrightarrow \begin{bmatrix} r \sin \beta \cos \alpha \\ r \sin \beta \sin \alpha \\ r \cos \beta \end{bmatrix} \quad (13)$$

In Figure 3.16, the vector of Salar de Uyuni Desert is  $\vec{V}_d = [R_E, 70^\circ, 67^\circ]$  and the equatorial orbit (nanosatellite) vector is  $\vec{V}_e = [R_E + h, 90^\circ, 0^\circ]$ .

Figure 3.17 illustrates the geometry for calculating the number of nanosatellites. The projection of the satellite onto the Earth is called the sub-satellite point (SSP) or nadir. The maximum Earth central angle measured at the center of the Earth from the sub-satellite point to the target is  $\lambda_{max}$ .



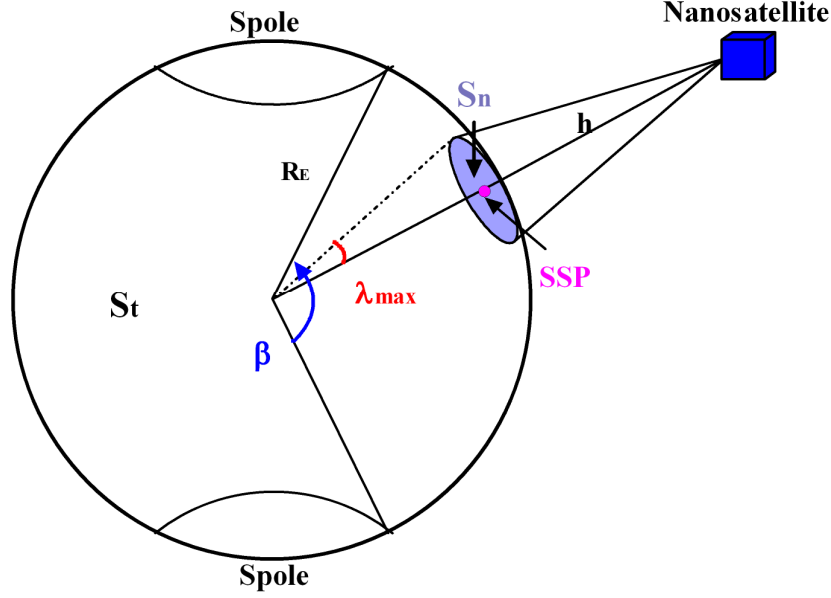


Figure 3.17 – Computational geometry for the number of nanosatellites

Let  $S_{Earth}$  be the area of the Earth:

$$S_{Earth} = 4\pi R_E^2 \quad (14)$$

, where  $R_E$  is the Earth radius (6378 km).

Let  $S_{pole}$  be the area of each icecap. We assumed that the two icecaps have an equal surface. By applying trigonometric formulas, we obtain:

$$S_{pole} = 2\pi R_E^2 \times (1 - \cos \beta) \quad (15)$$

According to Figure 3.17,  $S_t$  is the area of the Earth, excluding icecaps:

$$S_t = S_{Earth} - 2 \times S_{pole} \quad (16)$$

By replacing Eq. 14 and Eq. 15 in Eq. 16, we obtain:

$$S_t = 4\pi R_E^2 \times \cos \beta \quad (17)$$

$S_n$  denotes the nanosatellite coverage area. For a given minimum elevation angle  $\epsilon_{min}$ , the area covered by the nanosatellite will be:

$$S_n = 2\pi R_E^2 \times (1 - \cos \lambda_{max}) \quad (18)$$

We estimated the minimum number of nanosatellites  $N_n$ :

$$N_n \geq \frac{S_t}{S_n} \quad (19)$$

By replacing Eq. 17 and Eq. 18 into Eq. 19, we obtain the minimum number of nanosatellites as a function of maximum Earth central angle ( $\lambda_{max}$ ) and  $\beta$  angle:

$$N_n \geq \frac{2 \cos \beta}{1 - \cos \lambda_{max}} \quad (20)$$

Therefore, a nanosatellite constellation is defined by the vector  $\mathbf{C}[N_n, \mathbf{n}_p, \mathbf{h}, \epsilon_{min}, \mathbf{i}]$ , where  $N_n$  is the number of nanosatellites in the constellation,  $\mathbf{n}_p$  is the number of orbital planes,  $\mathbf{h}$  is the constellation altitude,  $\epsilon_{min}$  is the minimum elevation angle and  $\mathbf{i}$  is the inclination angle with respect to the equatorial plane.

### 3.3.8 Geometric relationships between nanosatellite and user terminal on Earth

Figure 3.18 describes the basic geometric relations between a nanosatellite and a user terminal on Earth.

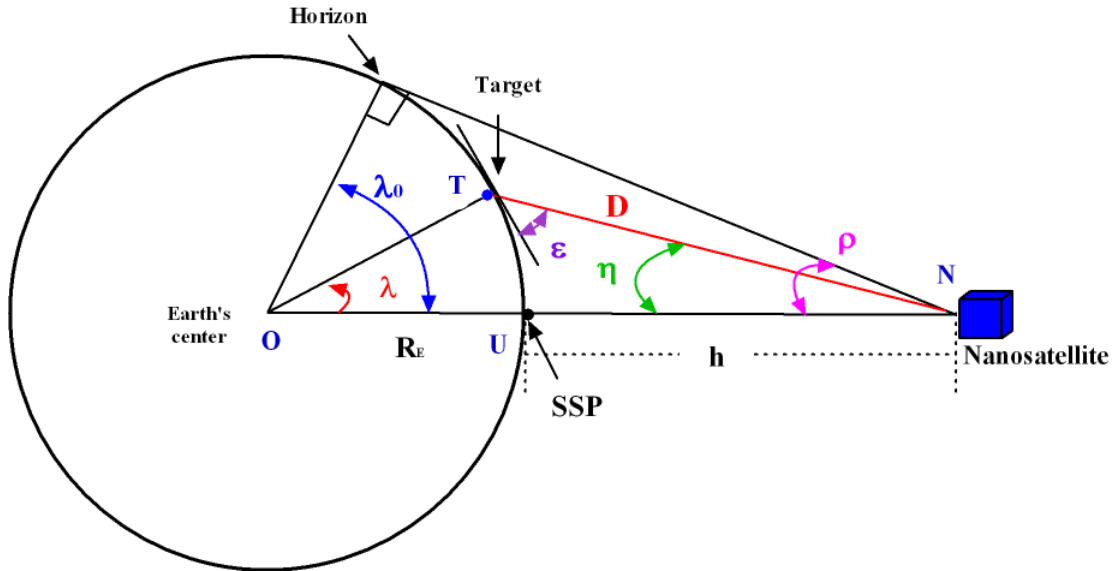


Figure 3.18 – Geometric relationships between nanosatellite, target area and Earth's center

Five important geometrical parameters can be identified:

1. The *nanosatellite elevation angle*  $\varepsilon$  is defined as the angle measured at the target between the nanosatellite and the local horizontal. It is the angle at which a user can see the nanosatellite above the horizon.
2. The *nadir angle*  $\eta$  is the angle measured at the nanosatellite from the sub-satellite point (nadir) to the target. It gives the deflection of the user from nadir as seen from the nanosatellite.
3. The *Earth central angle*  $\lambda$  is measured at the center of the Earth from the sub-satellite point to the target.
4. The *angular radius of the Earth*  $\rho$  is the angle seen from the nanosatellite to the horizon.
5. The slant range  $D$  denoting the distance between the user terminal and the nanosatellite.

Because we assumed that Earth is spherical, the line from the nanosatellite to the Earth's horizon is perpendicular to the Earth's radius.

Therefore,

$$\sin \rho = \cos \lambda_0 = \frac{R_E}{R_E + h} \quad (21)$$

and

$$\rho + \lambda_0 = 90^\circ \quad (22)$$

By applying trigonometric laws in Figure 3.18, we determine the nadir angle  $\eta$  and elevation angle  $\varepsilon$ :

$$\tan \eta = \frac{\sin \rho \sin \lambda}{1 - \sin \rho \cos \lambda} \quad (23)$$

$$\cos \varepsilon = \frac{\sin \eta}{\sin \rho} \quad (24)$$

Using the sine and cosine laws for the triangles NTU and OTN, the earth central angle and the nadir angle can be given as a function of the elevation angle:

$$\frac{R}{\sin \eta} = \frac{D}{\sin \lambda} = \frac{R_E + h}{\sin(90^\circ + \varepsilon)} = \frac{R_E + h}{\cos \varepsilon} \quad (25)$$

Since  $\eta = \pi - (\lambda + 90^\circ + \varepsilon) \leftrightarrow \eta = 90^\circ - (\lambda + \varepsilon)$  (26), we can observe that  $(\lambda + \varepsilon)$  is the complement angle of the  $\eta$  angle.

Replacing Eq. 26 in Eq. 25, we obtain that:

$$\lambda = \arccos\left(\frac{R_E}{R_E + h} \cos \varepsilon\right) - \varepsilon \quad (27)$$

$$\eta = \arcsin\left(\frac{R_E}{R_E + h} \cos \varepsilon\right) \quad (28)$$

The relationship between  $\eta$ ,  $\lambda$  and  $\varepsilon$  is given by:

$$\eta + \lambda + \varepsilon = 90^\circ \quad (29)$$

The distance  $D$  at which the satellite will be in view of the ground station is:

$$D = R_E \frac{\sin \lambda}{\sin \eta} \quad (30)$$

By replacing Eq. 27 and Eq. 28 in Eq. 30:

$$D = \sqrt{R_E^2 \sin^2 \varepsilon + 2R_E h + h^2} - R_E \sin \varepsilon \quad (31)$$

An important parameter is the total time in view  $T$  expressed as:

$$T = \frac{P}{180^\circ} \arccos \frac{\cos \lambda_{max}}{\cos \lambda_{min}} \quad (32)$$

As James R. Wertz states in paper [21], for communications, the satellite must be more than  $5^\circ$  above the horizon. In practice, we select a specific value of  $\varepsilon_{min}$  and we use this value. This parameter has a major influence on other computed parameters.

Given minimum elevation angle  $\varepsilon_{min}$ , we define the maximum Earth central angle  $\lambda_{max}$ , the maximum nadir angle  $\eta_{max}$ , measured at the nanosatellite from nadir to the ground station and the maximum slant range  $D_{max}$  at which the nanosatellite will still be in view:

$$\sin \eta_{max} = \sin \rho \cos \varepsilon_{min} \quad (33)$$

$$\lambda_{max} = \arccos\left(\frac{R_E}{R_E + h} \cos \varepsilon_{min}\right) - \varepsilon_{min} \quad (34)$$

$$\eta_{max} = \arcsin\left(\frac{R_E}{R_E + h} \cos \varepsilon_{min}\right) \quad (35)$$

$$\lambda_{max} = 90^\circ - \varepsilon_{min} - \eta_{max} \quad (36)$$

$$D_{max} = R_E \frac{\sin \lambda_{max}}{\sin \eta_{max}} \quad (37)$$

By replacing Eq. 35 and Eq. 36 into Eq. 37, we obtain that the maximum slant range is:

$$D_{max} = \sqrt{R_E^2 \sin^2 \varepsilon_{min} + 2R_E h + h^2} - R_E \sin \varepsilon_{min} \quad (38)$$

The maximum time in view  $T_{max}$  for any point P on the surface of the Earth occurs when the nanosatellite passes overhead and  $\lambda_{min}=0$ :

$$T_{max} = P \frac{\lambda_{max}}{180^\circ} \quad (39)$$

The orbit period  $P$  of each nanosatellite may be calculated as a function of the constellation altitude  $h$ :

$$P = 1.658669 \times 10^{-4} \times (R_E + h)^{3/2} \quad (40)$$

### 3.3.9 Earth coverage assessment

Earth coverage means the area of the Earth that the satellite antenna/instrument can see at one instant or over an extended period. Since one of our mission objectives is to provide coverage over a specific region of the Earth (Salar de Uyuni Desert), the coverage is a key element in our nanosatellite constellation design.

We define four parameters used for determining the Earth coverage:

- 1) Field of view (FOV) or antenna footprint ( $F_a$ ) is the actual area that the antenna can see at any moment;
- 2) Access area ( $A_a$ ) is the total area on the ground that might be seen at any moment by directing the antenna;
- 3) Coverage rate ( $R_{cov}$ ) is the rate at which the antenna accessing new land;
- 4) Access rate ( $R_a$ ) is the rate at which new land is coming into the satellite access area.

In the case of an omni-directional antenna, which is commonly used for CubeSat class nanosatellite, the footprint and the access area are always equal. For other instruments such as scanning sensors, radar, they are not the same.

If an antenna covers all of the area available to it as the satellite moves along, the coverage rate and the access rate are different. For instruments that continuously select the interest region, the coverage rate and the access rate are completely different.

In order to evaluate the coverage, we propose an analytical method that provides us the approximate formulas for coverage parameters.

The mathematical formulas presented in this section neglect the oblateness effect and the rotation of the Earth underneath the orbit, but they do consider the spherical surface of the Earth.

Since we envisaged telecommunication missions for all three models proposed in this thesis, we assumed that the instrument will be an antenna whose footprint is a beamwidth circular section.

One of the problems related to nanosatellites is the limited capability of RF section in terms of number and quality of available links. The uplink depends on the strength of the signal originating on the earth and the manner in which the nanosatellite receives it. The downlink, on the other hand, depends on how strongly the nanosatellite can transmit the received signal and how good the reception is at the ground station.

The main feature of nanosatellite antennas is the lightweight structure and the high degree of integration. For nanosatellites, it is preferred to use antennas placed on outer walls.

Nanosatellites need specific antennas (e.g., omni-directional, patch, micro-strip) due to their small size. Reflector antennas are inadequate, even if they are small, because they need a deployment mechanism. Inflatable antenna is another option, but the technology is still in its infancy. A new antenna concept, based on the idea of “structural radiators”

borrowed from Avionic and Naval applications, was proposed by *G. Marrocco et al.* in paper [104].

Figure 3.19 presents the nanosatellite geometry for computing antenna footprint.

Let  $h_F$  be the height of the antenna footprint:

$$h_F = Q(\lambda_o - \lambda_i) \cong D \frac{\sin \delta}{\sin \varepsilon} \quad (41)$$

, where  $\delta$  is the antenna beamwidth and the coefficient  $Q=111.319$  for length expressed in km.

The linear approximation in Eq. 41 is convenient from a computational point of view, but it can lead significant error near the horizon where elevation angle  $\varepsilon$  is small. To improve this approximation, we used the center of the antenna beam because the toe is the worst-case link budget.

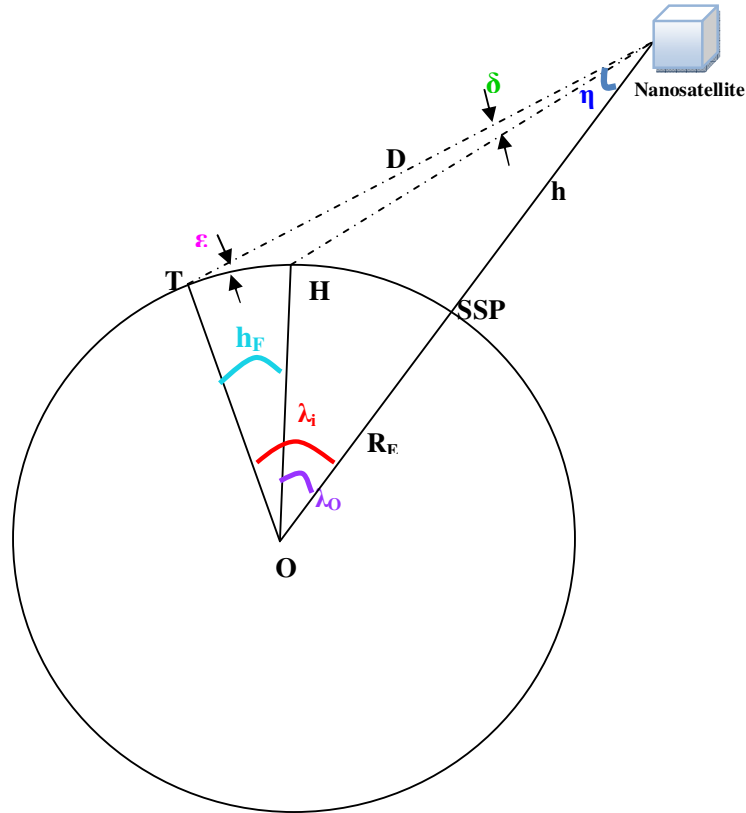


Figure 3.19 – Nanosatellite geometry for computing antenna footprint

Let  $w_F$  be the footprint width and it is given by:

$$w_F = R_E \sin^{-1} \left( D \frac{\sin \delta}{R_E} \right) \cong D \sin \delta \quad (42)$$

Assuming that antenna projection is an ellipse on the Earth surface, then the footprint area is:

$$F_a = \frac{\pi}{4} h_F w_F \quad (43)$$

By replacing Eq. 41 and Eq. 42 into Eq. 43, we obtain that footprint area is:

$$F_a = \frac{\pi D^2 \sin^2 \delta}{4 \sin \varepsilon} \quad (44)$$

The instantaneous coverage rate  $R_{cov}$  for an antenna with the beamwidth  $\delta$  is defined as ratio between the footprint area  $F_a$  and the antenna exposure time  $t_{exp}$ :

$$R_{cov} = \frac{F_a}{t_{exp}} \quad (45)$$

We consider that antenna exposure time is:

$$t_{exp} = \omega T \quad (46)$$

, where  $\omega=80\%$  for nanosatellites and  $T$  is the total time in view of the nanosatellite.

For general sensing instruments and omni-antennas, the access area  $A_a$  is given by:

$$A_a = Y(1 - \cos \lambda) \quad (47)$$

, where the coefficient  $Y$  has different values according to the unit of measure:

$$Y = \begin{cases} 2\pi, & \text{for area in steradians} \\ 2.556041 \times 10^8, & \text{for area in km}^2 \end{cases}$$

The access rate  $R_a$  is the rate at which new land is coming into the nanosatellite access area:

$$R_a = \frac{2Y \sin \lambda}{P} \quad (48)$$

We define the coverage vector  $C$  as:

$$C = \begin{bmatrix} F_a \\ A_a \\ R_{cov} \\ R_a \end{bmatrix} \quad (49)$$

### 3.3.10 Performance indicators for nanosatellite telecommunications

Since one of the objectives of this thesis is to study the telecommunication framework of nanosatellite networks, we define in this chapter, some parameters that allow us to evaluate nanosatellite constellations performance.

With the widespread availability of multimedia technology, and an increasing demand for electronic connectivity across the world, nanosatellite networks will play an indispensable role in providing low-cost, QoS guarantee communication services. Also, nanosatellite networks can be effectively used to provide real time as well as non-real time communications services to remote areas.

#### 3.3.10.1 Propagation delay and its relative deviation

When sending data over nanosatellite transmission channel, there is always a propagation delay, expressed by Eq. 50, which is the time it takes for the signal to travel from the transmitting ground station to the nanosatellite.

$$t_p = \frac{D}{c} \quad (50)$$

, where  $D$  is the distance at which the satellite will be in view of the ground station and  $c$  is the speed of light (300000 km/s).

During each nanosatellite orbit, distance  $D$  varies between  $h$ , the nanosatellite altitude and  $D_{max}$ , the maximum slant range at which the satellite will still be in view:

$$D \in [h, D_{max}] \quad (51)$$

Considering this, the propagation delay variation interval is written as:

$$t_p \in [t_m, t_M] \quad (52)$$

, where  $t_m$  is the minimum propagation delay and  $t_M$  is the maximum propagation delay:

$$t_m = \frac{h}{c} \quad (53)$$

$$t_M = \frac{D_{max}}{c} \quad (54)$$

By replacing Eq. 53 and Eq. 54 into Eq. 52, we obtain:

$$t_p \in \left[ \frac{h}{c}, \frac{D_{max}}{c} \right] \quad (55)$$

We define the relative deviation as:

$$\Delta = \frac{t_M - t_m}{t_m} \leftrightarrow \Delta = \frac{t_M}{t_m} - 1 \quad (56)$$

By replacing Eq. 38 in Eq. 56, we obtain:

$$\Delta = \sqrt{\left(\frac{R_E}{h}\right)^2 \sin^2 \varepsilon_{min} + 2 \frac{R_E}{h} + 1} - \frac{R_E}{h} \sin \varepsilon_{min} - 1 \quad (57)$$

We observe that Eq. 57 is a monotone function with the  $\frac{R_E}{h}$  argument. Considering this, the relative deviation is increasing with altitude decreasing. Therefore, even if LEO nanosatellites have the advantage of small propagation delay, their relative deviation is significant.

### 3.3.10.2 Nanosatellite latency

In this chapter, we develop a simple method to estimate the end-to-end delay, more commonly known as latency, in a nanosatellite network.

The end-to-end delay ( $L$ ) experienced by a data packet passing through a nanosatellite constellation is the sum of the propagation delay ( $t_p$ ), the transmission (packetizing) delay ( $t_t$ ), the inter-satellite link delay ( $t_i$ ), the on-board processing and switching delay ( $t_r$ ) and the buffering delay ( $t_b$ ).

$$L = t_p + t_t + t_i + t_r + t_b \quad (58)$$

The propagation delay ( $t_p$ ) has been already introduced in Chapter 3.2.10.1.

The transmission delay ( $t_t$ ) represents the time required to transmit a single data packet at the nanosatellite network data rate.

$$t_t = \frac{\text{Data packet size}}{\text{Data rate}} \quad (59)$$

The inter-satellite link delay ( $t_i$ ) is the sum of the propagation delays of the inter-satellite links (ISLs) traversed by the connection.

$$t_i = \frac{\sum \text{cross - links length}}{c} \quad (60)$$

, where  $c$  is the speed of light ( $3 \times 10^8$  m/s).

There are two types of inter-satellite links (or cross-links): in-plane links connect satellites within the same orbital plane and inter-plane links connect satellites in different orbital planes.

In LEO constellations, the ISL delays depend on the orbital radius, the number of satellites per plane, the number of orbital planes. Also, the ISL delays change over the life of a connection due to constant movement of satellite and adaptive routing techniques applied in LEO systems. Thus, LEO constellations can exhibit a high variation in ISL delay.

The data packets may experience additional delays ( $t_r$ ) at each nanosatellite hop depending on the amount of on-board switching and processing capacity. For our model, we consider switching and processing delays negligible as compared to the propagation delay.

Buffering delay ( $t_b$ ) is the sum of the delays that occur at each hop in the network due to queuing operation. Buffering delays depend on the congestion level, queuing and scheduling policies and connection priority.

The analysis of delay jitter in nanosatellite network is beyond the scope of this study. It could be considered in a more complex model of nanosatellite constellation.

Latency is one of the most important sources of concern especially in time-sensitive applications, since it has a direct impact on the Quality of Service of the network.

We briefly discuss here the basic qualitative requirements of three classes of applications: interactive voice/video applications, non-interactive voice/video applications and TCP/IP file transfer.

According to the ITU's "End-user multimedia QoS categories" paper [105], interactive voice requires very low delay (ITU-T specifies a delay of less than 400 ms to prevent echo effects) and delay variation (up to 3 ms specified by ITU-T). Although the propagation and inter-satellite link delays of LEOs are lower, LEO systems exhibit high delay variation due to connection handovers and high dynamics of satellites.

Non-interactive voice/video applications are real-time applications whose delay requirements are not as stringent as their interactive counterparts. However, these applications also have stringent jitter requirements. As a result, the jitter characteristics of LEO systems must be carefully studied before they can service real time voice-video applications.

The performance of TCP/IP file transfer applications is throughput dependent and has very loose delay requirements. As a result, LEO system with sufficient throughput can meet the delay requirements of file transfer applications.

### ***3.3.10.3 Calculating the amount of data transmitted at each nanosatellite pass***

In designing nanosatellite communication system, we must determine how fast the data rate must be in order to offer the desired telecommunication services and what kind of information can be transferred over the communication links.



We assumed that all nanosatellite constellation models proposed in this thesis use digital communication techniques.

Let  $d$  be the amount of data needed to be transfer from the nanosatellite to the ground station, and  $r$ , the data rate. The relationship between these two parameters is given by:

$$d = \frac{r}{m} (f_{view} T_{max} - t_{init}) \quad (61)$$

, where  $T_{max}$  is the maximum time in view, which occurs when the nanosatellite passes directly overhead (Eq. 39),  $f_{view}$  is the fraction of time in view,  $t_{init}$  is the time required to initiate a communication during each nanosatellite pass, and  $m$  is the margin needed to account for missed passes due to ground station down time.

As mention in paper [95], the average value for  $f_{view}$  is 80% for LEO satellites and  $m$  is estimated to be 1.25, since we assumed a dedicated ground station. Also, we consider that a reasonable time for initiate a communication is 1 minute.

### 3.3.11 A Markov modeling method for performance evaluation of nanosatellite constellations

This chapter presents a novel Markov modeling method for evaluating the performance of nanosatellite constellations. Firstly, we describe the reason for choosing Markov methods for assessing nanosatellite constellation performance. Then, the theoretical Markov model is briefly presented. Finally, the Markov method for assessing nanosatellite constellations performance is described. Chapter 4 will show how the Markov method has been applied to NanoDREAM constellation.

#### 3.3.11.1 Why Markov models for nanosatellites?

Before introducing the theoretical Markov model, we need to justify why did we chose a Markov-based approach to evaluate the performance of nanosatellite constellations.

We focus on Markov models because they have traditionally been used to evaluate the performance and the reliability of complex systems. Additionally, they are commonly used to study the dependability of complex systems. Since a nanosatellite is a complex system constituted of many sub-systems characterized by a high interdependency, Markov model is suited to study its reliability and performance.

Moreover, a nanosatellite constellation is a dynamic complex system, which involves many nanosatellites distributed in multiple orbital planes and whose state change over time due to nanosatellites movement. For this reason, we used Markov modeling techniques to describe how a nanosatellite constellation will perform with respect to time. This involves taking into account all of the possible failures that may occur within the nanosatellite constellation. As individual nanosatellites might fail over time, the size and the geometry of the constellation will also change in time. To take into account potential failures and the effect they have on constellation performance, a reliability model is needed.

In our research study we took benefit of the Markov process capacity of describing both the failure of a system and its subsequent repair. In our case, a system is nanosatellite or a nanosatellite constellation. Markov process develops the probability of the system being in

a given state, at a given time, as a function of a sequence of states previously experienced. Thus, it can describe the degradation states of the system operation process. In this states, the system has either partially failed or is not perform to the overall capacity (i.e., only few functions are performed).

Furthermore, Markov method has some significant advantages which make it an ideal method for nanosatellite constellation performance assessment:

- ✓ Simple modeling approach: the models are simple to develop even if complex mathematical approaches are needed.
- ✓ Redundancy management techniques: system reconfiguration required by failures is easily incorporated in the model. This feature is very useful for future nanosatellite constellations, since nowadays several self-reconfiguration and autonomous control techniques are tested on individual nanosatellites in order to be further applied to nanosatellite constellations. Nanosatellite constellation can be self-reconfigured if a certain degree of autonomy is integrated. Also, future nanosatellites can be envisaged as plug&play systems, whose failed sub-systems are easily replaced on-orbit.
- ✓ Complex systems: Markov models can easily handle complex system modeling by using several simplifying techniques. Nanosatellites are complex systems, involving many sub-systems that might failed for many reason during mission lifetime. Nanosatellite constellations are complex systems too, since they include many nanosatellites distributed in several planes and cooperatively working to accomplish a specific mission. Considering the high complexity of these systems, it is difficult to model them using classical techniques. For this reason, Markov model helps simplifying the modeling process of nanosatellites and nanosatellite constellations.

The major drawback of Markov methods is the boosting of the number of states as the size of the system increases. The resulting states diagrams for large systems are generally extremely complicated, difficult to construct and computationally extensive. However, for high complexity systems, a combined approach is recommended. Thereby, Markov model can be used to analyze smaller parts of the large system. Then, other analysis techniques may be used to assess the overall performance of the system.

#### *3.3.11.2 Markov model overview*

In probability theory and statistics, a Markov model is a stochastic model that assumes the Markov property. A stochastic process has the Markov property if the conditional probability distribution of future states of the process depends only upon the present state. The Markov model assumes that the future is independent of the past given the present. A process with this property is called a Markov process.

The simplest Markov model is the Markov chain which models the state of a system with a random variable that changes through time. It is defined as a random process with the property that the next state depends only on the current state. Often, the term Markov chain is used to mean a Markov process which has a discrete (finite or countable) state-space.

Markov analysis looks at a sequence of event and analyzes the tendency of one event to be followed by another. Using this analysis, we can generate a new sequence of random but related events, which appear similar to the original.

A Markov chain is a sequence of random variables  $X_1, X_2, X_3, \dots$  with the Markov property, namely that, given the present state, the future and past states are independent.

The mathematical formal definition of a Markov chain is:

$$P_r(X_{n+1} = x | X_1 = x_1, X_2 = x_2, \dots, X_n = x_n) = P_r(X_{n+1} = x | X_n = x_n) \quad (62)$$
, where the possible values of  $X_i$  form a countable set  $S$  called the state space of the chain.

### 3.3.11.3 Markov method for nanosatellite constellation performance evaluation

A set of first-order differential equations is developed to model the evolution of the nanosatellite constellation, as shown in Eq. 63, where  $\dot{\vec{P}}$  and  $\vec{P}$  are  $n \times 1$  column vectors,  $n$  is the number of states in the constellation,  $\vec{P}$  is the probability vector of being in any given state at any given time,  $[A]$  is  $n \times n$  transition state matrix, and  $\vec{P}$  is the state probability vector.

$$\dot{\vec{P}} = [A] \times \vec{P} \quad (63)$$

The number of first-order differential equations will be equal with the number of states of the constellation. The states of the constellation are defined by constellation's elements failures which mean by the nanosatellite failures. The transitional probabilities between states are a function of the failure rates of the nanosatellites.

The solution to this set of differential equations determines the probability of the nanosatellite constellation being in any given state at a particular time.

The performance of the constellation is calculated as:

$$P_C = \sum_{k=1}^m C_k \times P_k \quad (64)$$

, where  $C_k$  is the constellation capacity in each state  $k$ ,  $P_k$  is the probability of being in each state  $k$ ,  $m$  is the number of operational states.

The constellation capacity in each state  $k$  during one day (24h) is defined as:

$$C_k = O_d \times N_k \times d \quad (65)$$

, where  $O_d$  is the number of orbits made by each nanosatellite during one day,  $N_k$  is the number of nanosatellites available in state  $k$  and  $d$  is the amount of data transmitted at each nanosatellite pass. The amount of data transmitted at each nanosatellite pass is given by Eq. 61.

For calculating the performance of the nanosatellite constellation during the entire mission, an integration must be done:

$$p(t) = \int_0^{LF} \sum_{k=1}^m C_k P_k(t) dt \quad (66)$$

, where  $p(t)$  is the overall performance of the constellation (i.e., the amount of data transmitted by the entire constellation),  $LF$  is the constellation lifetime,  $m$  is the number of operational states,  $C_k$  is the constellation capacity in each state  $k$ , and  $P_k(t)$  is the probability of being in each state  $k$  as a function of time  $t$ .

The performance metric measures how well the nanosatellite constellation satisfies the mission requirements over the entire mission life time, taking into account the potential degradation of nanosatellites which leads to constellation's degradation. Thus, we determine both the probability that a nanosatellite constellation will continue to function over a given interval of time and the probability with which the nanosatellite constellation will function in different partially failed states throughout the mission.

Therefore, the overall performance of the constellation is expressed as the overall amount of data that the constellation delivers over the mission life time. To calculate this amount of data, we must take into account all possible failures that may occur within the constellation. As individual nanosatellites within the constellation fail over time, the instantaneous data delivery rate of the constellation will decrease. Replacing failed nanosatellites with new nanosatellites during the mission will increase the constellation performance at the desired availability. The number of operational nanosatellites in the constellation decreases when individual nanosatellites fail and increases when renewal nanosatellites are placed to orbit.

## 3.4 NanoICE model

### 3.4.1 NanoICE mission description

#### *Why Polar Regions?*

The Polar Regions are crucial to the stability of the planet due to their unique phenomena. Circulatory systems for air and water reach the surface, as do the majority of the Earth's magnetic field lines. Thick glaciers have trapped air and water from ancient times.

Nowadays, many Arctic and Antarctic mysteries have been unraveled. Still, many continue to puzzle us to this day. For instance, scientists have not yet calculate the Antarctic icecap balance, which is the ratio between the annual snow fallout and the amount of ice lost as icebergs thaw out.

Unfortunately, due to the characteristics of Polar Regions (i.e., very cold, deserted, distant regions with sparse infrastructure, rough terrain consisting mainly of ice blocks and crevasses), the research activity is very expensive. International cooperative programs share the costs and maximize the number of coordinated scientific observations. The IPY is the most famous example of such ambitious cooperative program.

International Polar Year (IPY) 2007-2008 is a project of \$1.2 billion, involving scientist from 60 countries. Its main goal was to delve into Arctic and Antarctic secrets, by exploring the poles and their influence on the rest of the planet, polar region peoples and global climate systems. Besides the detailed study of the geophysical and climatic systems of the poles, IPY projects studied biodiversity, by covering entire polar ecosystems, epidemiology, and even sociological studies. To conclude, there is a huge interest of scientific community to unveil the enigmas of Polar Regions.

## Why a nanosatellite constellation for Polar Regions?

We propose to deploy a polar nanosatellite constellation, named NanoICE (**N**anosatellite **I**nnovative **C**onst**E**llation), that provides a continuous coverage of Arctic and Antarctic regions. NanoICE constellation is operated by a nanosatellite operator in charge of offering telecommunication services to Polar Regions scientific research communities. Our motivation for NanoICE concept resides on the continuous growth of Polar Regions scientific community, sustained by innovative projects and technological progress. Figure 3.20 illustrates the research stations in Antarctica.

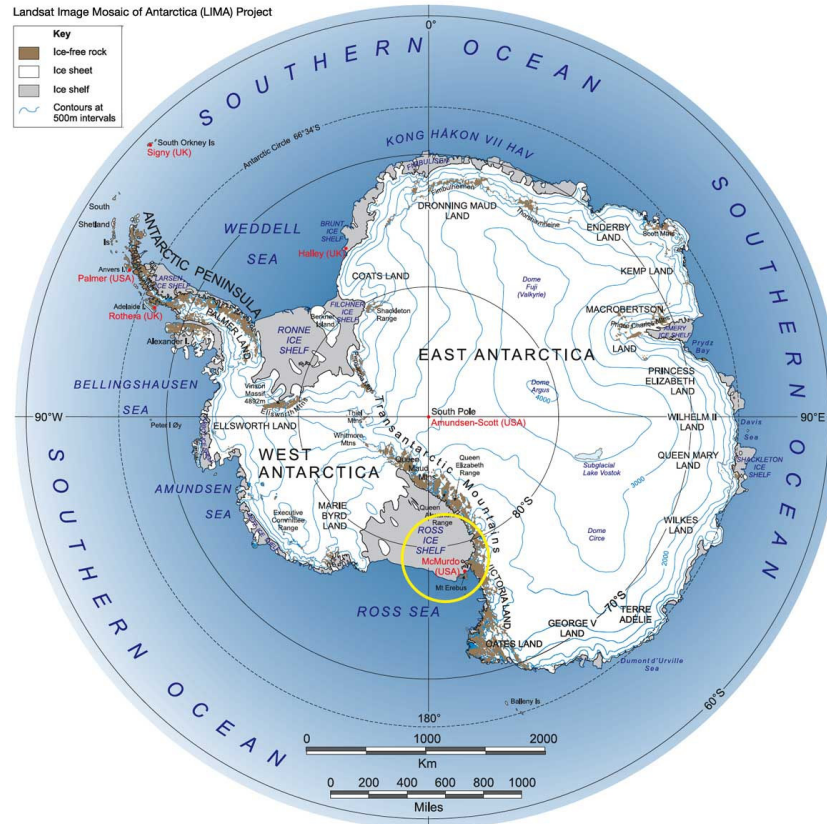


Figure 3.20 – Antarctic research stations

Our inquiry shows that new research stations were deployed in Polar Regions in the last five years. For example, the Princess Elisabeth Antarctic Research Station (Figure 3.21) is the first “zero emission” polar research station pre-built in Brussels and re-assembled in Antarctica from November 2007 to February 2008.



*Figure 3.21 – Princess Elisabeth Antarctic Research Station*

Moreover, in August 2010, the Canadian government has chosen Cambridge Bay – a hamlet midway along the Northwest Passage in the country's far north – as the site for a world-class Arctic research station.

Since some research stations are built on a floating ice shelf, British scientists are examining designs for the world's first walking building (Figure 3.22). It will need to stand up to harsh conditions without damaging this unique frozen environment.



*Figure 3.22 – Concept of the Antarctic walking research station*

Furthermore, innovative vehicles for Arctic and Antarctic exploration are proposed. A concept vehicle, named “Ninety Degrees South”, was proposed by the designer James Moon [106]. It is designed to meet the specific requirements, logistical challenges and harsh conditions of the Antarctic environment (Figure 3.23). Moreover, Remotely Operated Vehicles (ROV) remains an efficient technology to uncover the secrets of Antarctic and also be of great usefulness for daily operations in the close perimeter of Polar research stations.



*Figure 3.23 – Ninety Degrees South concept vehicle*

Nowadays, there are almost 70 Antarctic research stations and approximately 30 field camps are established each austral summer to support specific projects. A total of 30 countries (as of October 2006) operate seasonal and year-round research stations on the continent and in its surrounding oceans. The population of persons doing and supporting science on the continent and its nearby islands varies from approximately 4000 persons during the summer season to 1000 persons during winter. [107]

Considering this framework, we believe that a dedicated nanosatellite solution (i.e., NanoICE) is the best way to provide Polar Regions scientists with telecommunications services that responds to their needs.

Traditional broadband satellite systems are very expensive to develop, launch and operate. Indeed GEO satellites support voice, data, and video services, but they provide intermittent coverage since the ground stations at higher than 60° latitude have difficulty receiving signals at low elevations. Deploying a wireless network across the icecaps is not feasible because the research stations are sparse over large areas.

NanoICE is aimed to meet the voice and data transfer needs of the entire Antarctic community. NanoICE system supports the remote monitoring of scientific experiments, the data transfer, and enables scientists to communicate with their colleagues around the world. NanoICE takes advantage of the technological advances in small satellite field, by providing QoS guarantee services at lower price.

Our choice of using nanosatellites is sustained by the fact that small satellites have already been used as research tools of Polar Regions mysteries. A successful example is the Swedish microsatellite Astrid-2 [108], launched in December 1998, which began a new era of auroral research. During its seven month lifetime, Astrid-2 collected more than 26 GB of high-quality data of auroral electric and magnetic fields, and auroral particle and plasma characteristics from approximately 3000 orbits at an inclination of 83° and an altitude of about 1000 km. By achieving both the technological and the scientific mission objectives, Astrid-2 has opened entirely new possibilities to carry out low-budget multipoint measurements in near-Earth space.

NanoICE constellation is placed on a polar orbit, thus being capable of providing the best coverage performance at high latitudes, in concentric rings around the poles. The Poles turn out to be the only geographic region where continuous coverage may be achieved. As the name suggests, polar orbits pass over the Earth's Polar Regions from north to south. Since the orbital plane is nominally fixed in space, the planet rotates below a polar orbit, allowing the satellite low-altitude access to virtually every point on the surface.

We placed NanoICE constellation on a sun-synchronous orbit, which means that each successive orbital pass occurs at the same local time of day. Keeping the same local time on a given pass implies the choice of the orbit as short as possible, which is to say as low as possible. However, very low orbits would rapidly decay due to atmospheric drag. We assumed an altitude of 700 km, since this is a commonly altitude used for polar satellites.

### 3.4.2 NanoICE framework development

In this sub-chapter, the NanoICE framework development is set up, by pointing out the objectives and the assumptions. Due to the complexity of the problem, some assumptions have to be made that simplifies numerical calculations.

For covering the Polar Regions, the nanosatellites are placed on a single orbital plane, on a polar, sun-synchronous LEO type orbit. We assume that Earth is a perfect sphere, which is an adequate assumption for most mission geometry applications. For precise calculation, a correction for oblateness must be applied. In our calculations, we neglected the Earth's rotation in the short time interval in which the nanosatellite passes over the target area.

Since the regions of interest include the Poles, a polar constellation having several nanosatellites placed on a LEO, sun-synchronous orbital plane, inclined at  $90^\circ$  with respect to equatorial orbital plane and with enough altitude to provide the appropriate coverage at the smallest elevation angle ( $\varepsilon$ ) is the best solution for our mission.

NanoICE is a simple model which gives a general idea of nanosatellite polar constellation behavior. For this reason, we consider it as a good starting concept for providing telecommunications services to Polar region scientific community. NanoICE model has its own limitation, by not being capable of describing real on-orbit behavior of nanosatellite polar constellations because it does not consider all the perturbation effects that act on each nanosatellite. For these reasons, a high complexity model needs to be developed.

The main aim is to find a polar nanosatellite constellation which satisfies the following objectives:

- **Objective 1:** the number of nanosatellites in the constellation ( $N_n$ ) has to be minimized;
- **Objective 2:** the time in view ( $T$ ) spent by each nanosatellite over any point of the target regions has to be maximized;
- **Objective 3:** the quantity of data ( $d$ ) downloaded at each nanosatellite pass has to be maximized.

Once the objectives have been formulated and the assumptions have been described, the next step is to define NanoICE model and its parameters.



### 3.4.3 Formal mathematical problem definition

In order to calculate the coverage area between  $70^{\circ}$ -  $90^{\circ}$  N latitude and  $70^{\circ}$ -  $90^{\circ}$  S latitude, we use an artifice, by considering the Earth tilted with  $90^{\circ}$ , as shown in Figure 3.24.

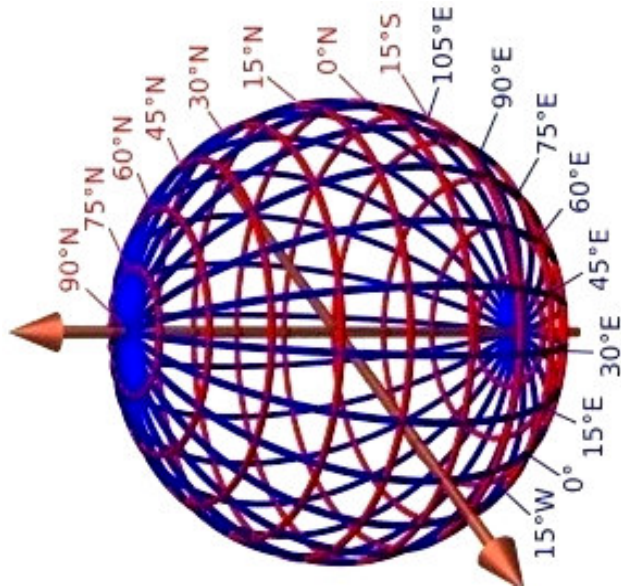


Figure 3.24 – View of the Earth tilted with  $90^{\circ}$

Between  $70^{\circ}$  and  $90^{\circ}$  N latitude and also between  $70^{\circ}$  and  $90^{\circ}$  S latitude, there are  $20^{\circ}$  of latitude. Thus, the Polar Region coverage area can be considered as a coverage band delimited by two red curves, as depicted in Figure 3.25.

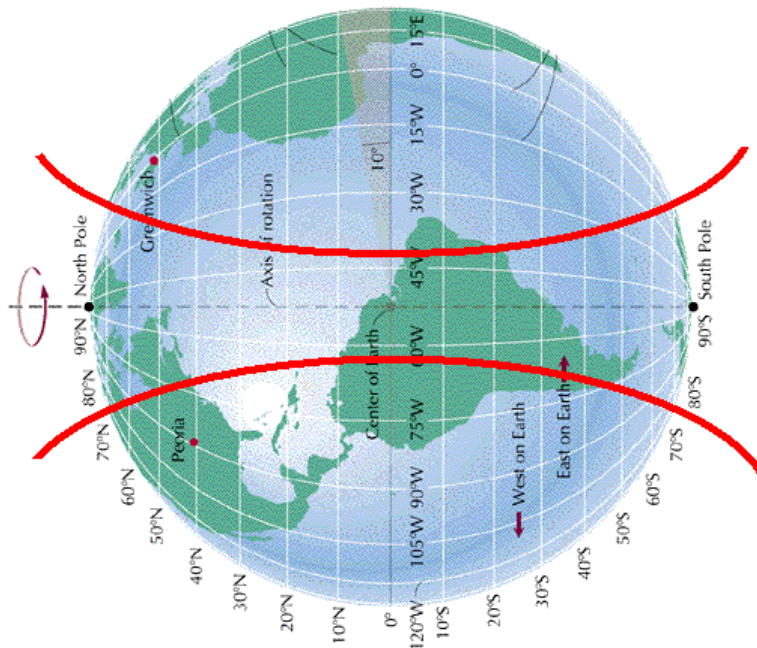


Figure 3.25 – Coverage area for NanoICE constellation

Considering this geometric translation, the number of nanosatellites in a polar constellation can be determined in the same way as for the NanoDREAM model, which considers a coverage band of 20° latitude on the Equator.

By using the Eqs. 1 to 6 from NanoDREAM model (Chapter 3.2.4), the formal mathematical problem definition for NanoICE mission could be written as:

**Objectives: min  $N_s$  and max  $Cov$**

**Constraints: Subject to**

*Altitude  $500 \text{ Km} \leq h \leq 1000 \text{ Km}$*

*Minimum elevation angle  $5^\circ \leq \varepsilon_{min} \leq 30^\circ$*

*Latitude  $L = L_{North} \cup L_{South}$  where:*

$$L_{North} = [70^\circ, 90^\circ]$$

$$L_{South} = [70^\circ, 90^\circ]$$

*Sun-synchronous, polar orbit  $i=90^\circ$*

*Downlink data rate  $9.6 \text{ Kbps} \leq r \leq 1024 \text{ Kbps}$*

The objective vector  $V$  is summarized in Eq. 62:

$$V = \begin{bmatrix} N_n \\ T \\ d \end{bmatrix} = \begin{bmatrix} \text{Number of nanosatellites in the constellation} \\ \text{Time in view} \\ \text{Data quantity} \end{bmatrix} \quad (67)$$

NanoICE-type constellation is defined by the vector  $C[N_n, n_p, h, \varepsilon_{min}, i]$ , where  $N_n$  is the number of nanosatellites in the constellation,  $n_p$  is the number of orbital planes,  $h$  is the constellation altitude,  $\varepsilon_{min}$  is the minimum elevation angle and  $i$  is the inclination angle with respect to the equatorial plane.

**3.4.4 Design vector and constant vector**

For NanoICE model we defined a design vector and a constant vector. As Eq. 68 shows, three variables – constellation altitude, downlink data rate and minimum elevation angle – make up the design vector.

$$\Sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{bmatrix} = \begin{bmatrix} \text{km} \\ \text{Kbps} \\ \text{degrees} \end{bmatrix} \quad (68)$$

Latitude ( $L$ ), inclination angle ( $i$ ) and  $\beta$  angle are variables of constant vector, given by Eq. 69.

$$\Gamma = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix} = \begin{bmatrix} \text{degrees} \\ \text{degrees} \\ \text{degrees} \end{bmatrix} \quad (69)$$

Table 3.5 summarizes design vector variables while Table 3.6 presents the values for constant vector parameters.

Design vector variable	$\Sigma$	Range
Constellation altitude	$\sigma_1$	$500 \text{ km} \leq h \leq 1000 \text{ km}$
Downlink data rate	$\sigma_2$	$9.6 \text{ Kbps} \leq r \leq 1024 \text{ Kbps}$
Minimum elevation angle	$\sigma_3$	$5^\circ \leq \epsilon_{\min} \leq 30^\circ$

Table 3.5 – NanoICE design vector

Constant vector variable	$\Gamma$	Value
Latitude	$\gamma_1$	$L_{North} = [70^\circ, 90^\circ] L_{South} = [70^\circ, 90^\circ]$
Inclination angle	$\gamma_2$	$90^\circ$
$\beta$ angle	$\gamma_3$	$70^\circ$

Table 3.6 – NanoICE constant vector

Since NanoICE model can be reduced to NanoDREAM model, we used the same methodology for estimating the number of nanosatellites in the constellation, which is described in Chapter 3.2.7. Also, the geometric relationships between nanosatellite and user terminal on Earth, defined in Chapter 3.2.8, can be applied to NanoICE constellations. The parameters used for NanoDREAM coverage assessment (i.e., antenna footprint, access area, coverage rate, access rate), presented in Chapter 3.2.9, are also valid for NanoICE constellations.

Moreover, the indicators defined for evaluating the performance of NanoDREAM constellation in providing telecommunications services hold true for NanoICE constellations.

## 3.5 NanoSPHERE model

### 3.5.1 NanoSPHERE mission description

We envisaged the NanoSPHERE concept in the context of a robust nanosatellite telecommunications market, where many nanosatellite operators are in concurrence. We assumed that a nanosatellite operator could use partial deployment techniques for assuring the desired coverage requirements existed at a certain moment, and to progressively extend the coverage area as the service demand is growing.

Partial deployment options prove to be very useful particularly for Walker constellations [109], [110]. A Walker constellation is a symmetric, inclined constellation which can provide a higher diversity than a polar constellation. Diversity means the average number of satellites simultaneously in view of a user on the ground. A high diversity will bring technical benefits such as higher availability, fewer dropped connections and reduced multipath fading. Moreover, inclined orbit constellations are capable of providing continuous service to bands of latitude near the maximum and minimum latitudes of the satellite ground track. For these reason, we based our NanoSPHERE model on Walker-type constellation.

The scenario proposed for NanoSPHERE constellation deployment implies two phases:

- **Phase 1**

The nanosatellite operator deploys only a portion of the NanoSPHERE constellation over a specific remote region. For example, this portion could be represented by a NanoDREAM-type constellation deployed over Salar de Uyuni Desert for providing telecommunications services to an industrial company in charge of lithium resources exploitation. Thus, a segment of the entire NanoDREAM constellation is deployed to satisfy the coverage requirements of a restrained, specific remote area.

By deploying only a portion of the full NanoSPHERE system, the nanosatellite operator could begin early revenue operations while the remaining orbital planes are progressively populated with nanosatellites.

- **Phase 2**

Due the increasing demand of telecommunications services by some industrial companies in charge of mineral resources exploitation in different remote regions of the Earth, the NanoSPHERE constellation need to be upgraded, by adding nanosatellites into orbit, for extending the coverage area. Global coverage might be achieved, by deploying the entire NanoSPHERE constellation, in the context of a significant demand of telecommunications services from many industrial companies involved in mineral resources exploitation.

Nowadays, we cannot speak of the existence of a commercial telecommunication market for nanosatellites. However, there is a solid niche of leading suppliers of microsatellites, such as SSTL (UK), OCS (USA), CAST (China), ISS (Russia) and nanosatellites based on Cubesat standard, such as Pumpkin Inc. (USA), ISIS (Netherlands), Clyde Space (UK), GomSpace (Denmark), Stras Space (Canada), Princeton Satellite Systems, Inc. (USA), Adaptive Radio Technologies LLC. (USA). This is the first step – the basic pillar – in the effort of establishing, in the near future, a robust telecommunications market for nanosatellites.

### 3.5.2 NanoSPHERE mathematical model

For global coverage, we must determine the number of nanosatellites and their spatial arrangement (i.e., how many orbital planes and how many nanosatellites per plane).

The following assumptions are considered:

- the Earth is a perfect sphere;
- the rotation of the Earth underneath the orbit is neglected.

Let  $n_p$  be the number of orbital planes and  $n_m$ , the number of nanosatellites per plane.

$$n_p = \left\lceil \frac{360^\circ}{2\lambda_{max}} \right\rceil + 1 \quad (70)$$

$$n_m = \left\lceil \frac{180^\circ}{2\lambda_{max}} \right\rceil + 1 \quad (71)$$

The maximum Earth angle is defined by the following equation (see Eq. 34):

$$\lambda_{max} = \arccos\left(\frac{R_E}{R_E + h} \cos \varepsilon_{min}\right) - \varepsilon_{min}$$

Thus, the number of orbital planes and the number of nanosatellites per plane are written as:

$$n_p = 1 + \frac{180^\circ}{\arccos\left(\frac{R_E}{R_E + h} \cos \varepsilon_{min}\right) - \varepsilon_{min}} \quad (72)$$

$$n_m = 1 + \frac{180^\circ}{2 \left[ \arccos\left(\frac{R_E}{R_E + h} \cos \varepsilon_{min}\right) - \varepsilon_{min} \right]} \quad (73)$$

$N_n$  denotes the total number of nanosatellites in the constellation:

$$N_n = n_p \times n_m \quad (74)$$

Equations 69 to 72 do not take into account for the oblateness and the Earth rotation underneath the orbit.

Once that we defined the formulas for calculating, we need to find a method to uniformly distribute the nanosatellites within the constellation. Based on our studies, we identified Walker pattern which provides continuous multiple coverage of all Earth's surface with the smallest number of satellites.

The Walker method is used to obtain an optimal constellation where the constellation must follow the followings:

- the orbits are circular (eccentricity  $e=0$ ) with the same altitude  $h$ ;
- the orbital planes have the same inclination angle with respect to equatorial plane in order to have the same perturbation effects acting on all satellites;
- it provides the same coverage continuously, whether it is zonal coverage or global coverage;
- it consists of minimum numbers of satellites.

By applying Walker's method, the NanoSPHERE model is defined by the following parameters.  $N_n$  is the total number of nanosatellites in the constellation, with  $n_m$  nanosatellites evenly distributed in each of  $n_p$  orbital planes. All orbit planes are placed at the same inclination angle  $i$  relative to Earth's equator. The ascending nodes of the orbit planes are uniformly distributed around the equator at intervals of  $\frac{360^\circ}{n_p}$ . Within each orbit plane, the nanosatellites are uniformly distributed at intervals of  $\frac{360^\circ}{n_m}$ .

Since the pattern unit is defined as  $q = \frac{360^\circ}{N_n}$ , the in-plane spacing between nanosatellites is  $u \times n_p$  and the node spacing is  $u \times n_m$ .

The phase difference between adjacent planes is  $\Delta\Phi = u \times \mu$ , where  $\mu$  is an integer from 0 to  $n_p-1$ .

The NanoSPHERE pattern is fully specified by the following vector, which uniquely identify the set of orbits and nanosatellites orbital elements:

$$NS = [N_n, n_p, n_m, q, \Delta\Phi, h, i] \quad (75)$$

### 3.6 Summary

This chapter presented three nanosatellite constellation models. All three models were designed for providing telecommunications services to remote regions. The difference consists in the region on which the coverage is assured. Thereby, NanoDREAM model is designed for Bolivia's Salar de Uyuni Desert, a region which detains 70% of the global lithium reserve. Also, we proposed to deploy a wireless-based network over the exploitation area of Salar de Uyuni Desert in order to provide telecommunication services via nanosatellite constellation. NanoICE model is intended for Polar Regions, in order to meet the voice and data transfer needs of the entire Antarctic and Arctic scientific community. NanoSPHERE model is aimed to provide global coverage in the context of a robust telecommunications market and assuming a significant demand of telecommunications services from different industrial companies in charge of mineral resources exploitation in many regions of the Earth.

Moreover, a methodology for calculating the number of nanosatellites in constellation has been proposed. The parameters for Earth coverage assessment have been defined in order to evaluate nanosatellite constellations in terms of coverage. Several performance indicators (i.e., the amount of data transmitted at each nanosatellite passes, propagation delay, end-to-end delay) have been introduced in order to evaluate nanosatellite constellations in terms of their ability to provide telecommunication services.

A novel Markov modeling method for evaluating the performance of nanosatellite constellations has also been proposed, along with the reasons for choosing Markov method as a way of assessing nanosatellite constellation performance.

The next chapter presents and discusses the simulations conducted for these three constellation models.

Firstly, we briefly describe the simulation tools (i.e., SaVi, OPNET) used to evaluate the nanosatellite constellations' performance in terms of coverage and the performance of the wireless-based network respectively.

Secondly, the SaVi simulation results in terms of coverage area for each type of constellation (i.e., NanoDREAM, NanoICE, NanoSPHERE) are presented. Also, the numerical calculations of Earth coverage parameters and performance indicators (i.e., end-to-end delay, propagation delay and its variation, the amount of data transferred at each nanosatellite pass) for the proposed constellation models are described and interpreted.

Thirdly, the OPNET simulation results issued from testing our ground segment architecture envisaged for a lithium exploitation region are discussed.

Since XSTP (eXtended Satellite Transport Protocol) has been identified as transport protocol targeted for nanosatellite constellations, various simulations were conducted in NS2 modeler in order to evaluate XSTP performance over traditional satellite network and nanosatellite network respectively. As a starter, the simulation environment is presented along with simulation scenarios and XSTP software implementation solution. Then, we describe the simulation network topologies that were implemented in NS2 modeler. Since QoS aspect is an important focus of this thesis, we defined several QoS performance metrics, such as effective throughput, transmission overhead, channel efficiency and reverse channel

utilization. Thus, the XSTP performance is assessed with respect to QoS metrics and for every type of network (i.e., satellite, nanosatellite). The XSTP performance comparison between satellite network and nanosatellite network concludes Chapter 4.





# CHAPTER 4

## Chapitre 4. LES RESULTATS DE SIMULATIONS

Dans ce chapitre, nous présentons et discutons les résultats de simulations des trois modèles de constellations de nano-satellites (i.e., NanoDREAM, NanoICE et NanoSPHERE) proposés dans le Chapitre 3. Dans un premier temps, nous présentons une courte introduction sur les simulateurs utilisés (i.e., SaVi, OPNET) dans cette étude des performances. L'évaluation des performances des constellations de nano-satellites de type NanoDREAM, NanoICE et NanoSPHERE en termes de couverture a été faite en utilisant le simulateur SaVi. Le but principal était d'identifier la meilleure constellation qui satisfait les requis de mission (i.e., maximiser la couverture et minimiser le nombre de nano-satellites). Ainsi, les calculs numériques des paramètres de couverture et des indicateurs de performances ont été présentés pour chaque type de constellation nano-satellitaire.

Nos simulations montrent qu'une constellation NanoDREAM ayant 9 nano-satellites, placés sur un seul plan orbital équatorial à 1500 km d'altitude et avec un angle d'élévation de 15° est la meilleure configuration car elle fournit une couverture totale du désert Salar de Uyuni, en ayant aussi un nombre minimal de nano-satellites. Pour offrir des services de télécommunications pour la communauté scientifique des Régions Polaires, une constellation de type NanoICE ayant 15 nano-satellite placés sur une orbite polaire à 700 km d'altitude et avec un angle d'élévation de 10° est la meilleure solution. Nous avons aussi identifié qu'une constellation de type NanoSPHERE avec 45 nano-satellites placés sur 5 plans orbitaux avec 9 nano-satellites par plane, à 1500 km d'altitude est la meilleure solution pour fournir une couverture globale de la Terre, sauf aux Régions Polaires. Cette constellation peut être déployée dans un contexte d'une forte demande de services de télécommunications par des entreprises industrielles chargées d'exploitation des ressources minières dans plusieurs régions de la Terre.

De plus, l'architecture du segment terrestre destinée à fournir des services de télécommunications dans la zone d'exploitation du désert Salar de Uyuni est implémentée dans le simulateur OPNET. Ce réseau est un réseau de type Ad hoc qui permet de connecter tous les bâtiments de façon efficace. Nous avons choisi le protocole réactif AODV (*Ad hoc On-Demand Distance Vector*) parce qu'il correspond à l'approche recommandée pour les réseaux de nano-satellites, décrit dans le Chapitre 2.4.3. Nous avons conduit plusieurs simulations afin d'évaluer son efficacité en termes de communications via un réseau nano-satellitaire. Les résultats de nos simulations démontrent que l'architecture proposée est capable de fournir une bande passante supérieure à la bande passante offerte par les nano-satellites actuels.

Puisque le protocole de transport XSTP a été identifié comme un candidat pour les constellations de nano-satellites, nous conduisons une étude des performances pour évaluer sa capacité à fournir des services de télécommunications. Ainsi, le protocole de transport XSTP a été implémenté dans le simulateur NS2 et plusieurs simulations ont été faites afin d'évaluer ses performances à travers un réseau de satellites classiques et un réseau de nano-satellites. Deux scénarios de simulation ont été définis : la communication unidirectionnelle, où le canal de transmission est symétrique et la communication bidirectionnelle pour considérer le canal

asymétrique. De plus, deux topologies de réseau ont été implémentées dans le simulateur NS2 : un réseau de satellites traditionnels basé sur la constellation de satellites Teledesic et une constellation de type NanoDREAM identifiée comme la meilleure solution pour fournir la couverture sur le désert de Salar de Uyuni, avec un nombre minimal de nano-satellites dans la constellation.

La Qualité de Service (QoS) dans les réseaux de nano-satellites sera un grand défi pour la communauté scientifique, en considérant l'évolution de la technologie multimédia et l'intérêt commercial des futurs opérateurs nano-satellites pour fournir des services de télécommunications de haute qualité au grand public. Pour cette raison, nous avons défini plusieurs paramètres de performances de QoS, comme la bande passante effective, l'overhead, l'efficacité du canal de transmission et la bande passante nécessaire pour la transmission en sens inverse. Le but est de comparer les performances du protocole XSTP avec celle de clones TCP. Dans un premier temps, nous présentons les résultats des simulations pour le réseau de satellites traditionnels et ensuite, les résultats de simulation pour le réseau de nano-satellites.

Une analyse intéressante est la comparaison des performances de XSTP entre le réseau satellitaire et le réseau nano-satellitaire.

Dans le cas du scénario unidirectionnel, les deux types de réseau (i.e, satellites, nano-satellites) fournissent approximativement le même niveau d'overhead pour chaque catégorie de taux d'erreurs définie. Le protocole XSTP a une bonne capacité d'adaptabilité dans des conditions caractérisées par un taux d'erreurs faible, mais ses performances dans un environnement avec un très haut taux d'erreurs restent un problème qui doit être résolu. De plus, les deux réseaux ont des résultats comparatifs en termes d'efficacité pour chaque catégorie de taux d'erreurs. Le protocole XSTP a des bonnes performances (96%) dans des conditions de bas taux d'erreurs et même pour des haut taux d'erreurs (86%), ce qui signifie que le canal de transmission est très bien utilisé pendant la transmission des données.

Quant au scénario bidirectionnel, les deux réseaux ont les mêmes performances pour des conditions de bas taux d'erreurs. Cependant, nous remarquons que le réseau nano-satellitaire fournit un *overhead* inférieur au réseau de satellites conventionnels, dans des conditions de haut et très haut taux d'erreurs. Par contre, les performances du protocole XSTP pour les deux réseaux, dans un environnement de très haut taux d'erreurs, reste un problème qui doit être résolu. L'*overhead* est une mesure qui permet d'évaluer l'efficacité des protocoles vis à vis de la puissance des nano-satellites, car la transmission de plus de paquets consomme plus d'énergie. En outre, envoyer plus de données augmente la probabilité de collision de paquets et peut retarder des paquets dans les files d'attente. À cet égard, nos simulations démontrent que le protocole XSTP est un bon candidat pour les réseaux de nano-satellites parce qu'il considère comme limitée les ressources des nano-satellites. Quant à l'efficacité du canal de transmission, les deux réseaux ont des performances comparables dans des conditions de bas et haut taux d'erreurs. L'efficacité du protocole XSTP à travers le réseau de nano-satellites, dans des conditions de très haut taux d'erreur, est meilleure (presque 90%) que celle offert par le réseau de satellites. Cela signifie que le canal de transmission est mieux exploité pendant les communications nano-satellites. C'est une raison de plus pour considérer le protocole XSTP comme une bonne solution pour les télécommunications via les réseaux de nano-satellites.



## 4 SIMULATION RESULTS AND ANALYSIS

### 4.1 Introduction

In this chapter, we present and discuss the simulation results of the three nanosatellite constellations models (i.e., NanoDREAM, NanoICE, and NanoSPHERE) proposed in Chapter 3. Nanosatellite constellations' performance evaluation in terms of coverage was done using computer simulations in SaVi modeler. The main purpose was to identify the best constellation which satisfies mission requirements in terms of coverage and minimal number of nanosatellites. Also, the numerical calculations of Earth coverage parameters and performance indicators were discussed for each nanosatellite constellation type. Then, the ground segment architecture for Salar de Uyuni exploitation site is built in OPNET modeler and simulations are run for testing its communication efficiency.

Since XSTP (eXtended Satellite Transport Protocol) has been identified as transport protocol targeted for small satellite constellations, we conduct a simulation study in order to assess its ability to provide efficient communications services. Thus, we implemented XSTP in NS2 simulator and we run simulations for XSTP communications via traditional satellite network and nanosatellite network respectively. Two simulation scenarios were defined: one-way communication, aiming to meet symmetric channel, and bidirectional communication for considering asymmetric channel.

Moreover, the software implementation of XSTP protocol is described along with simulation parameters and data link parameters. For running NS2 simulations, we focus on two network topologies: a traditional satellite network based on Teledesic satellite constellation and a NanoDREAM-type constellation identified as the best solution for providing coverage over Salar de Uyuni Desert, by minimizing the number of nanosatellite in the constellation.

Because of the rising popularity of multimedia applications and potential commercial usage of nanosatellite networks, QoS support for nanosatellite networks will become an unavoidable task. For this reason, we defined several QoS performance metrics, such as effective throughput, transmission overhead, channel efficiency and reverse channel utilization, in order to compare XSTP performance to some TCP clones, in case of a high BER environment. In the first place, we present the simulation results for traditional satellite network and then, the simulation results for nanosatellite network. Finally, a comparative study regarding XSTP performance over satellite network and nanosatellite network concludes this chapter.

### 4.2 Simulation results of nanosatellite constellations

#### 4.2.1 Simulation environment

SaVi (Satellite Visualization) software [111] is a simulator, originally written at the Geometry Center, which allows satellite orbits and coverage simulations, in two and three dimensions. For real-time 3D animations (i.e., videos, interactive java animations and renderings of constellations), SaVi can use Geomview.

SaVi runs on Microsoft Windows (under Cygwin, which emulates a Unix environment), on Macintosh OS X, Linux and Unix. SaVi requires Tcl/Tk (Tool Command Language/ToolKit), an open source programming language. The most common Tcl extension is the Tk toolkit, which provides a graphical user interface library for a variety of operating systems.

This simulator is particularly useful to load in simulations of theoretical constellations, known satellite constellations (e.g., Globalstar, Iridium, Orbcmm), navigation constellations, and various system proposals.

For simulating the ground segment, we used OPNET [112], a simulator built on top of a discrete event system, as NS-2. It is known as the industry's leading simulator specialized for network R&D. It allows users to design and study communication networks, devices, protocols, and applications with great flexibility. It also provides a graphical editor interface to build models for various network entities from physical layer modulator to application processes.

#### 4.2.2 Nanosatellite constellation implementation solution

This chapter presents how nanosatellite constellations were implemented in SaVi modeler. Also, some useful explanations concerning SaVi interface are included for a good understanding and interpretation of the nanosatellite constellation simulation results presented in this chapter.

In order to define a new constellation in SaVi simulator, a script is created, by using the following parameters:

- *SATS\_PER\_PLANE* = the number of nanosatellites on every orbital plane;
- *NUM\_PLANES* = the number of orbital planes;
- *INTERPLANE\_SPACING* = the distance (in degrees) between two orbital plans;
- *a* = the distance entre between Earth's center and nanosatellite ( $= R_E + h$ );
- *e* = eccentricity;
- *inc* = orbit inclination angle
- *Omega* = the distance in longitude measured between two orbital plans;
- *coverage\_angle* = coverage angle ( $=\varepsilon_m/2$ );
- *T\_per* = orbit period.

The main window of SaVi simulator is shown in Figure 4.1. This is where satellite parameters are edited. The default simulation time interval is 60 seconds for each step. The >> and << buttons allows to run simulation forwards and backwards in time, while > and < step forwards a single interval of time; the default time interval is set to sixty seconds for each step.

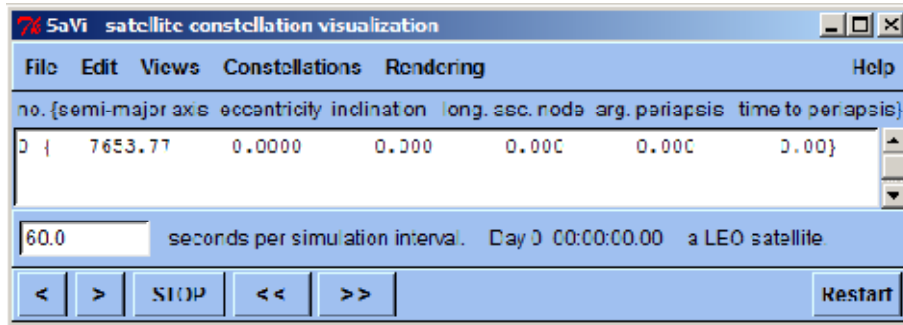


Figure 4.1 – Main SaVi window

By clicking the menu **File** → **Load**, we could load the script of a constellation (Figure 4.2).

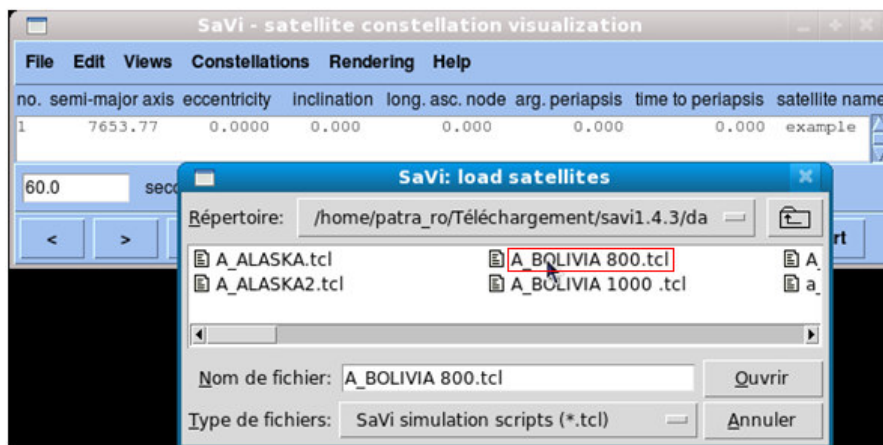


Figure 4.2 – Script loading in SaVi modeler

Once the file is loaded, we could see the constellation parameters (e.g., number of satellite within the constellation, inclination angle, eccentricity, etc.) in the main window (Figure 4.3).

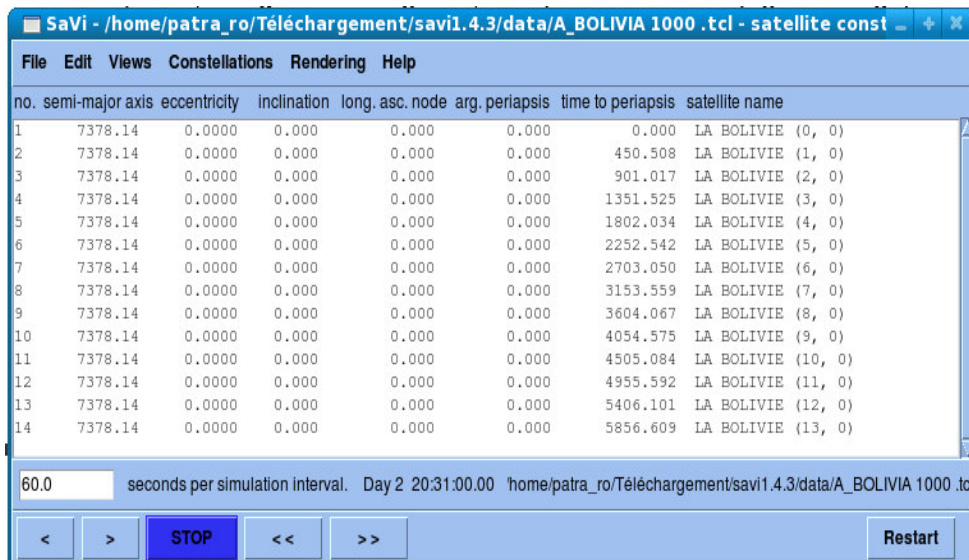


Figure 4.3 – Constellation visualization

In terms of visualization, the coverage panel is the most used feature of SaVi simulator and where most work will be done. For viewing a constellation in 2D, we need to access **View** menu → **Global coverage** option and to choose map settings (Figure 4.4):

- the map projection size (600×300 pixels or 1024×512 pixels);
- the number of coverage shading levels.

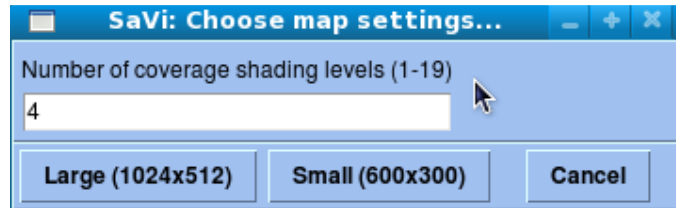


Figure 4.4 – Map projection settings window

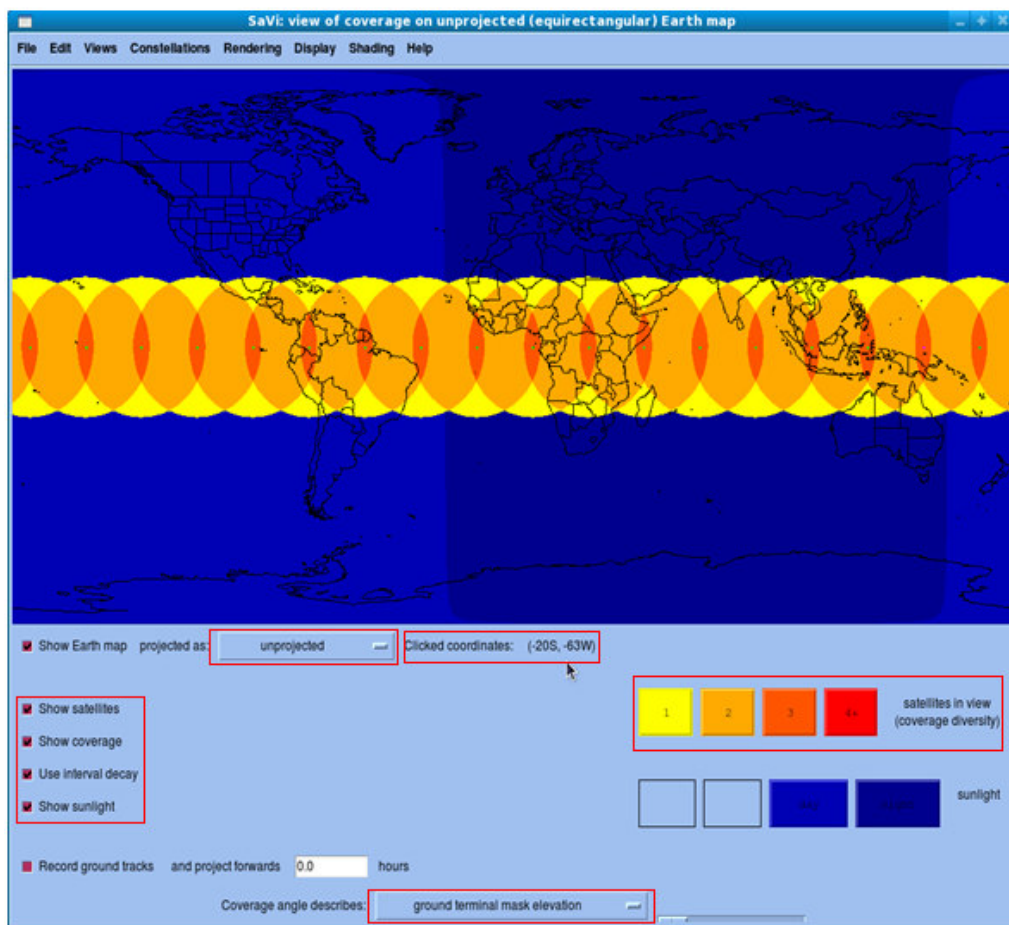


Figure 4.5 – 2D constellation view

Figure 4.5 illustrates a 2D view of a constellation. We observe that various settings are available:

- ✓ Show Earth map;
- ✓ Type of map projection;
- ✓ Show satellites;
- ✓ Show coverage;



- ✓ Use interval decay;
- ✓ Show sunlight.

A number of different map projections can be chosen:

- cylindrical view is useful for sending texture maps to Geomview;
- unprojected map shows high latitudes and poles more clearly than the cylindrical view.
- spherical view is substitute for not using Geomview in order to have an idea of “real” coverage on sphere.
- sinusoidal view is only used for US coverage.

In our simulations, we have generally used unprojected map to have a clear view of constellation coverage.

Satellite coverage, represented by default in yellow/red, is intended to give an idea of the number of satellites visible from a point, or available diversity. The higher the number of satellites covering a point, the deeper the shade of red is.

Interval decay option, which by default is represented with shades of blue, is intended to give an idea of where a satellite footprint has been and is going to be, even when you look at a still map snapshot.

By choosing « ground terminal mask elevation » option, the maximum coverage of every satellite is shown.

SaVi software also has the possibility of showing the geographic coordinates (latitude and longitude) of any point on the Earth's surface. Bolivia’s Salar de Uyuni Desert geographical coordinates are depicted in Figure 4.5.

### 4.2.3 NanoDREAM results

This chapter presents the simulation results of NanoDREAM constellation model. Firstly, the area of Salar de Uyuni Desert has been calculated. Then, several NanoDREAM constellations have been evaluated in terms of coverage and number of nanosatellites in the constellation. Also, an analysis based on performance indicators (data rate, propagation delay and its relative deviation) has been done.

#### 4.2.3.1 Dimensioning target coverage area

Firstly, we need to calculate the target area that our nanosatellite constellation has to cover. By using the online calculator [113], we found that Salar de Uyuni Desert is delimited by the following geographic coordinates (Table 4.1 and Figure 4.6):

Points	Latitude (S)	Longitude (W)
A	19° 39' 13"	67° 38' 19"
B	20° 11' 8"	66° 46' 35"
C	20° 50' 11"	67° 36' 1"
D	20° 10' 22"	68° 21' 10"

Table 4.1 – Geographical coordinates of Salar de Uyuni Desert

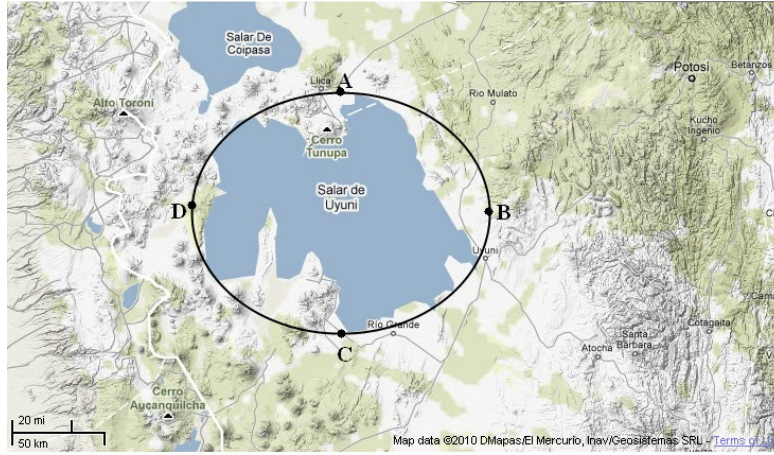


Figure 4.6 – Estimated coverage area of Salar de Uyuni Desert

Figure 4.7 illustrates the main meridians and parallels that bound the desert.

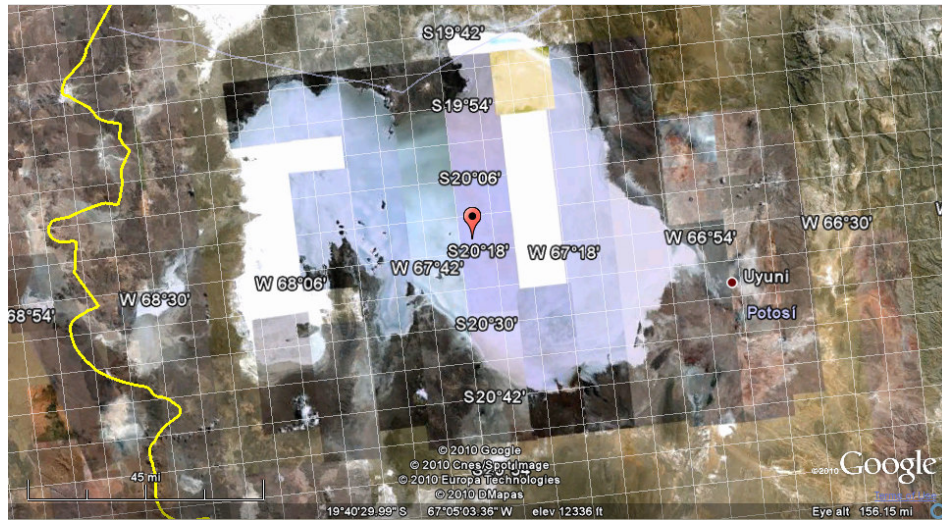


Figure 4.7 – Main meridians and parallels crossing Salar de Uyuni Desert

Then, by using an online calculator [114], which allows calculating the distance between two points of latitude and longitude, we determined the following distances:

$$d_1(A, C) \cong 132 \text{ km}$$

$$d_2(B, D) \cong 164 \text{ km}$$

We model the coverage area as an ellipse, with semi-major axis of length  $a$ :

$$a = \frac{d_2}{2} = \frac{164 \text{ km}}{2} = 82 \text{ km}$$

and semi-minor axis of length  $b$ :

$$b = \frac{d_1}{2} = \frac{132 \text{ km}}{2} = 66 \text{ km}$$

Knowing that the ellipse area is:

$$A = \pi ab$$

The area of coverage will give a surface of:

$$S = 5412\pi \cong 17000 \text{ km}^2$$

Thus, we estimated that the area of Salar de Uyuni Desert is 17000 km<sup>2</sup>. This parameter is important for ground segment and space segment dimensioning.

#### 4.2.3.2 Numerical calculations for NanoDREAM model

This section presents numerical calculations of NanoDREAM model which corresponds to Salar de Uyuni Desert exploitation mission, described in Chapter 3.2.1.

In our numerical calculations, we consider three different altitudes:

- 800 km, which is a common altitude for CubeSat launching; in order to validate our model, it is very important to use altitudes that correspond to real on-orbit nanosatellites.
- 1000 km and 1500 km, altitudes that allows us to minimize the number of nanosatellites within the constellations. Also, for these altitudes, the atmospheric drag resulting in satellite re-entry is significantly reduced.

By using nanosatellite model equations from Chapter 3, we calculate the following parameters:

$\lambda_{max}$  – maximum Earth central angle;

$\eta_{max}$  – maximum nadir angle, measured at the satellite from nadir to the ground station;

$T_{max}$  – maximum time in view;

$N_{min}$  – minimum number of nanosatellites within the constellation;

$D_{max}$  – maximum slant range at which the satellite will still be in view;

$t_p$  – propagation delay;

$\Delta$  – propagation delay relative deviation;

$P$  – nanosatellite period;

$v$  – nanosatellite velocity;

In this chapter, a nanosatellite constellation is defined by the vector  $C[N_n, n_p, h, \epsilon_{min}, i]$ , where  $N_n$  is the number of nanosatellites in the constellation,  $n_p$  is the number of orbital planes,  $h$  is the constellation altitude,  $\epsilon_{min}$  is the minimum elevation angle and  $i$  is the inclination angle with respect to the equatorial plane.

An important QoS parameter in satellite communication is round-trip propagation delay, which has a great impact on multimedia applications that cannot tolerate delay. For our study, this metric shows the suitability of our nanosatellite architectures for this type of applications. We found appropriate to present here the numerical results of the propagation delay because this parameter is calculated for every nanosatellite constellation, as shown in the following tables.

Table 4.2 to Table 4.4 summarizes the main parameters of NanoDREAM-type constellations. These parameters were calculated by varying the minimum elevation angle between 5 degrees and 30 degrees and considering three altitude values: 800 km, 1000 km and 1500 km respectively.

<i>Altitude =800 km, P =100.87 min, v=7.4561 m/s</i>									
$C[N_n, n_p, h, \varepsilon_{min}, i]$	$\varepsilon_{min}$ ( $^\circ$ )	$\lambda_{max}$ ( $^\circ$ )	$\eta_{max}$ ( $^\circ$ )	$T_{max}$ (min)	$N_{min}$	$D_M$ (km)	$t_m$ (ms)	$t_M$ (ms)	$\Delta$
$C [9, 1, 800 \text{ km}, 5^\circ, 0^\circ]$	5	22.72	62.28	12.73	9	2782.73	2.66	9.27	2.48
$C [13, 1, 800 \text{ km}, 10^\circ, 0^\circ]$	10	18.95	61.05	10.62	13	2367	2.66	7.89	1.96
$C [18, 1, 800 \text{ km}, 15^\circ, 0^\circ]$	15	15.87	59.13	8.9	18	2032	2.66	6.77	1.54
$C [25, 1, 800 \text{ km}, 20^\circ, 0^\circ]$	20	13.38	56.62	7.5	25	1767.48	2.66	5.89	1.21
$C [35, 1, 800 \text{ km}, 25^\circ, 0^\circ]$	25	11.36	53.64	6.36	35	1560	2.66	5.2	0.95
$C [48, 1, 800 \text{ km}, 30^\circ, 0^\circ]$	30	9.69	50.31	5.43	48	1395.07	2.66	4.65	0.75

Table 4.2 – Numerical results for NanoDREAM constellations placed at 800 km of altitude

In case of a communication via nanosatellite network, the most important latency component is propagation delay. Below, we analyze three groups of six NanoDREAM constellations each and we point out the “best case” solution and “worst case” solution in terms of transmission delay. For every solution, the transmission delay is represented as  $t \in [t_l; t_u]$ , where  $l$  denote low interval limit and  $u$ , upper interval limit.

Based on numerical results from Table 4.2, the following remarks can be made:

- the constellation  $C [9, 1, 800 \text{ km}, 5^\circ, 0^\circ]$  is the “worst case” solution, having a transmission delay  $t \in [10.64; 37.08]ms$ , as shown in the following calculations:

$$t_l = 2 \times (2.66ms + 2.66ms) \cong 10.64ms$$

$$t_u = 2 \times (9.27ms + 9.27ms) \cong 37.08ms$$

Therefore, the maximum propagation delay in case of a communication between two user terminals, by passing through a nanosatellite of this constellation, is about 37 ms, while the minimum propagation delay will be about 11 ms.

- the constellation  $C [48, 1, 800 \text{ km}, 30^\circ, 0^\circ]$  is the “best case” solution in terms of propagation delay, having  $t \in [10.64; 18.6]ms$ , as shown in the following calculations:

$$t_l = 2 \times (2.66ms + 2.66ms) \cong 10.64ms$$

$$t_u = 2 \times (4.65ms + 4.65ms) \cong 18.60ms$$

In case of a communication between two users, by passing through a nanosatellite of this constellation, the minimum round-trip propagation delay is around 11 ms while the maximum propagation delay is about 19 ms.

The constellations identified as “worst case” and “best case” solutions among the nanosatellite constellations placed on circular orbit at 800 km of altitude don’t take into account our mission requirements because none of them provides coverage of Salar de Uyuni Desert.

Altitude =1000 km, P =105.11 min, nanosatellite velocity=7.3507 m/s									
$C[N_n, n_p, h, \varepsilon_{min}, \iota]$	$\varepsilon_{min}$ ( $^\circ$ )	$\lambda_{max}$ ( $^\circ$ )	$\eta_{max}$ ( $^\circ$ )	$T_{max}$ (min)	$N_{min}$	$D_M$ (km)	$t_m$ (ms)	$t_M$ (ms)	$\Delta$
$C [7, 1, 1000 \text{ km}, 5^\circ, 0^\circ]$	5	25.55	59.45	14.92	7	3194.23	3.33	10.64	2.2
$C [10, 1, 1000 \text{ km}, 10^\circ, 0^\circ]$	10	21.64	58.36	12.63	10	2762.68	3.33	9.2	1.76
$C [14, 1, 1000 \text{ km}, 15^\circ, 0^\circ]$	15	18.38	56.62	10.73	14	2408.38	3.33	8.02	1.4
$C [19, 1, 1000 \text{ km}, 20^\circ, 0^\circ]$	20	15.67	54.33	9.15	19	2120.5	3.33	7.06	1.12
$C [25, 1, 1000 \text{ km}, 25^\circ, 0^\circ]$	25	13.42	51.58	7.83	25	1889.34	3.33	6.3	0.89
$C [34, 1, 1000 \text{ km}, 30^\circ, 0^\circ]$	30	11.52	48.48	6.72	34	1701.22	3.33	5.67	0.7

Table 4.3 – Numerical results for NanoDREAM constellations placed at 1000 km of altitude

Numerical results from Table 4.3 lead us to the following observations:

- the constellation  $C [7,1,1000 \text{ km}, 5^\circ, 0^\circ]$  is the “worst case” solution, having a propagation delay  $t \in [13.32; 42.56]ms$ , as shown in the following calculations:

$$t_l = 2 \times (3.33ms + 3.33ms) \cong 13.32ms$$

$$t_u = 2 \times (10.64ms + 10.64ms) \cong 42.56ms$$

Therefore, the maximum propagation delay in case of a communication between two terminals, by passing through a nanosatellite of this constellation, is about 43 ms, while the minimum propagation delay is about 14 ms.

- the constellation  $C [34,1,1000 \text{ km}, 30^\circ, 0^\circ]$  is the “best case” solution in terms of propagation delay, having  $t \in [13.32; 22.68]ms$ , as shown in the following calculations:

$$t_l = 2 \times (3.33ms + 3.33ms) \cong 13.32ms$$

$$t_u = 2 \times (5.67ms + 5.67ms) \cong 22.68ms$$

In case of a communication between two user terminals, by passing through a nanosatellite of this constellation, the minimum round-trip propagation delay is 14 ms, while the maximum propagation delay is about 23 ms.

The constellations identified as “worst case” and “best case” solutions don’t take into consideration our mission requirements because none of them provides coverage of Salar de Uyuni Desert. These observations were made only on “propagation delay” basis.

The constellation  $C [14,1,1000 \text{ km}, 15^\circ, 0^\circ]$  provides a coverage band between  $0^\circ$  and  $20^\circ$  S latitude, including also Salar de Uyuni desert region. This constellation offers a propagation delay  $t \in [13.32; 32.08]ms$ , according to calculations above:

$$t_l = 2 \times (3.33ms + 3.33ms) \cong 13.32ms$$

$$t_u = 2 \times (8.02ms + 8.02ms) \cong 32.08ms$$

Altitude =1500 km, P =115.98 min, nanosatellite velocity=7.1136 m/s									
$C[N_n, n_p, h, \varepsilon_{min}, i]$	$\varepsilon_{min}$ (°)	$\lambda_{max}$ (°)	$\eta_{max}$ (°)	$T_{max}$ (min)	$N_{min}$	$D_M$ (km)	$t_m$ (ms)	$t_M$ (ms)	$\Delta$
$C [5, 1, 1500 \text{ km}, 5^\circ, 0^\circ]$	5	31.24	53.76	20.13	5	4101.16	5	13.67	1.734
$C [7, 1, 1500 \text{ km}, 10^\circ, 0^\circ]$	10	27.12	52.88	17.47	7	3646.28	5	12.15	1.43
$C [9, 1, 1500 \text{ km}, 15^\circ, 0^\circ]$	15	23.55	51.45	15.17	9	3258.45	5	10.86	1.172
$C [11, 1, 1500 \text{ km}, 20^\circ, 0^\circ]$	20	20.46	49.54	13.18	11	2930.17	5	9.76	0.952
$C [15, 1, 1500 \text{ km}, 25^\circ, 0^\circ]$	25	17.8	47.2	11.47	15	2657.28	5	8.85	0.77
$C [19, 1, 1500 \text{ km}, 30^\circ, 0^\circ]$	30	15.48	44.52	9.97	19	2427.84	5	8.09	0.618

Table 4.4 – Numerical results for NanoDREAM constellations placed at 1500 km of altitude

Based on numerical results in Table 4.4, the following observations can be made:

- the constellation  $C [5,1,1500 \text{ km}, 5^\circ, 0^\circ]$  is the “worst case” solution, having a propagation delay  $t \in [20; 54.68]ms$ , as shown in the following calculations:

$$t_l = 2 \times (5ms + 5ms) \cong 20ms$$

$$t_u = 2 \times (13.67ms + 13.67ms) \cong 54.68ms$$

Therefore, the maximum propagation delay in case of a communication between two terminals, by passing through a nanosatellite of this constellation, is about 55 ms, while the minimum propagation delay will be about 20 ms.

- the constellation  $C [19,1,1500 \text{ km}, 30^\circ, 0^\circ]$  is the “best case” solution in terms of propagation delay, having  $t \in [20; 32.36]ms$ , as shown in the following calculations:

$$t_l = 2 \times (5ms + 5ms) \cong 20ms$$

$$t_u = 2 \times (8.09ms + 8.09ms) \cong 32.36ms$$

In case of a communication between two user terminals, by passing through a nanosatellite of this constellation, the minimum round-trip propagation delay is 20 ms, while the maximum propagation delay is about 33 ms.

The previous remarks concerning the “worst case” and “best case” solutions were made only from “propagation delay” point of view.

The constellation  $C [9,1,1500 \text{ km}, 15^\circ, 0^\circ]$  provides a coverage band between  $0^\circ$  and  $22^\circ$  S latitude, including also Salar de Uyuni desert region. This constellation meets our two mission requirements (i.e., minimizing the number of nanosatellites and maximizing the time in view) and offers a propagation delay  $t \in [20; 43.44]ms$ , according to calculations above:

$$t_l = 2 \times (5ms + 5ms) \cong 20ms$$

$$t_u = 2 \times (10.86ms + 10.86ms) \cong 43.44ms$$

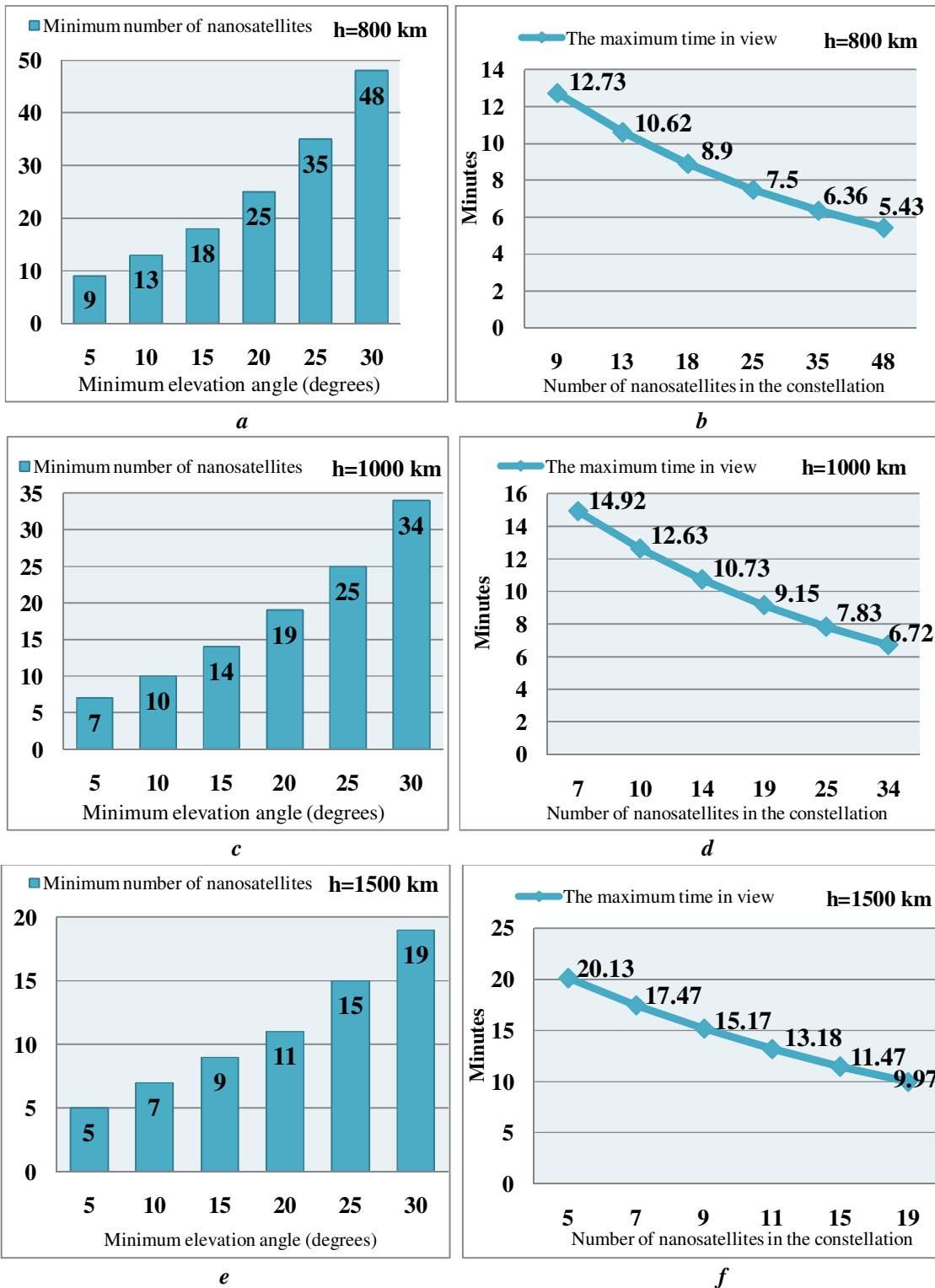


Figure 4.8 – Number of nanosatellites as a function of  $\epsilon_{min}$  for: a) 800 km, c) 100 km, e) 1500 km; Maximum time in view variation as a function of number of nanosatellites in the constellation for: b) 800km, d) 1000 km, f) 1500 km

Figure 4.8a to Figure 4.8f illustrates two important diagrams for every altitude value considered in this study:

- variation of the number of nanosatellites with respect to minimum elevation angle;
- variation of the maximum time in view as a function of the number of nanosatellites within the constellation.

By analyzing these figures, we observe the following types of variations:

- for the same altitude, the minimum number of nanosatellites is increasing as the minimum elevation angle is increasing;
- for the same elevation angle, the minimum number of nanosatellites is decreasing as the altitude is increasing;
- for the same elevation angle, the maximum time in view of any given point on Earth is increasing as the altitude is increasing.

In Chapter 3.2.9, we have introduced four parameters for Earth coverage assessment: antenna footprint, coverage rate, access area and access rate. The first two parameters are dependent of the antenna beamwidth while the last two parameters depend only of the Earth central angle ( $\lambda$ ).

Below, we presented the numerical results for constellation  $C$  [9,1,1500 km, 15°, 0°] identified as the optimal solution which meets our mission objectives. For calculating the coverage parameters for this constellation, we consider five types of antennas, as shown in Table 4.5.

Antenna type	Antenna beamwidth
Monopole	77.3°
Single patch	101.4°
Helical	66°
Horn	51.4°
2 element patch	77.2°

Table 4.5 – Beamwidth values for various nanosatellite antennas

Table 4.6 presents the coverage parameters of the constellation  $C$  [9,1,1500 km, 15°, 0°]. We observe that monopole, single patch and 2 patch antennas provides a comparative footprint area and coverage rate.

Coverage parameter	Monopole	Single patch	Helical	Horn	2 element patch
$F_a$ (km <sup>2</sup> )	30.66*10 <sup>6</sup>	30.96*10 <sup>6</sup>	26.89*10 <sup>6</sup>	19.67*10 <sup>6</sup>	30.63*10 <sup>6</sup>
$R_{cov}$ (km <sup>2</sup> /min)	2.53*10 <sup>6</sup>	2.55*10 <sup>6</sup>	2.22*10 <sup>6</sup>	1.62*10 <sup>6</sup>	2.52*10 <sup>6</sup>
The access area ( $A_a$ ) and the access rate ( $R_a$ ) are not dependent of the antenna type used during communications. $A_a=21.28*10^6$ km <sup>2</sup> and $R_a=1.76*10^6$ km <sup>2</sup> /min					

Table 4.6 – Coverage parameters for the constellation of 9 nanosatellites placed at 1500 km of altitude and having  $\epsilon_{min}=15^\circ$

We were also interested in evaluating the amount of data that a nanosatellite could transmit at each pass. Table 4.7 presents the amount of data transmitted by a nanosatellite placed at 1500 km of altitude and having a minimum elevation angle of 15°.



In this case, we have considered a downlink data rate between 9.6 Kbps and 1024 Kbps, which corresponds to the real nanosatellites launched in space. We remark that during a pass (time in view) of almost 12 minutes, the maximum amount of data transmitted by a nanosatellite to a ground station is 9.1 Mbps if a data rate of 1 Mbps is considered. For a low downlink rate (9.6 Kbps), the nanosatellite will be able to transmit only 86 Kbps on each pass over the ground station.

Data rate (Kbps)	Data quantity (Kbps)
9.6	85.52
16	142.54
32	285.08
64	570.16
128	1140.32
256	2280.65
512	4561.3
1024	9122.61

Table 4.7 – Amount of data transmitted at each nanosatellite pass (altitude=1500 km,  $\epsilon_{min}=15^\circ$ )

#### 4.2.3.3 SaVi simulations of NanoDREAM constellations

In this chapter, we discuss SaVi simulation results of four NanoDREAM constellations, by considering only the coverage criterion.

Constellation	$C [18, 1, 800 \text{ km}, 15^\circ, 0^\circ]$	$C [9, 1, 1500 \text{ km}, 10^\circ, 0^\circ]$	$C [14, 1, 1000 \text{ km}, 15^\circ, 0^\circ]$	$C [9, 1, 1500 \text{ km}, 15^\circ, 0^\circ]$
Number of nanosatellites	18	14	14	9
Coverage latitude	$0^\circ - 18^\circ$	$0^\circ - 19^\circ$	$0^\circ - 20^\circ$	$0^\circ - 22^\circ$
Maximum Time in view	8.9 min	10.62 min	10.73 min	15.17 min
Minimum elevation angle	$15^\circ$	$10^\circ$	$15^\circ$	$15^\circ$
Number of orbital planes	1	1	1	1
Constellation altitude	800 km	800 km	1000 km	1500 km
Orbital period	100.87 min	100.87 min	105.11 min	115.98 min
Number of orbits per day	14.23	14.23	13.66	12.38
Nanosatellite velocity	7.4561 m/s	7.4561 m/s	7.3507 m/s	7.1136 m/s

Table 4.8 – Nanosatellite constellations modeled in SaVi simulator

Table 4.8 summarizes the parameters of four NanoDREAM constellations simulated using SaVi modeler. We observe that constellation  $C [9,1,1500 \text{ km}, 15^\circ, 0^\circ]$  satisfies our mission objectives because:

- it has a minimum number of nanosatellites (9 nanosatellites);
- it offers a coverage band between  $0^{\circ}$  and  $22^{\circ}$  S latitude, thus assuring a total coverage of Salar de Uyuni Desert;
- the time in view of every nanosatellite is maximized; every nanosatellite will stay maximum 15 minutes over each point of the coverage area.

As shown in Figure 4.9 to Figure 4.12, satellite coverage, represented in yellow/red, is intended to give an idea of the number of nanosatellites visible from a point on Earth. The higher the number of nanosatellites covering a point, the deeper the shade of red is. Also, coverage decay, illustrated in shades of blue, gives an idea of where a satellite footprint has been and is going, even when you look at a still map snapshot.

Constellation C [ $18,1,800\text{ km}, 15^{\circ}, 0^{\circ}$ ] is constituted of 18 nanosatellites placed on an equatorial orbit at 800 km of altitude and having a minimum elevation angle of  $15^{\circ}$ . As seen in Figure 4.9, the coverage area will be between  $0^{\circ}$  and  $18^{\circ}$  of S latitude, but our target region is situated at  $20^{\circ}$  S latitude. Thus, this configuration does not satisfy our mission goal in terms of coverage.

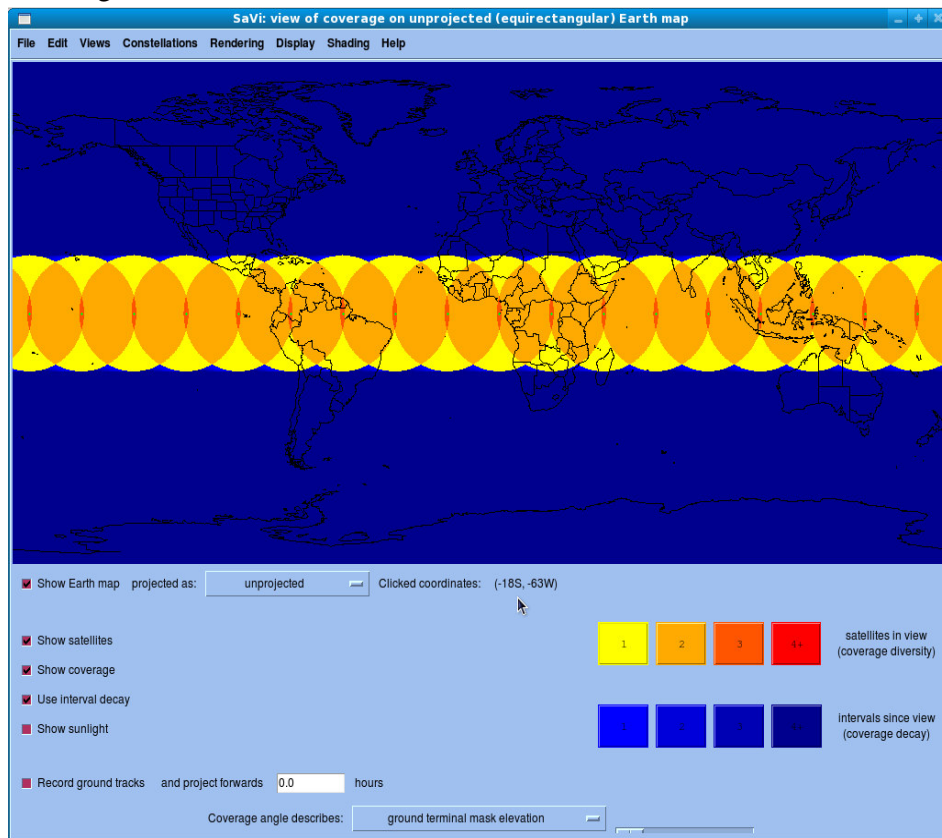


Figure 4.9 – Coverage of nanosatellite constellation including 18 nanosatellites placed on a LEO, equatorial orbit at an altitude of 800 Km and minimum elevation angle of  $15^{\circ}$

In order to obtain the desired coverage, we modified the minimum elevation angle of  $10^{\circ}$  and we obtained constellation C [ $9,1,1500\text{ km}, 10^{\circ}, 0^{\circ}$ ] of 14 nanosatellites placed at 800 km of altitude. Unfortunately, the coverage area (Figure 4.10) will be between  $0^{\circ}$  and  $19^{\circ}$  S latitude, solution that still not corresponds to our mission. Additionally, this constellation might suffer of bad visibility, given the natural and manmade obstacles that would obstruct nanosatellites at lower elevation angles.

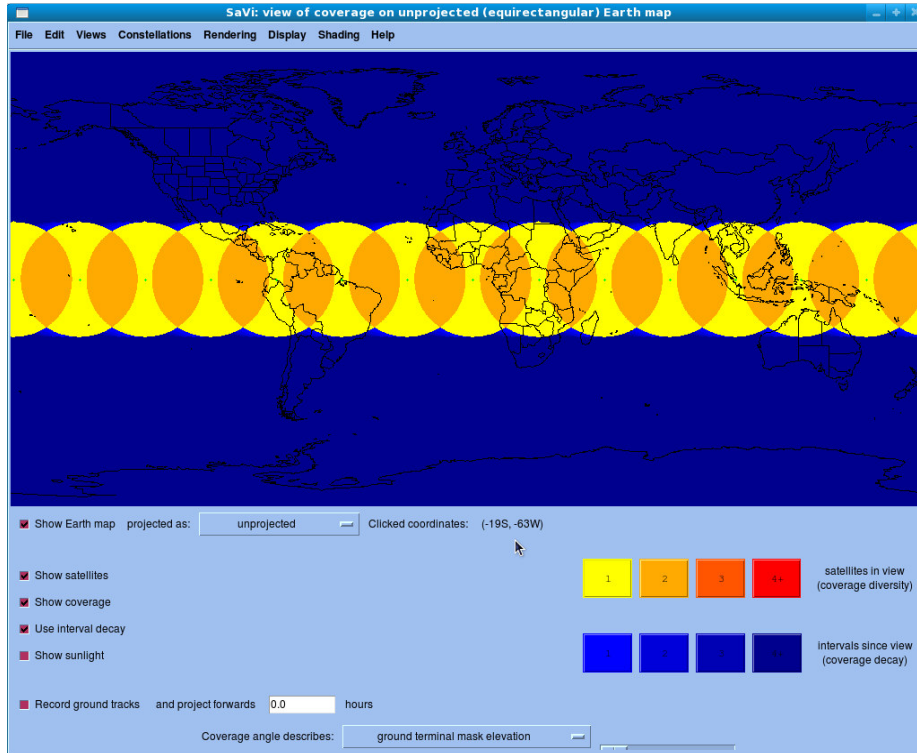


Figure 4.10 – Coverage of nanosatellite constellation including 14 nanosatellites placed on a LEO, equatorial orbit at an altitude of 800 Km and minimum elevation angle of  $10^\circ$

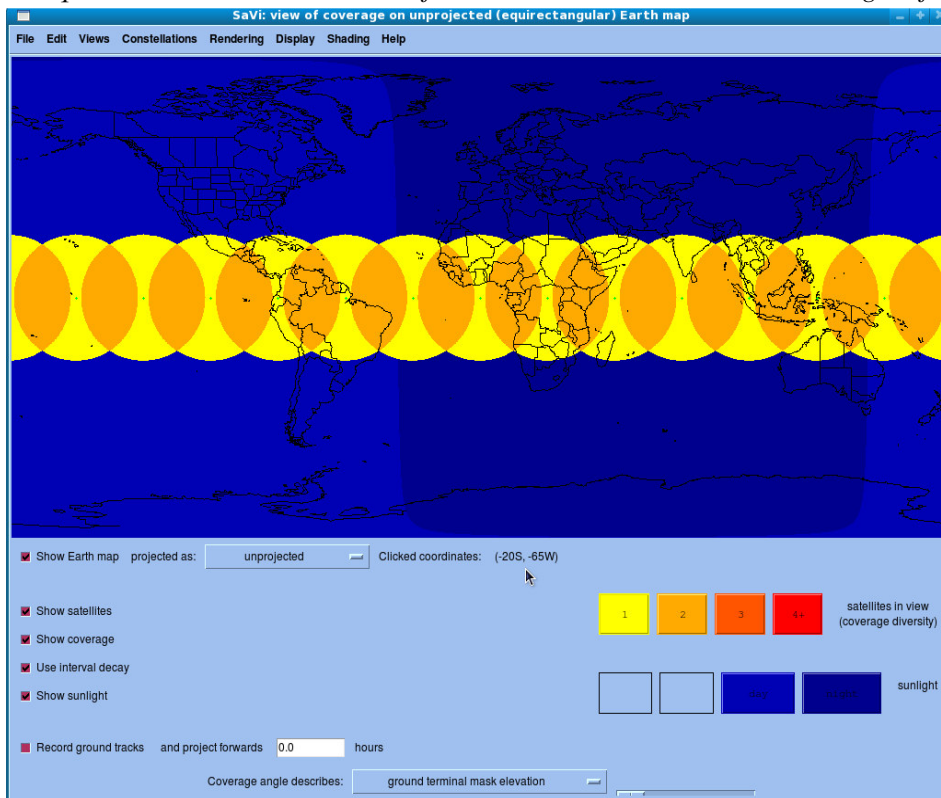


Figure 4.11 – Coverage of nanosatellite constellation including 14 nanosatellites placed on a LEO, equatorial orbit at an altitude of 1000 Km and minimum elevation angle of  $15^\circ$

Due to attenuation and terrain shadowing effects, reliable communication is not possible at low elevation angles. The low altitude of the satellites and the need for high elevation angles for successful communications necessitate small satellite footprints.

Knowing that Salar de Uyuni Desert has a flat surface, we thought that a minimum elevation angle of  $15^\circ$  is sufficient to have visibility at any given point on the desert. Thus, a possible solution to our coverage problem seems to be constellation altitude increasing. By increasing altitude at 1000 km and for  $\epsilon_{min}=15^\circ$ , we obtain constellation  $C [14,1,1000 \text{ km}, 15^\circ, 0^\circ]$  of 14 nanosatellites (Figure 4.11). This constellation defines a coverage band between  $0^\circ$  and  $20^\circ$  S latitude, solution that satisfy the second mission objective (the coverage), but not the first one (minimizing the number of nanosatellites within the constellation).

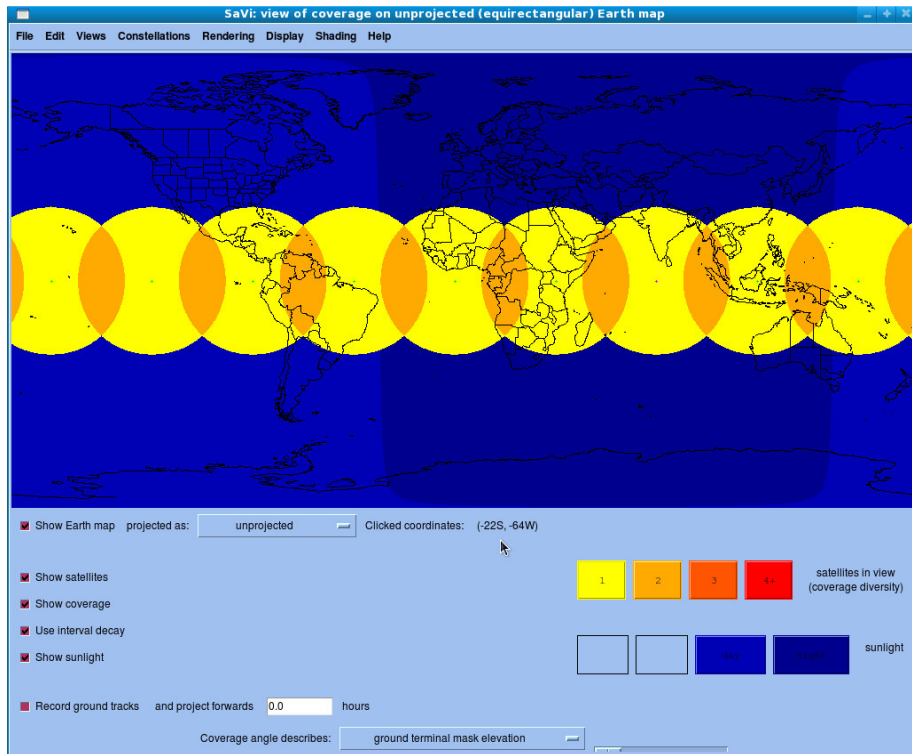


Figure 4.12 – Coverage of nanosatellite constellation including 9 nanosatellites placed on a LEO, equatorial orbit at an altitude of 1500 Km and minimum elevation angle of  $15^\circ$

Our numerical calculations have shown that the number of nanosatellites is decreasing with altitude increasing. Considering this type of variation and for minimizing the number of nanosatellites, a solution might be to increase constellation altitude to a value that satisfies our requirements. Thus, for an altitude of 1500 Km and  $\epsilon_{min}=15^\circ$ , we obtain constellation  $C [9,1,1500 \text{ km}, 15^\circ, 0^\circ]$  of 9 nanosatellites (Figure 4.12), which is the best nanosatellite system configuration that satisfy our two mission goals.

#### 4.2.3.4 Applying Markov method for evaluating the performance of NanoDREAM-type constellation

In this chapter, we applied the Markov method proposed in Chapter 3.3.11 to a NanoDREAM constellation of 9 nanosatellites placed on a single equatorial orbital plane at 1500 km of altitude.

We assumed that minimum four nanosatellites are required to maintain a minimum level of availability. Thereby, NanoDREAM model contains five possible functioning states, as shown in Table 4.9.

State number	Number of nanosatellites in service	Number of failed nanosatellites
1	9	0
2	8	1
3	7	2
4	6	3
5	5	4
6	4	5

Table 4.9 – Functioning state of NanoDREAM constellation

The number of failed nanosatellites is identical with the number of nanosatellites that need to be replaced.

The remaining four states in the Markov model state diagram represent system failure states as the NanoDREAM constellation will no longer be available for providing the minimum service level. These states are:

- State 7: three of the nine nanosatellites are working (six have failed);
- State 8: two of the nine nanosatellites are working (seven have failed);
- State 9: one of the nine nanosatellites is working (eight nanosatellites have failed);
- State 10: all nine nanosatellites have failed.

Figure 4.13 describes the Markov model state diagram for NanoDREAM constellation needed for developing the proper set of differential equations. From the Markov model state diagram, a set of differential equations can be written to determine the probability of the NanoDREAM constellation being in any given state at any given time.

Let  $a$  be the failure rate of a nanosatellite and  $b$ , the renewal rate (i.e., the rate at which a failed nanosatellite will be replaced by a new nanosatellite).

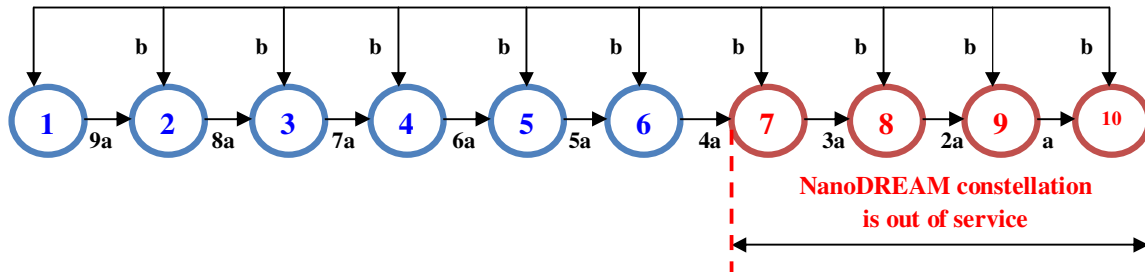


Figure 4.13 – Markov state diagram for NanoDREAM constellation

Therefore, the NanoDREAM constellation of nine nanosatellites placed on a single equatorial orbital plane at 1500 km of altitude requires a set of ten differential equations to model this constellation (Eq. 76):

$$\begin{bmatrix} \dot{P}_1 \\ \dot{P}_2 \\ \dot{P}_3 \\ \dot{P}_4 \\ \dot{P}_5 \\ \dot{P}_6 \\ \dot{P}_7 \\ \dot{P}_8 \\ \dot{P}_9 \\ \dot{P}_{10} \end{bmatrix} = \begin{bmatrix} -9a & b & b & b & b & b & b & b & b & b \\ 9a & -(8a+b) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8a & -(7a+b) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 7a & -(6a+b) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6a & -(5a+b) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5a & -(4a+b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4a & -(3a+b) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3a & -(2a+b) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2a & -(a+b) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a & -b \end{bmatrix} \times \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \\ P_{10} \end{bmatrix} \quad (76)$$

In order to find the solution to Eq. 76, the failure rate and renewal rate are required as well as the initial conditions of the NanoDREAM constellation. At the beginning of the operational mission, the probability to be in state 1 is 100% and the probability of being in all nine successive states is 0%.

We assumed that the failure rate is  $a=0.00833$  and renewal rate is  $b= 0.2$ . Thus, the exact probability of being in any of the six operational states is given by the probability vector  $\vec{P}$  :

$$\begin{bmatrix} \dot{P}_1 \\ \dot{P}_2 \\ \dot{P}_3 \\ \dot{P}_4 \\ \dot{P}_5 \\ \dot{P}_6 \\ \dot{P}_7 \\ \dot{P}_8 \\ \dot{P}_9 \\ \dot{P}_{10} \end{bmatrix} = \begin{bmatrix} 0.825 \\ -0.164 \\ -0.147 \\ -0.128 \\ -0.11 \\ -0.092 \\ -0.074 \\ -0.055 \\ -0.037 \\ -0.018 \end{bmatrix} \quad (77)$$

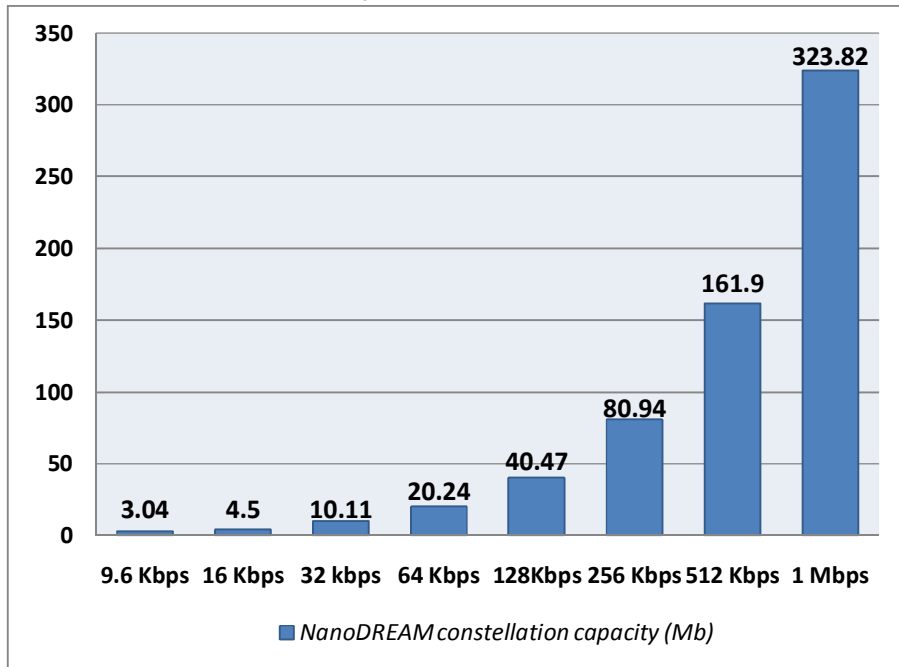


Figure 4.14 – NanoDREAM constellation capacity during one day of service

Figure 4.14 illustrates the capacity of NanoDREAM constellation during one day of service. This capacity was calculated taking into consideration the probability of failure of nanosatellites. We considered a set of eight downlink rates (9.6 Kbps to 1 Mbps). We can observe that the maximum capacity is attained by a NanoDREAM constellation with 9 nanosatellites having a downlink rate of 1 Mbps. Thus, it could deliver almost 324 Mbps during one day of service. If we consider the low downlink rate (9.6 Kbps) of nanosatellites, the same constellation could deliver only 3 Mbps in one day of service.

## 4.2.4 NanoICE results

### 4.2.4.1 Numerical calculations for NanoICE constellation

This chapter presents numerical calculations for NanoICE model. For this type of model, we chose an altitude of 700 km because it assures a good coverage of icecaps, being also a common altitude used by polar satellites.

Table 4.10 presents the parameters of six NanoICE constellations. Minimum elevation angle  $\epsilon_{min}$  is varied between  $5^\circ$  and  $30^\circ$  and the altitude is considered fixed (700 km).

<i>Altitude =700 km, P =98.77 min, nanosatellite velocity=7.5 m/s</i>									
$C[N_n, n_p, h, \epsilon_{min}, i]$	$\epsilon_{min}$ ( $^\circ$ )	$\lambda_{max}$ ( $^\circ$ )	$\eta_{max}$ ( $^\circ$ )	$T_{max}$ (min)	$N_{min}$	$D_M$ (km)	$t_m$ (ms)	$t_M$ (ms)	$\Delta$
$C [10, 1, 700 \text{ km}, 5^\circ, 90^\circ]$	5	21.14	63.86	11.6	10	2562.28	2.33	8.54	2.66
$C [15, 1, 700 \text{ km}, 10^\circ, 90^\circ]$	10	17.45	62.55	9.57	15	2155.24	2.33	7.18	2.08
$C [22, 1, 700 \text{ km}, 15^\circ, 90^\circ]$	15	14.5	60.5	7.95	22	1834.8	2.33	6.11	1.62
$C [31, 1, 700 \text{ km}, 20^\circ, 90^\circ]$	20	12.14	57.86	6.66	31	1584.05	2.33	5.28	1.26
$C [43, 1, 700 \text{ km}, 25^\circ, 90^\circ]$	25	10.24	54.76	5.62	43	1388.23	2.33	4.62	0.98
$C [60, 1, 700 \text{ km}, 30^\circ, 90^\circ]$	30	8.7	51.3	4.77	60	1236.16	2.33	4.12	0.76

Table 4.10 – Numerical results for polar nanosatellite constellations

Since icecaps have a flat surface, so there are not many obstacles as compared to habited areas, we considered that an elevation angle of  $10^\circ$  will provide a good visibility in all conditions. Therefore, we observe that the constellation  $C [15, 1, 700 \text{ km}, 10^\circ, 90^\circ]$  responds to our two mission goals: maximizing the time in view and minimizing the number of nanosatellites within the constellation. The orbital period is 98.77 minutes, which means that every nanosatellite will pass 15 times per day over any point of the coverage area. The half-orbit on the sun side takes only 49 minutes, during which local time of day does not greatly vary. All nanosatellites will be travelling at a speed of 7.5 km per second. Also, the maximum time in view of each nanosatellite is 9.5 minutes.

In case of a communication between two terminals, by passing through a nanosatellite of this polar constellation, the minimum round-trip propagation delay is 10 ms while the maximum propagation delay is about 29 ms:

$$t_l = 2 \times (2.33ms + 2.33ms) \cong 9.32ms$$

$$t_u = 2 \times (7.18ms + 7.18ms) \cong 28.72ms$$

By considering the same types of antennas as for NanoDREAM constellations, we have calculated the coverage parameters of the polar constellation  $\mathcal{C}$  [15, 1, 700 km, 10°, 90°] (Table 4.11).

Coverage parameter	Monopole	Single patch	Helical	Horn	2 element patch
$F_a$ (km <sup>2</sup> )	20*10 <sup>6</sup>	20.18*10 <sup>6</sup>	17.53*10 <sup>6</sup>	12.83*10 <sup>6</sup>	19.97*10 <sup>6</sup>
$R_{cov}$ (km <sup>2</sup> /min)	2.61*10 <sup>6</sup>	2.63*10 <sup>6</sup>	2.29*10 <sup>6</sup>	1.675*10 <sup>6</sup>	2.6*10 <sup>6</sup>
The access area ( $A_a$ ) and the access rate ( $R_a$ ) are not dependent of the antenna type used during communications. $A_a=11.76*10^6$ km <sup>2</sup> and $R_a=1.55*10^6$ km <sup>2</sup> /min					

Table 4.11 – Coverage parameters for the polar constellation of 15 nanosatellites placed at 700 km of altitude and having  $\varepsilon_{min}=10^\circ$

We were also interested in evaluating the amount of data that a nanosatellite placed on a polar orbit could transmit at each pass. Table 4.12 presents the amount of data transmitted by a nanosatellite placed at 700 km of altitude and having a minimum elevation angle of 10°. In this case, we have considered a downlink data rate between 9.6 Kbps and 1024 Kbps, which corresponds to the real nanosatellites launched in space. We remark that during a pass (time in view) of 7.6 minutes, the maximum amount of data transmitted by a nanosatellite to a ground station is 5.3 Mbps if a data rate of 1 Mbps is considered. For a low downlink rate (9.6 Kbps), the nanosatellite will be able to transmit only 51 Kbps on each pass over the ground station.

Data rate (Kbps)	Data quantity (Kbps)
9.6	51.11
16	84.03
32	168.06
64	336.12
128	672.25
256	1344.51
512	2689.02
1024	5378.04

Table 4.12 – Amount of data transmitted at each nanosatellite pass (altitude=700 km,  $\varepsilon_{min}=10^\circ$ )

#### 4.2.4.2 SaVi simulations of NanoICE constellations

Figure 4.15 shows a sinusoidal view of NanoICE constellation which provides coverage for the area situated between 70° S latitude and 90° S latitude, and 70° N latitude and 90° N latitude respectively.



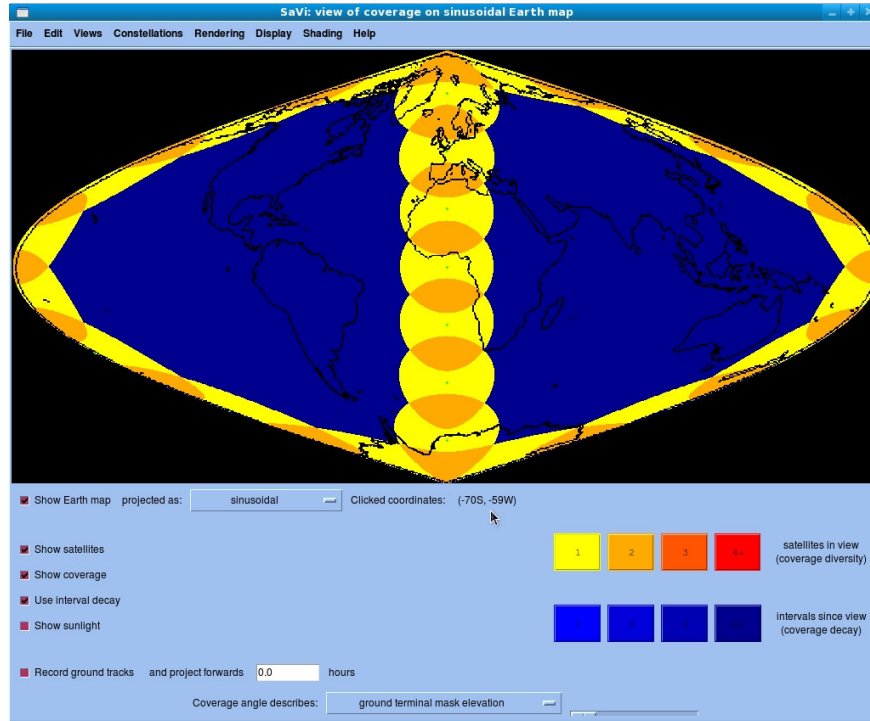


Figure 4.15 – Polar constellation of 15 nanosatellites (altitude: 700 Km,  $\epsilon_m=10^\circ$ )

## 4.2.5 NanoSPHERE results

This chapter presents numerical calculations and SaVi simulations for NanoSPHERE constellations. NanoSPHERE is a Walker-type constellation model that we propose in order to achieve global, permanent and homogeneous coverage of the Earth’s surface. We envisaged that coverage extension will be needed in the scenario of an increasing demand of telecommunications services by some industrial companies in charge of mineral resources exploitation in different remote regions of the Earth.

### 4.2.5.1 Numerical calculations for NanoSPHERE constellation

Table 4.13 summarizes NanoSPHERE constellation parameters calculated for three type of altitudes based (800 km, 1000 km, 1500 km), by varying the minimum elevation angle from  $5^\circ$  to  $30^\circ$ .

$\epsilon_{\min}(\circ)$	h=800 km			h=1000 km			h=1500 km		
	$n_p$	$n_m$	$N_n$	$n_p$	$n_m$	$N_n$	$n_p$	$n_m$	$N_n$
5	9	5	45	5	8	40	4	7	28
10	10	6	60	5	9	45	4	8	32
15	12	7	84	6	11	66	5	9	45
20	14	8	112	7	12	84	5	10	50
25	17	9	153	8	14	112	6	11	66
30	20	10	200	9	17	153	7	13	91

Table 4.13 – NanoSPHERE constellations parameters

Based on Table 4.13, some interesting variation could be noted:

- for the same altitude, the number of nanosatellites increases as the minimum elevation angle increases;
- for the same elevation angle, the number of nanosatellites decreases as the constellation altitude increases.

Considering these two observations and the fact that for higher altitudes, the footprint of each nanosatellite becomes bigger, we chose the altitude constellation of 1500 km.

Our goal is to minimize the number of nanosatellite in the constellation and maximizing the time in view. The constellation which satisfies these requirements is constituted of 45 nanosatellites, distributed in 5 orbital planes, with 9 nanosatellites per plane. We assumed that a minimum elevation angle of 15° is enough to assure an adequate coverage.

Furthermore, a variety of perturbations acts on the nanosatellites, the most significant being the atmospheric drag. All these perturbations tend to alter the relative positions of nanosatellites in the constellation. Therefore, some constellation maintenance strategies are necessary for maintaining the desired constellation pattern. Most of these strategies rely on on-board propulsion resources for occasional boosts, each time adding energy to the orbit in order to counteract the atmospheric drag effect. Atmospheric drag removes energy from the orbit, thus slowly decreasing the altitude of nanosatellites. Additionally, as the altitude decreases, the atmospheric drag effect on nanosatellites increases. Considering the very limited power and propulsion resources of nanosatellites, a high altitude is desirable for nanosatellite constellations for not spending a lot of power constellation maintenance maneuvers.

Moreover, NanoSPHERE constellation neglects polar coverage. The NanoICE model is specifically designed for polar region coverage. NanoSPHERE constellation provides the highest degree of coverage at the mid-latitudes. However, the number of nanosatellites per plane depends on the altitude. It decreases when the altitude increases in order to maintain global coverage. This is another reason for justifying our choice in terms of constellation altitude.

<b><i>Number of nanosatellites (<math>N_n</math>)</i></b>	45
<b><i>Number of orbit planes (<math>n_p</math>)</i></b>	5
<b><i>Number of nanosatellites per orbital plane (<math>n_m</math>)</i></b>	9
<b><i>Pattern unit (<math>q</math>)</i></b>	8°
<b><i>Phase difference between adjacent planes (<math>\Delta\Phi</math>)</i></b>	24°
<b><i>Constellation altitude (<math>h</math>)</i></b>	1500 km
<b><i>Inclination angle of orbital planes (<math>i</math>)</i></b>	65°

*Table 4.14 – Optimal NanoSPHERE constellation parameters*

As depicted in Table 4.14, NanoSPHERE constellation contains a total number of 45 nanosatellites with 9 nanosatellites evenly distributed in 5 orbital planes. The orbital planes in NanoSPHERE constellation have ascending nodes that are evenly distributed around the equator at intervals of 72°. Each nanosatellite in the orbital plane is uniformly distributed on intervals of 65° and each orbital plane has the same inclination (65°) with respect to the

equatorial plane. NanoSPHERE constellation emphasize symmetry thus, there are 9 uniformly distributed nanosatellites per plane. The pattern unit is  $8^\circ$  and in-plane spacing between nanosatellites is  $40^\circ$ . The phase difference between adjacent planes is  $24^\circ$ .

The even spacing of the right angles of the ascending nodes across the full  $360^\circ$  of longitude means that ascending and descending planes of nanosatellites and their coverage continuously overlap.

#### 4.2.5.2 SaVi simulations of NanoSPHERE constellations

This sub-chapter presents SaVi simulations for NanoSPHERE constellation. Figure 4.16 is a SaVi view of NanoSPHERE constellation of 45 nanosatellites placed at 1500 km of altitude and having a minimum elevation angle of  $15^\circ$ . NanoSPHERE constellation coverage, represented in yellow/red shades, shows the number of nanosatellites visible from a point on the Earth surface. The deeper shade of red means that there are a high number of nanosatellites covering a certain point on the Earth surface. We also used the « ground terminal mask elevation » option to see the maximum coverage of every nanosatellite.

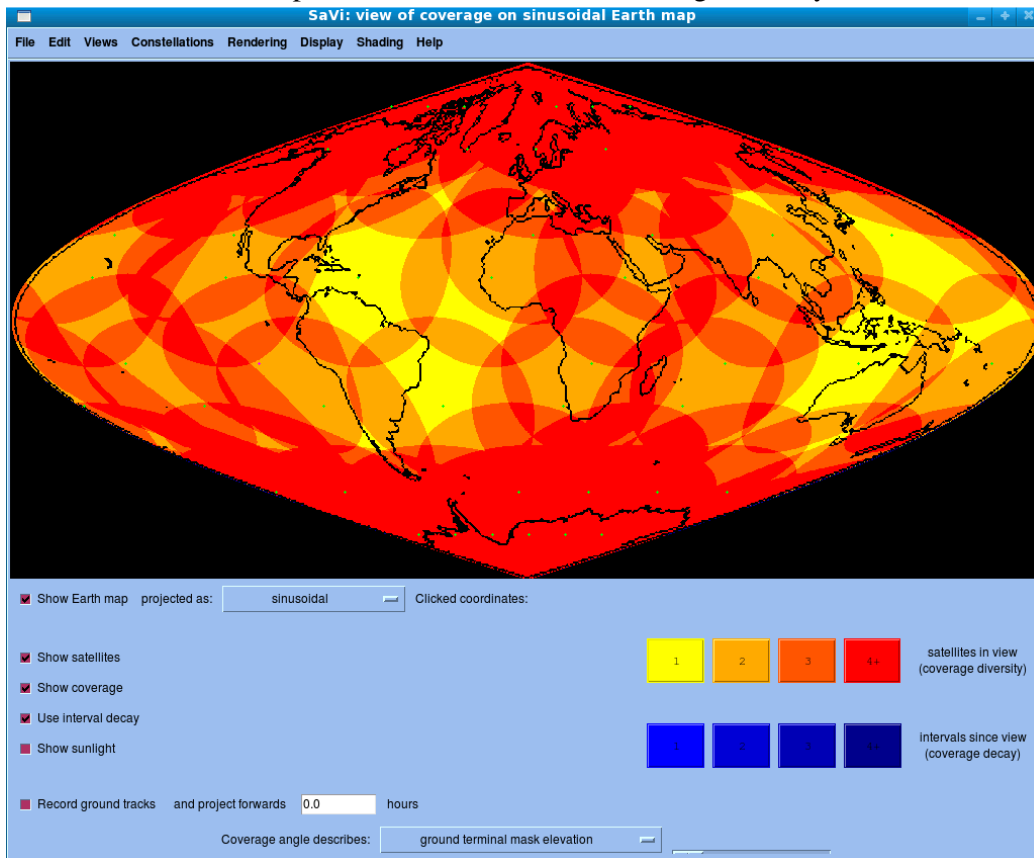


Figure 4.16 – SaVi view of NanoSPHERE constellation of 45 nanosatellites placed at 1500 km of altitude and having  $\epsilon_{min}=15^\circ$

#### 4.2.6 Simulation results of ground segment architecture for Salar de Uyuni Desert mission

This chapter presents simulation results issued from testing our ground segment architecture envisaged for a lithium exploitation region. This architecture is an Ad hoc network, based on wireless technology, as described in Chapter 3. The simulations were done using OPNET modeler. For conducting simulations on our ground segment wireless-based network, we considered AODV (Ad hoc On-Demand Distance Vector) protocol, as explained in Chapter 3.3.2.

Taking into considerations the lithium plant architecture and the personal needs in terms of communications, we used six access points for an optimal coverage of the exploitation area. Figure 4.17 illustrates location of routers within the plant.

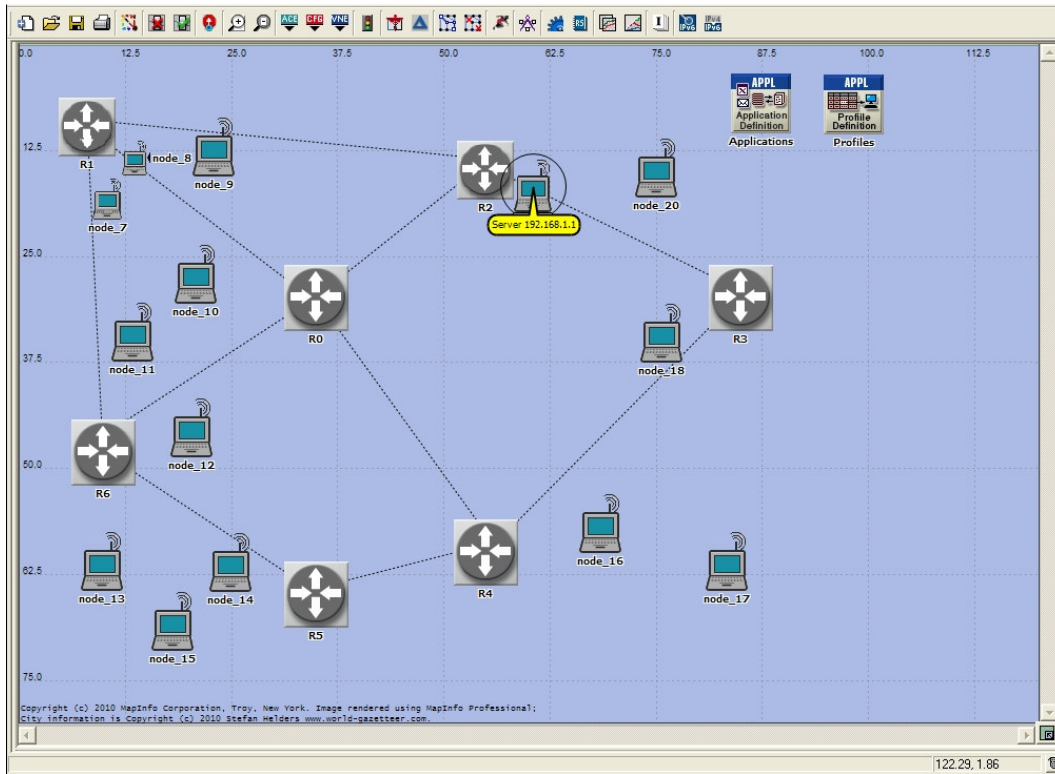


Figure 4.17 – Routers placing into the plant

Every router corresponds to one building and the laptops represent the users who access the network. A dedicated computer was considered as server for which we assigned the IP address 192.168.1.1. We configured every computer and every router so that they inter-communicate, thus creating a wireless mesh network. To accomplish this objective, we modified the AODV protocol settings so that it corresponds to our architecture. Thus, we defined two new wireless interfaces for every router and we added directional antenna for inter-routers links.

In a plant, most buildings have metal walls, this being an important source of interferences on which wireless networks are very sensitive. In order to reduce the interferences and for a more reliable communication, it is advisable to use directional antennas.

Because OPNET modeler does not dispose of directional antennae model implementations, we create our own antenna model with a maximum gain of 17 dB, by using the module available for creating antennas. Figure 4.18 shows the antenna model used in our network.

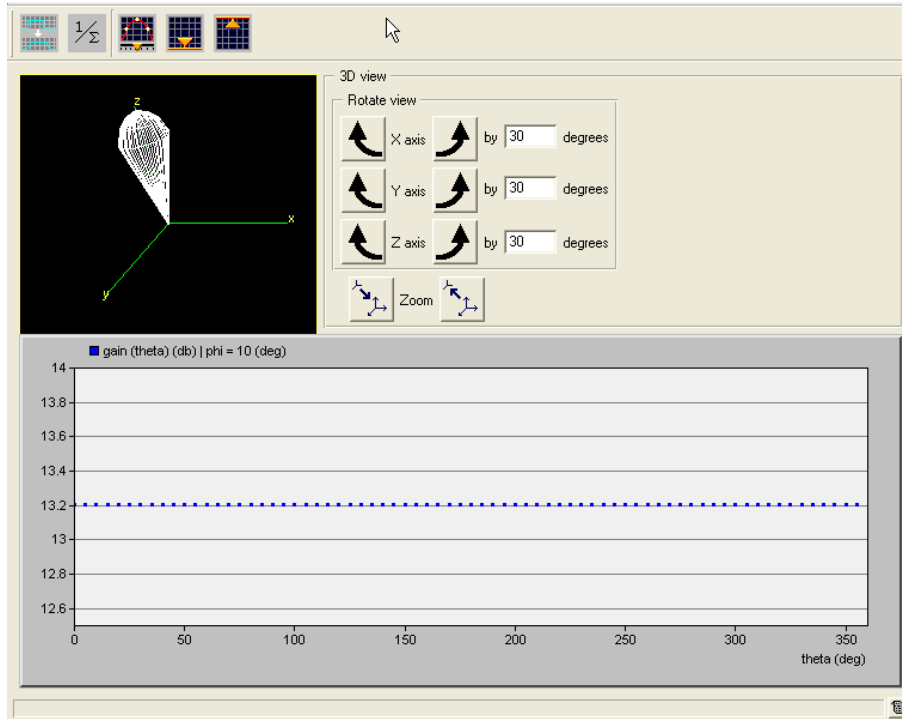


Figure 4.18 – Directional antenna model implemented in OPNET

We have also added a processor module which allows to direct antenna towards the desired router. The logical structure of the modified router is presented Figure 4.19.

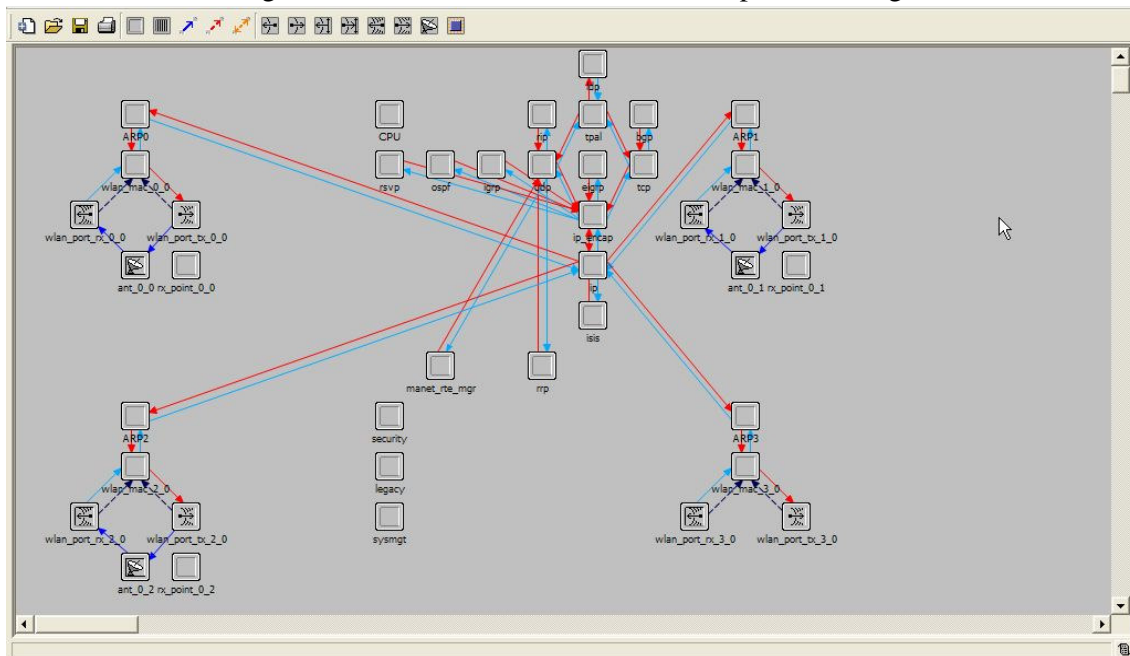


Figure 4.19 – Router configuration

All computers were configured to generate traffic towards the server (IP: 192.168.1.1). The time interval of every simulation is 60 minutes.

According to the Figure 4.20, there are not significant losses over the network, almost all traffic generated being received by the destination node.

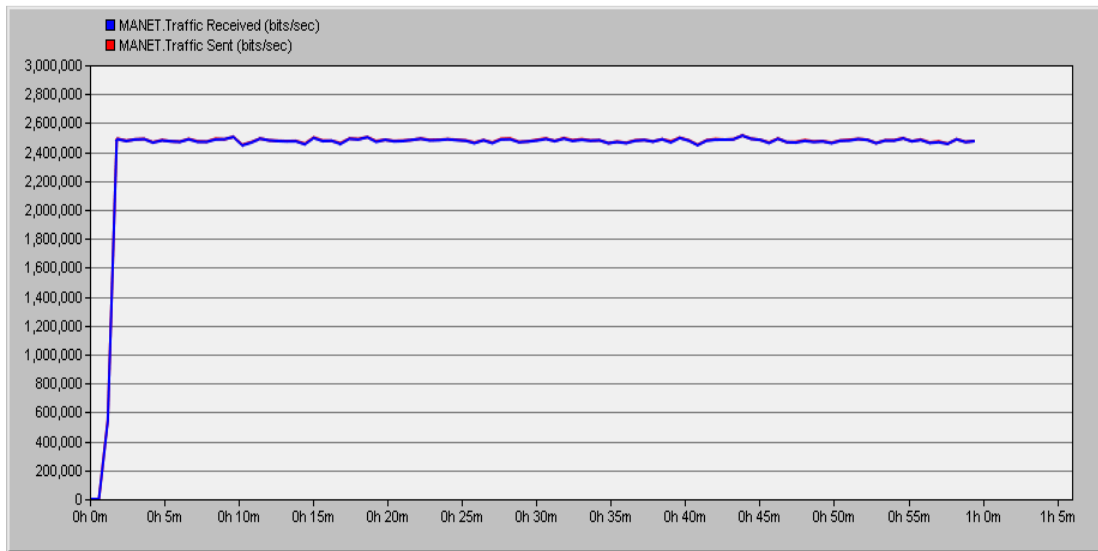


Figure 4.20 – Global traffic variation over the network

An important parameter to consider in our survey is the delay between the computers and the server. As depicted in Figure 4.21, the maximum end-to-end delay is 30 ms, this value being attained after few minutes of network simulation. Furthermore, the delay recorded for computers which are closer to the server, is even smaller (5 ms). Considering this, we can conclude that our network can support VoIP traffic.

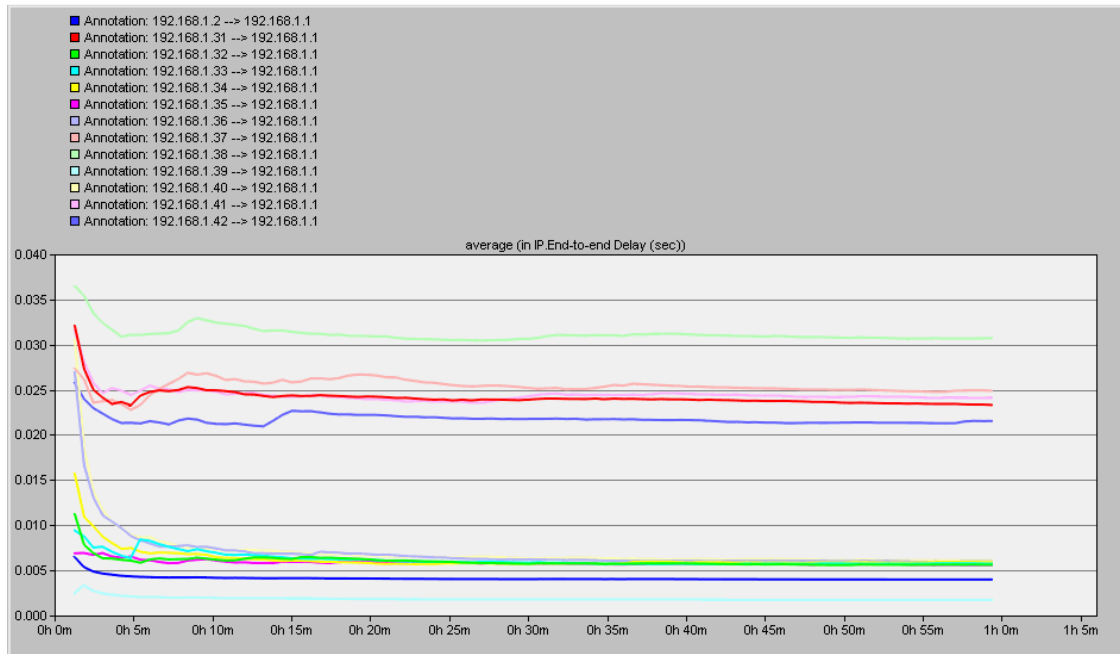


Figure 4.21 – End-to-end delay over the ground segment network

Another important aspect is the effective throughput that can be attained in this network. According to the Figure 4.22, the maximum effective throughput is 2.8 Mbps, which is a good value compared to real nanosatellite uplink and downlink rates, that are considerable much smaller (i.e., uplink = 9.6 bps; downlink = 32 – 256 Kbps, 1 Mbps theoretically).

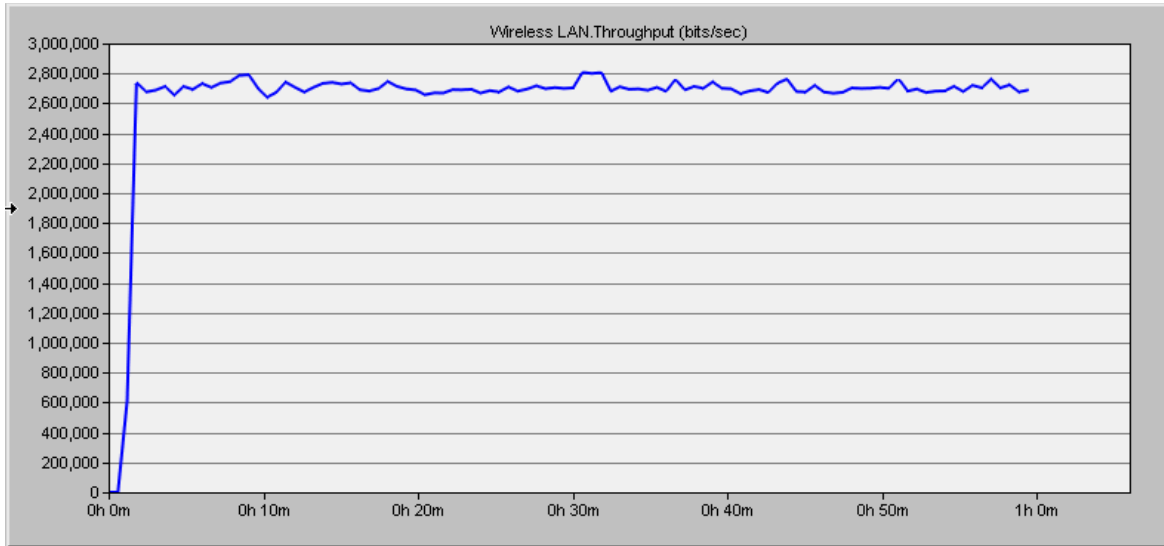


Figure 4.22 – Effective throughput over the network

As regards to AODV protocol, the global resources used during packet routing are very modest compared to maximum effective throughput attained in this network. As shown in Figure 4.23, the maximum bandwidth used by AODV protocol is only 9 kbps.

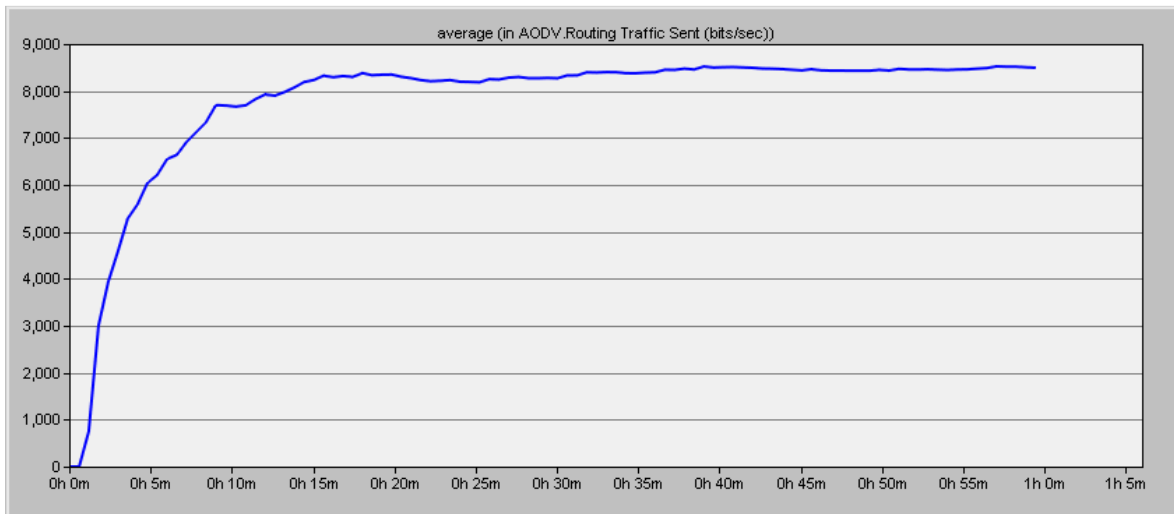


Figure 4.23 – AODV routing traffic

Our OPNET simulations show that this Ad hoc network proposed for a lithium exploitation plant of Salar de Uyuni Desert is suited for telecommunications throughout a nanosatellite network, by providing an effective throughput superior to nanosatellite uplink and downlink rates.

## 4.3 Simulation study of XSTP protocol

This chapter presents and discusses the NS2 simulations conducted for evaluating XSTP performance over satellite and nanosatellite networks respectively. Firstly, the simulation environment is presented along with simulation scenarios and XSTP software implementation solution. Then, we describe the simulation network topologies that were implemented in NS2 modeler. Since QoS aspect is an important focus of this thesis, we defined in this chapter several QoS performance metrics, such as effective throughput, transmission overhead, channel efficiency and reverse channel utilization. Thus, the XSTP performance is assessed with respect to QoS metrics and for every type of network (i.e., satellite, nanosatellite). The XSTP performance comparison between satellite network and nanosatellite network concludes this chapter.

### 4.3.1 Simulation environment (NS-2)

NS2 is a discrete event network simulator, developed by Berkeley University, which was initially designed for IP network simulations, but it is constantly enriched by new models: satellite, Ethernet, mobiles, etc. NS2 provides substantial support for simulation of TCP, routing, and multicast protocols.

NS2 is an object-oriented simulator, written in C++, with an OTcl interpreter as a front-end. The simulator supports a class hierarchy both within C++ (compiled hierarchy) and within OTcl interpreter (interpreted hierarchy). These two hierarchies are inter-related which means that, from the user's point of view, there is one-to-one correspondence between a class in the interpreted hierarchy and one in the compiled hierarchy.

NS2 includes different transport protocols. The most important is TCP and its "clones" which is implemented as an agent (Agent/TCP). The most general implementation of TCP is "Tahoe" version of a uni-directional connection. Some specific derivations are the "Reno" and "NewReno" agents (with two different versions of fast recovery), the "Sack" agent (with selective repeat), the "Vegas" agent, and the "Fack" agent (with forward acknowledgement). All these agents are one-way sending agents (i.e., they need an appropriate receiving agent at the destination node).

The most general TCP sink is implemented in Agent/TCPSink. To achieve more specific behavior, some subclasses are defined: the selective acknowledgement sink TCPSink/Sack1 and TCPSink/DelAck and TCPSink/Sack1/DelAck respectively for a configurable delay per acknowledgement.

Another feature of NS2 is asymmetric links support. Thus, TCP/Asym ("tahoe"), TCP/Reno/Asym ("Reno") and TCP/NewReno/Asym ("NewReno") agents are sending their packets to the TCPSink/Asym agent.

Installation guides, documentation and configuration aspects are founded on web links [115] and [116].

In order to analyze XSTP protocol performance, two new simulation modules for STP and XSTP were implemented in NS2. Also, a satellite network module and a nanosatellite constellation module were created. These modules enable NS2 to model a traditional LEO



satellite network and a LEO, equatorial nanosatellite constellation. Additionally, we have used TCP modules corresponding to common variants of TCP (e.g., New Reno, Reno, SACK, Tahoe, Vegas) in order to make a comparison study between these TCP “clones” and XSTP.

### 4.3.2 Simulation scenarios and XSTP implementation solution

Using simulation, XSTP-probing mechanism is tested in various error conditions and performance is quantified.

We defined two scenarios – one-way communication, aiming to meet symmetric channel, and bidirectional communication for considering asymmetric channel. Each time, we quantify the QoS metrics defined in Chapter 4.2.2.3.

XSTP protocol is a derived class from STP class, the latter being derived from transport Agent class. Firstly, TCP like congestion mechanism is implemented. Then, we extended STP to XSTP by implementing the probing mechanism, described in Chapter 2.4.4.2, with three configuration parameters:

- Maximum number of trackable probe exchanges (MAX\_PROB);
- Number of requested probe exchanges (REQ\_PROB);
- RTT tolerance ratio (RTT\_TOL).

The simulation configuration consists of two network nodes: source node and destination node. In the first scenario, the destination node is considered as a well of data, while in the second one, both endpoints are going to play the role of transmitter / receiver at the same time.

As Figure 4.24 shows, we attach an XSTP agent to the source node and a STPSink agent to the destination node. Because an XSTP agent does not generate application data, we connected it to a FTP traffic generator so that we can send large data packets.

By using a background HTTP traffic generator, HTTP traffic is added for emulating the current use of WWW. The purpose was not to block the network, but to add a variability component to simulation.

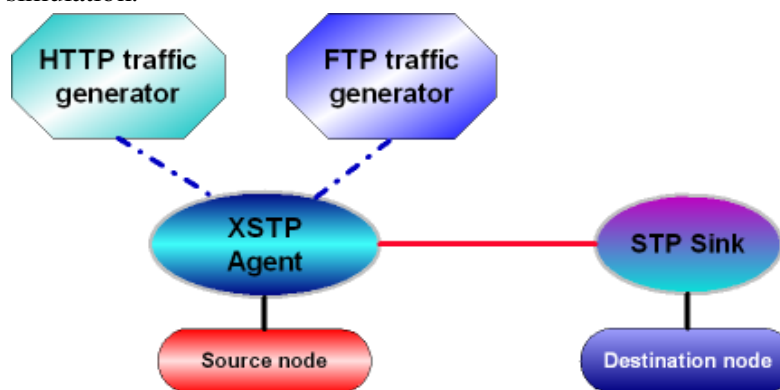


Figure 4.24 – Nodes configuration

Firstly, the files *stp.h*, *stp.cc*, *xstp.cc* and *stp-sink.cc* have been added to STP folder. Then, the files *packet.h*, *ns-default.tcl* and *ns-packet.tcl* were modified in order to correspond to our simulation configuration.

In the *packet.h* file from *common* folder, the new types of packets specific to STP and XSTP need to be defined:

```
PT_SD
PT_POLL
PT_STAT
PT_USTAT
```

Then, a name was associated for every packet type as follows:

```
name_[PT_SD]="sd";
name_[PT_POLL]="poll";
name_[PT_STAT]="stat";
name_[PT_USTAT]="ustat";
```

Furthermore, the file *ns-packet.tcl* from *tcl/lib* path is modified by adding the name of every new package:

```
SD
POLL
STAT
USTAT
```

Lastly, we have included in *ns-default.tcl* file, the configuration parameters for *stp.cc* sender class and *stp-sink.cc* receiver class:

```
Agent/STP set window_ 20           # sender window size
Agent/STP set windowInit_ 1        # initial congestion window size
Agent/STP set packetSize_ 1000     # packet size
Agent/STP set poll_interval_ 0.2   # time interval between POLL messages
Agent/STP set initial_rtt_ 0.08    # initial RTT
Agent/STPSink set win_ 100         # receiver window size
```

The size of packages sent by the source node is 1000 bytes. The size of receiver's window is fixed to 100 and the initial size of transmitter's congestion window is 1. The maximum number of trackable probes is set to 4, and the number of consecutive RTT measurements sufficient to finish the probing cycle is set to 2. The polling frequency is set to 3 per RTT, and when the probing mechanism is triggered, the polling rate becomes 1 per RTT. The duration of every simulation is 60 seconds. For traditional satellite network simulations, BER varies between  $10^{-8}$  and  $10^{-3}$ , while for nanosatellite model simulations, we consider a BER interval of  $[10^{-7}, 10^{-3}]$ .

Due to the random behavior of the Web traffic, every simulation is repeated four times and the final results are calculated by making the average between the intermediate simulation results.

Table 4.15 summarizes the simulation parameters.

<i>Parameter</i>	<i>Value</i>
<b>Sender buffer size</b>	<b>64 Kb</b>
<b>Receiver buffer size</b>	<b>64 Kb</b>
<b>MSS (maximum segment size)</b>	<b>1000 bytes</b>
<b>Maximum window size</b>	<b>64 segments</b>
<b>Sender's initial congestion window</b>	<b>1 segment</b>
<b>Maximum burst size</b>	<b>8 segments</b>
<b>Initial RTT</b>	<b>0.08 s</b>

*Table 4.15 – NS2 simulation parameters*

For describing a network and its associated traffic, we need to define in order:

- 1) network topology (nodes and arcs);
- 2) transport layer (TCP, STP, ...) between nodes pairs;
- 3) application layer which supplies user data;
- 4) timers that specify the moments at which transmission is going to start.

Below, we describe in details every step of the network implementation procedure.

We start by creating a simulator in an OTcl file (file\_name.tcl):

```
set ns [new Simulator]
```

We define two files that will preserve the simulation's history, as follows:

```
set f [open out.tr w]
```

```
$ns trace-all $f
```

```
set nf [open out.nam w]
```

```
$ns namtrace-all $nf
```

Then, we create the network topology (the nodes and the links), by specifying their rate and delays, the drop technique (in our case, *DropTail*) and the maximum number of packets in the queue.

```
set n1 [$ns node]
```

```
# creating first node
```

```
set n2 [$ns node]
```

```
# creating second node
```

```
$ns duplex-link $n1 $n2 2Mb 5ms DropTail # creating the link between the nodes
```

```
$ns queue-limit $n1 $n2 100
```

```
# queue limit
```

Satellite network parameters are implemented as follows:

```
set opt(inc) 0;
```

```
# orbit inclination angle.
```

```
set opt(alt) 1500;
```

```
# altitude
```

Also, the transport agents have been created, attached to nodes and inter-connected.

Among available agents, we could mention: *Agent/Null*, *Agent/XSTP*, *Agent/TCP* and *Agent/STPSink*. The associated code has the following syntax:

```
set xstp1 [$ns _create-connection XSTP $node_(n1) STPSink $node_(n2) 0]
```

```
$xstp1 set window_200
```

The third step defines the application layer that is the traffic sources. In our scenario, we use as data source, a HTTP traffic generator.

```
Source httpModel.tcl
```

```
# class definition file
```

```
Set ftp1 [$xstp1 attach-source FTP]
```

```
# attaching data source generator to transport agent
```

```
$ns_ at 0.0 '$ftp1 start'
```

```
# starting the source generator
```

### 4.3.3 Simulation network topologies

The conventional satellite network and the nanosatellite network considered in our simulations are shown in Figure 4.25 and Figure 4.26 respectively.

The first one is based upon the LEO satellite constellation proposed by Teledesic [117], [118] because the specifications of this system are well documented in the literature. Teledesic network uses a “geodesic” or mesh network topology.

The second one corresponds to the best nanosatellite constellation identified in Chapter 4.1.3 using SaVi simulations. Precisely, the constellation of 9 nanosatellite placed at 1500 km of altitude, having a minimum elevation angle of 15° was implemented in NS2 modeler in order to evaluate the performance of XSTP protocol over this type of network. We assumed a mesh solution for our nanosatellite network because it is the ideal topology for voice and data when direct communication from any site to any site in the network is required. Thus, this solution is suited for providing communications over a lithium exploitation plant in Salar de Uyuni Desert.

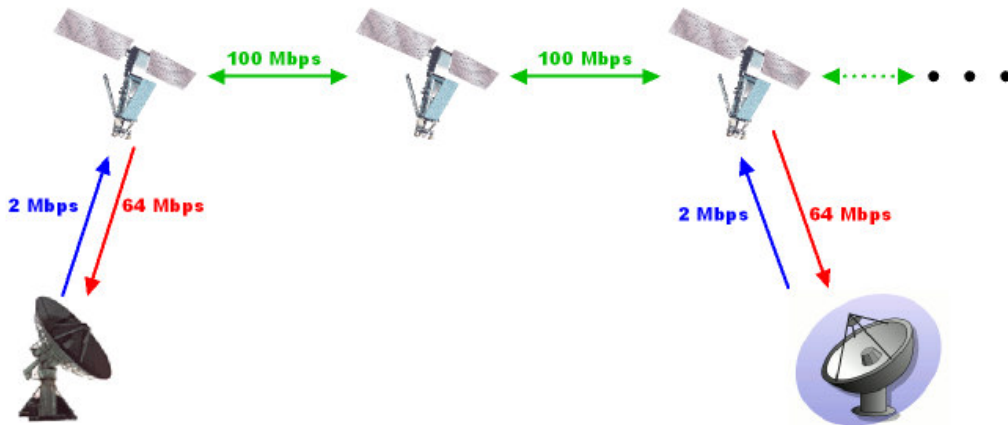


Figure 4.25 - Satellite network topology

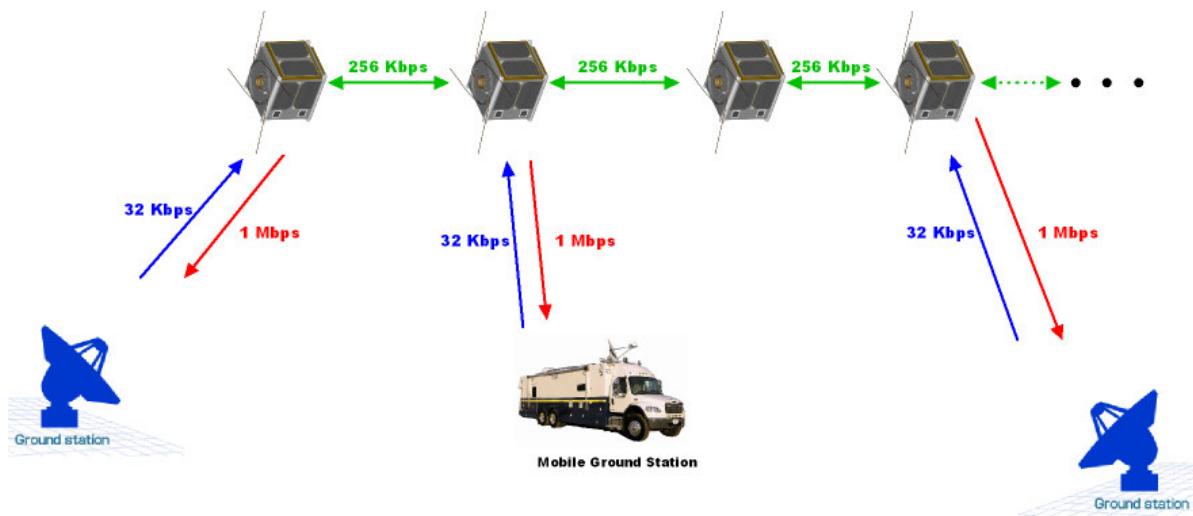


Figure 4.26 – Nanosatellite network topology

Table 4.16 presents the main parameters for conventional satellite network and nanosatellite constellation, while Table 4.17 summarizes data link parameters.

<i>Parameter</i>	<i>Satellite network</i>	<i>Nanosatellite constellation</i>
Constellation nominal altitude	1375 km	1500 km
Number of satellites within the constellation	288	9
No. of planes	12	1
No. of satellites/plane	24	9
Planes separation distance in altitude	2 km	-
Nominal inclination angle	84.7 °	0°
Minimum Earth elevation angle	40°	15°
Orbital period	113.25 min	115.98 min

Table 4.16 – Space segment parameters

<i>Parameter</i>	<i>Satellite network</i>	<i>Nanosatellite constellation</i>
Uplink frequency	28.6 - 29.1 GHz	VHF, UHF
Downlink frequency	18.8- 19.3 GHz	S band (2-4GHz)
Uplink data rate	2 Mbps	32 Kbps
Downlink data rate	64 Mbps	1 Mbps
Inter-satellite link (ISL) rate	100 Mbps	256 Kbps
ISL propagation delay	10 ms	50 ms
Ground-to-satellite link propagation delay	5 ms	15 ms

Table 4.17 – Data link parameters

#### 4.3.4 QoS performance metrics

The data transmitted in a nanosatellite system has certain transfer requirements, or Quality of Service (QoS) parameters. In this thesis, we defined, based on paper [94], four QoS parameters: effective throughput, transmission overhead, channel efficiency and reverse channel utilization.

- **Effective throughput** is defined as the average data rate (bps) as seen by the data link session and it is calculated as follows:

$$Effective\ throughput = \frac{original\ size}{simulation\ time} \quad (4.1)$$

**Transmission overhead** is defined as the percentage of extra bytes expended in the reliable transmission of the original data bytes. The overhead is important to compare the scalability of the protocols and their way of adapting to low-bandwidth environments. It is also a measure to evaluate protocol efficiency in relation to nanosatellite battery power, as sending more packets consumes more power. Furthermore, sending more data increases the probability of packet collision and can delay data packets in the queues. The transmission overhead is calculated, in %, using the following formula:

$$Transmission\ overhead = \frac{Total\ size - Original\ size}{Original\ size} \times 100 \quad (4.2)$$

- **Channel efficiency** describes how the channel is used during data transmission process. It is defined as the ratio between the packet original size and the total size of transmitted data:

$$\text{Channel efficiency} = \frac{\text{Original size}}{\text{Total size}} \quad (4.3)$$

- **Reverse channel utilization** describes the backwards channel utilization. It shows the protocol efficiency on asymmetric links where the bandwidth is not the same in both directions. It is calculated using the following formula:

$$\text{Reverse channel utilization} = \frac{\text{Backward original size}}{\text{Simulation time}} \quad (4.4)$$

#### 4.3.5 NS2 simulation results for conventional satellite network

In this sub-chapter, simulation results for conventional satellite network are reported and discussed. Also, we were interested to compare XSTP performance to some TCP clones, in case of a high BER environment. Table 4.18 presents the best performance protocol, the worst performance protocol and TCP clone's best performance in terms of: effective throughput, transmission overhead, channel efficiency and reverse channel utilization. The main aim of our simulations is to see how the protocols perform in very high BER conditions ( $10^{-4}$ – $10^{-3}$ ). Therefore, we insist on pointing out the parameters values for high BER environment.

Scenario		Effective throughput	Transmission overhead	Channel efficiency	Reverse channel utilization
One-way transmission	Best protocol	XSTP 1402 Kbps, BER= $10^{-7}$ 68.49 Kbps, BER= $10^{-3}$ 391.85 Kbps, BER= $10^{-4}$	XSTP 3.63%, BER= $10^{-7}$ 66.36%, BER= $10^{-3}$ 13.82%, BER= $10^{-4}$	XSTP 96.37%, BER= $10^{-7}$ 86.18%, BER= $10^{-4}$	XSTP 8.19 Kbps, BER= $10^{-7}$
	TCP clone best protocol	Sack 1382 Kbps, BER= $10^{-7}$ 120 Kbps, BER= $10^{-4}$	Vegas 4.49%, BER= $10^{-7}$ 16.43%, BER= $10^{-4}$	Vegas 95.51%, BER= $10^{-7}$	Vegas 0.01 Kbps, BER= $10^{-3}$
	Worst protocol	Vegas 0.13Kbps, BER= $10^{-3}$	Vegas 91.27%, BER= $10^{-3}$	Vegas 8.73%, BER= $10^{-3}$	Sack 31.23 Kbps, BER= $10^{-7}$ 0.04 Kbps, BER= $10^{-3}$
Two-way transmission	Best protocol	XSTP 1266 Kbps, BER= $10^{-7}$ 42.59 Kbps, BER= $10^{-3}$ 234.13 Kbps, BER= $10^{-4}$	XSTP 4.2%, BER= $10^{-7}$ 6.59%, BER= $10^{-4}$	XSTP 93.41%, BER= $10^{-4}$	XSTP 7.92 Kbps, BER= $10^{-3}$
	TCP clone best protocol	Sack 1151 Kbps, BER= $10^{-7}$ NewReno 131.07 Kbps, BER= $10^{-4}$	Vegas 4.26%, BER= $10^{-7}$ 9.15%, BER= $10^{-4}$	Vegas 95.74%, BER= $10^{-7}$ Sack 90.85%, BER= $10^{-3}$	Vegas 11.74 Kbps, BER= $10^{-7}$ 2.83 Kbps, BER= $10^{-4}$
	Worst protocol	Vegas 557 Kbps, BER= $10^{-7}$ Sack 1.02 Kbps, BER= $10^{-3}$	Vegas 28%, BER= $10^{-3}$	Vegas 72%, BER= $10^{-3}$	Sack 26.05 Kbps, BER= $10^{-7}$

Table 4.18 – XSTP performance versus TCP clones performance over conventional satellite network

#### 4.3.5.1 One-way transmission scenario

In this scenario, we consider symmetric channels. Figure 4.27 illustrates effective throughput variation with respect to BER. XSTP outperforms all TCP clones mainly due to its probing mechanism. Unlike XSTP, STP and TCP clones reduce their transmission rate at every error detection.

While TCP Sack has a comparative throughput to STP and XSTP (roughly, 1400 Kbps) for low BER, a significant difference is observed as BER increases. As depicted in Figure 4.28, XSTP succeed in offering 4 times more throughput for  $BER=10^{-4}$  with respect to the average value of TCP clones. Additionally, while TCP clones offers almost zero throughput for  $BER=10^{-3}$ , XSTP still has a good level of throughput ( $\approx 70$  Kbps) for the same error conditions.

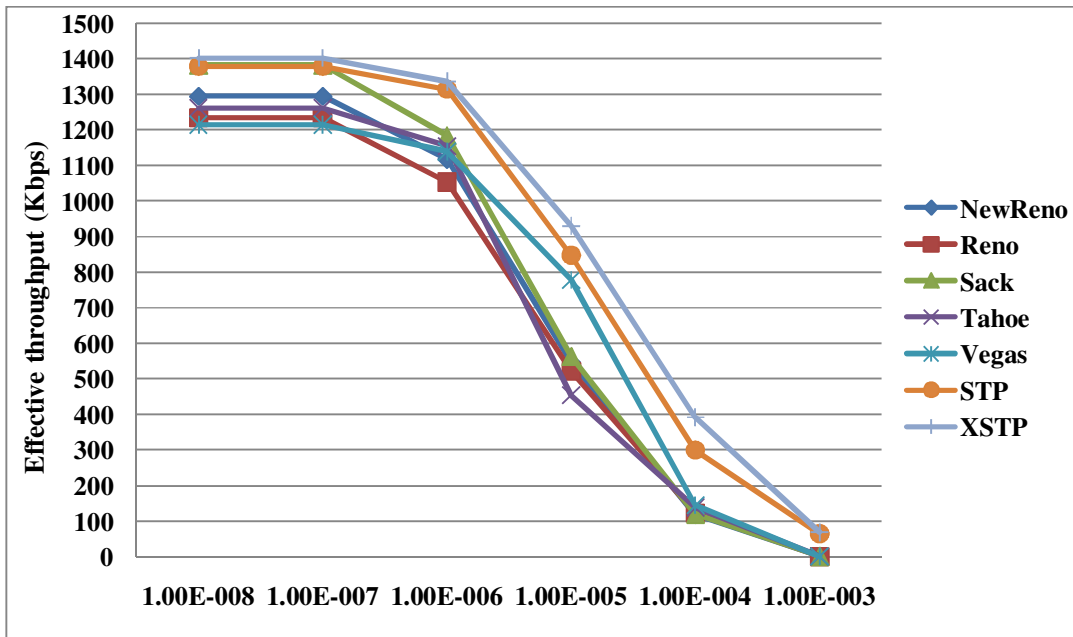


Figure 4.27 – Effective throughput variation for satellite network model (one-way scenario)

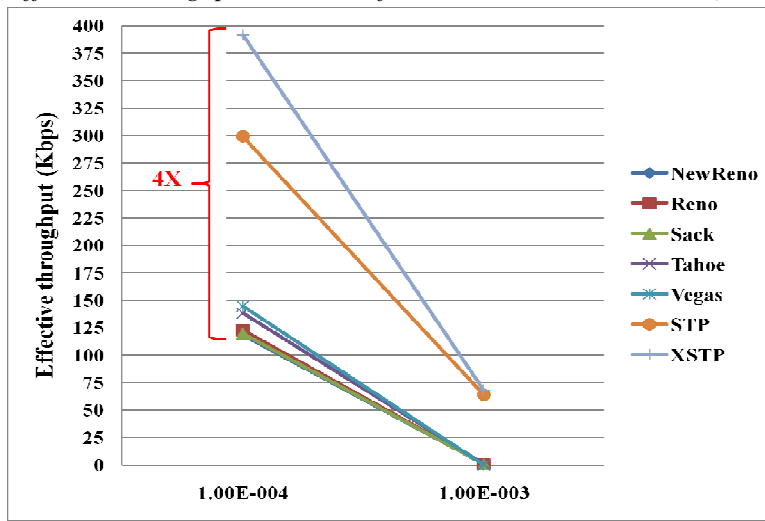


Figure 4.28 – Effective throughput variation for satellite network model (detail for high BER conditions)

Figure 4.29 illustrates transmission overhead variation with respect to bit error rate. We can observe all protocols (excepting Vegas) converge to the same level of overhead in very high BER conditions ( $10^{-3}$ ). Considering this, XSTP works well only for low bit error rates. As seen in Figure 4.30, STP, XSTP and Vegas transmission overhead is two times less than NewReno, Reno, Tahoe and Sack, in case of low BER conditions ( $10^{-8}$ – $10^{-6}$ ).

According to Eq. 4.2 and Eq. 4.3, the overhead test is complement to efficiency test. Unlike efficiency, the overhead increases with BER increasing. During probing cycle, receiver sends one POLL per RTT and stops data transmission in order to avoid data losses. At the end of this cycle and if there is no congestion, sender doesn't reduce its congestion window; thus, it gives user the possibility to send much more data over the network.

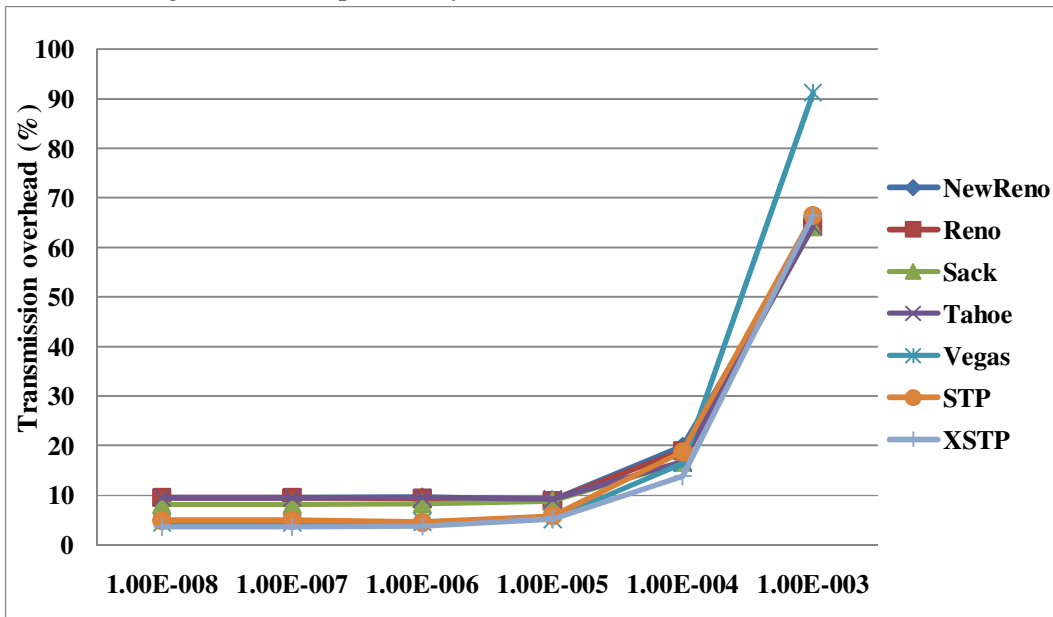


Figure 4.29 – Transmission overhead variation for satellite network model (one-way scenario)

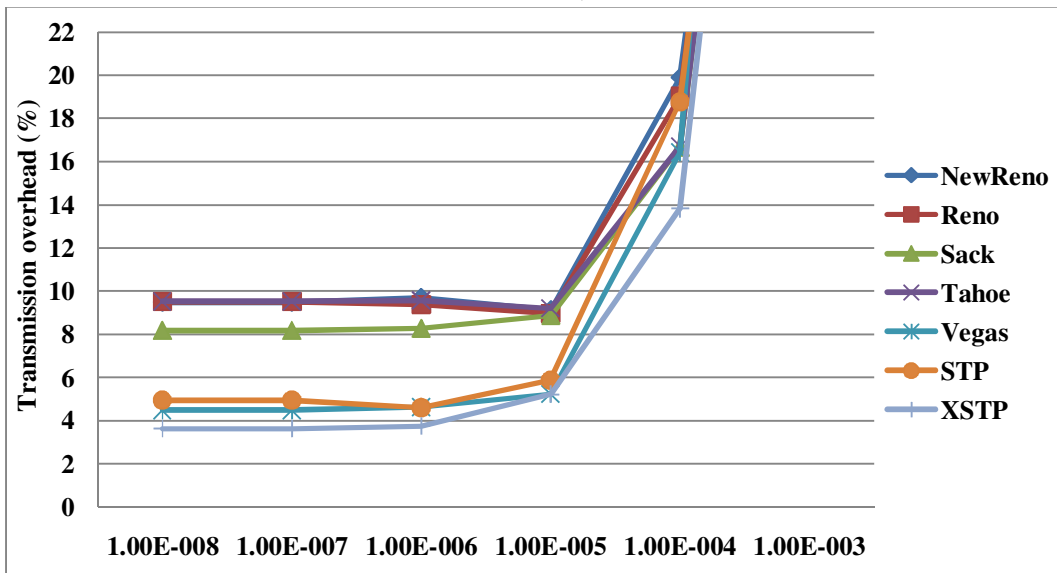


Figure 4.30 – Overhead variation for satellite network model (detail for low BER conditions)



One of the most important aspects in satellite networks is energy consumption. Researchers have always tried to minimize the energy spend by satellites for data transmission.

Channel efficiency metric shows how transmission channel is used. In case of significant amount of data user, efficiency is closed to 1, which means that channel is well used. Contrary, if efficiency is closed to 0, the channel is not well exploited.

According to Figure 4.31, XSTP has roughly the same performance as STP and Vegas, providing 5% higher efficiency than the other protocols, for low BER conditions. For very high BER environment ( $10^{-3}$ ), TCP Vegas attains the lowest channel efficiency (8.73%), which is four times less than the other protocols.

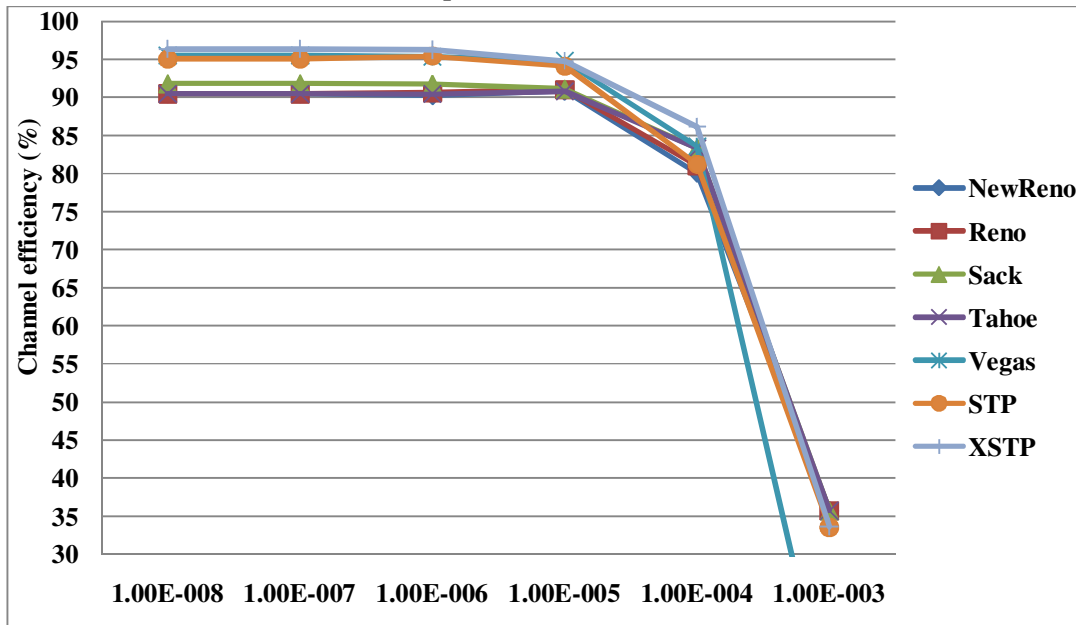


Figure 4.31 – Channel efficiency for satellite network model (one-way scenario)

Generally, reverse channel is used for ACKs transmission. Reverse channel bandwidth varies as a function of the number of ACKs transmitted over the channel, their type and size. It is important to mention that reverse channel bandwidth has to be minimized at the very most due to satellite link asymmetry.

As seen in Figure 4.32, XSTP and STP reverse channel bandwidth increases as BER increases; this means that XSTP needs a low bandwidth for reverse channel. Instead, reverse channel bandwidth for TCP clones decreases with BER increasing. This is explain by the fact that receiver sends one or many ACKs for received data packets. If there are no losses, the reverse channel bandwidth is increasing as many packets are received. Contrary, in high BER conditions, receiver doesn't transmit many ACKs; therefore, reverse channel bandwidth decreases.

Unlike TCP clones, STP and XSTP send STAT and USTAT messages over the reverse channel. When BER is low, receiver sends many small size STAT messages that demand a low reverse channel bandwidth. For high BER, receiver sends many large size USTAT messages that demand a large reverse channel bandwidth.

XSTP needs a lower reverse channel bandwidth than STP because the number of STAT messages transmitted during probing cycle is decreasing as the number of POLL per RTT decreases (1 STAT message per POLL).

In case of STP, the number of POLL per RTT remains unchanged (i.e., 3 POLL per RTT). Because STP doesn't suspend transmission, it sends many USTAT messages even when BER is high.

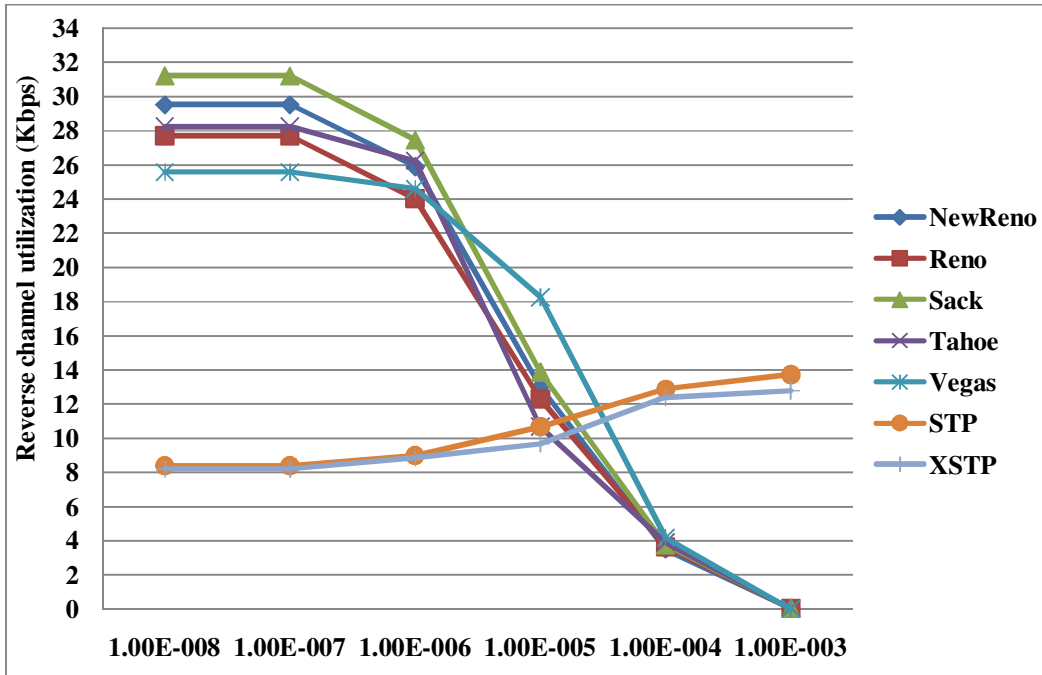


Figure 4.32 – Reverse channel utilization for satellite network model (one-way scenario)

#### 4.3.5.2 Bidirectional transmission scenario

In this scenario, data transmission is made in both ways (a node is sender and receiver too). As compare to one-way communication case, data rate of all protocols decreases because of reverse path transmission.

XSTP effective throughput has a smoothness decrease with respect to one-way scenario results.

As seen in Figure 4.33, XSTP outperforms all the other protocols in case of low BER scenario. Also, XSTP outperforms all TCP clones in case of high BER ( $10^{-4}$ ), by assuring an effective throughput two times more than TCP clones. Even in very high error environment ( $10^{-3}$ ), XSTP provides an acceptable level of effective throughput, while the other protocols have a zero level (Figure 4.34).

We also observed that TCP Vegas is strongly influenced by reverse path transmission, having, even in low BER conditions, a data rate two times less than the other protocols.

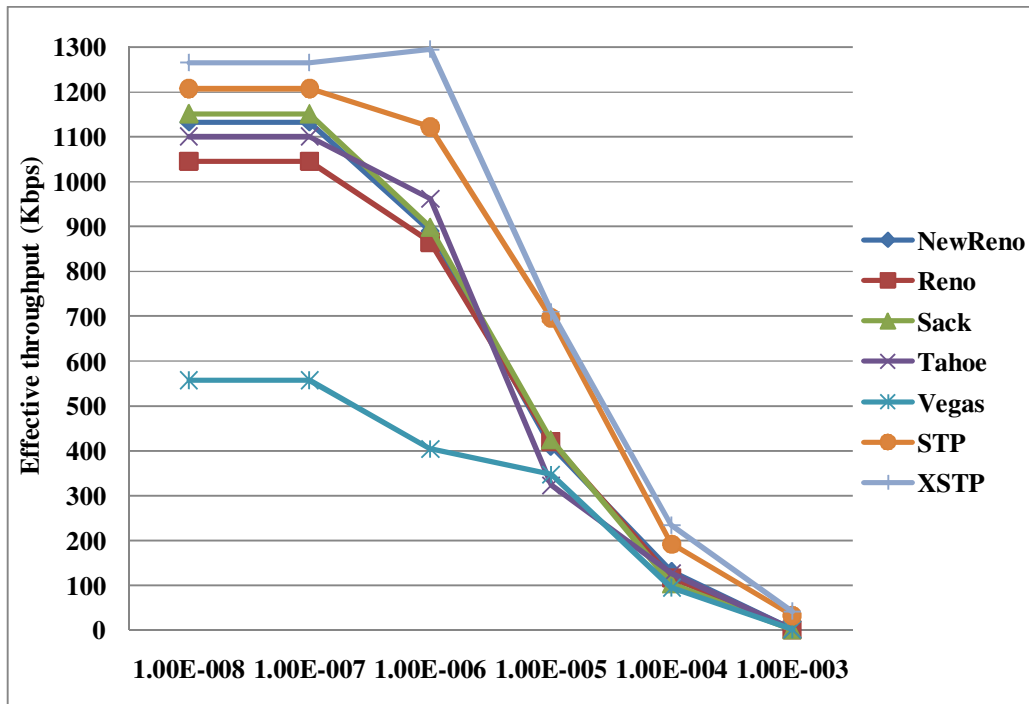


Figure 4.33 – Effective throughput variation for satellite network model (two-way scenario)

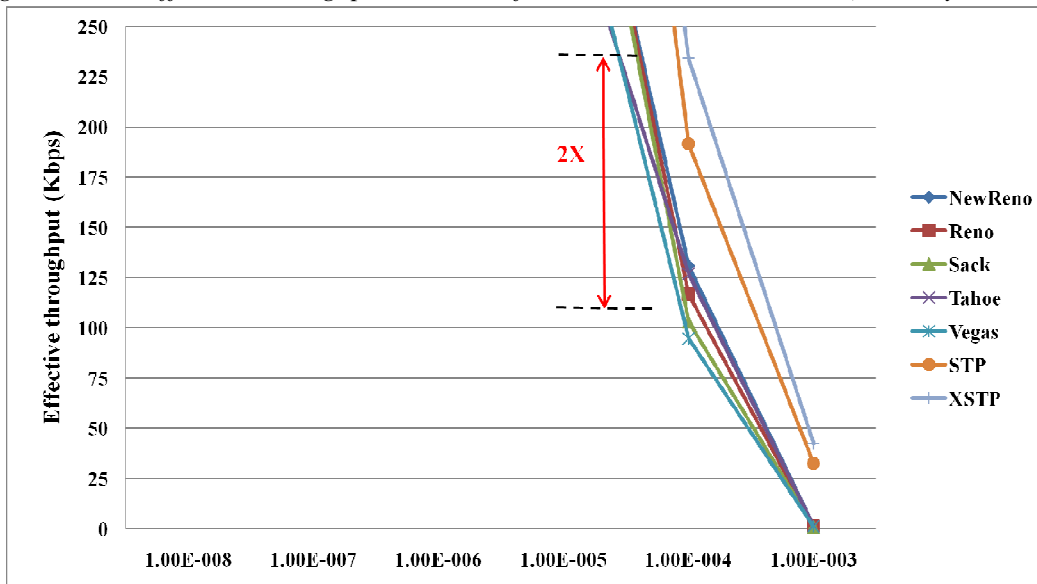


Figure 4.34 – Effective throughput variation for satellite network model (detail for high BER conditions; two-way scenario)

According to Figure 4.29 and Figure 4.35, all protocols provide 3 times less overhead than in one-way scenario, for high BER conditions ( $10^{-4} - 10^{-3}$ ). XSTP, STP and Sack assure two times less overhead than the rest of protocols in low BER conditions.

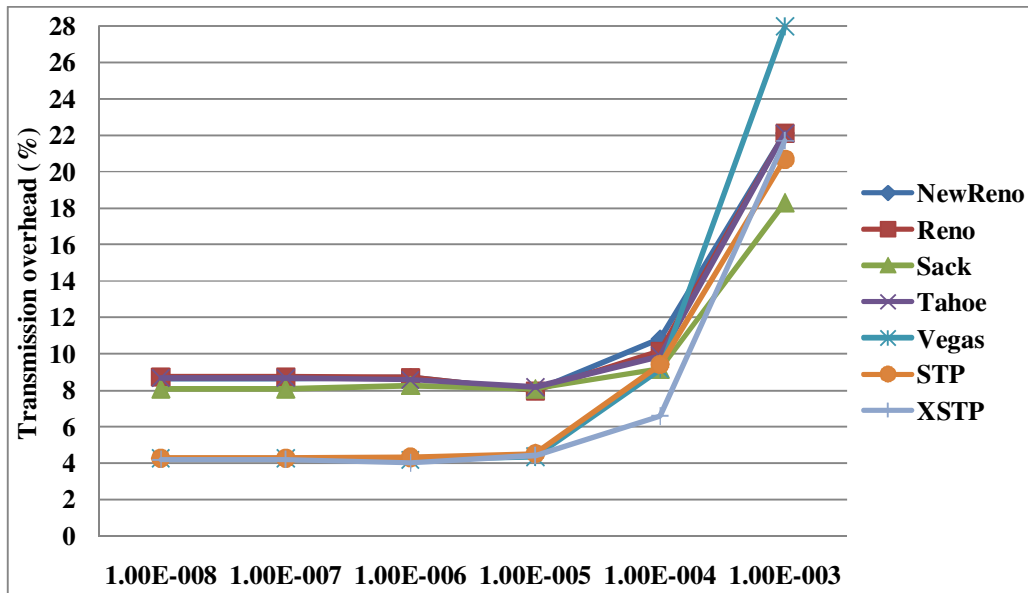


Figure 4.35 – Transmission overhead variation for satellite network model (two-way scenario)

From Figure 4.31 and Figure 4.36, we observe a significant improvement of XSTP efficiency with respect to the first scenario (78% versus 33%), for high BER conditions. TCP clones and also STP attain an efficiency two times higher than in one-way scenario for the same error conditions. As for low BER scenario, all protocols maintain the same level of efficiency as in one-way scenario.

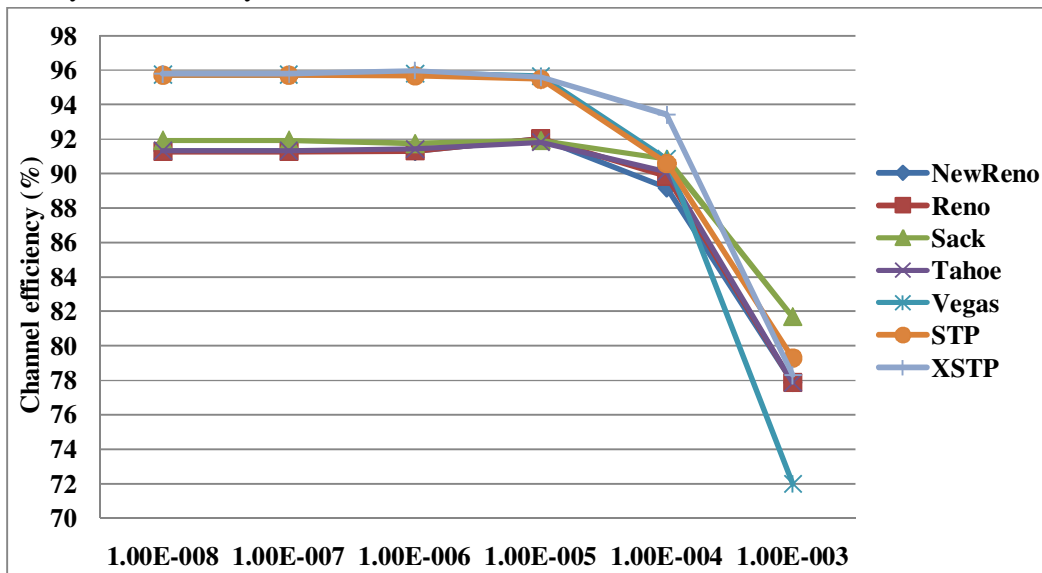


Figure 4.36 – Channel efficiency for satellite network model (two-way scenario)

From Figure 4.32 and Figure 4.37, we observe a small decrease of reverse bandwidth for TCP clones as compared to one-way scenario. TCP Sack still uses a lot of bandwidth for reverse channel. Interestingly, TCP Vegas uses a low reverse channel bandwidth (2.83 Kbps), for high BER conditions, performing much better than STP and XSTP.

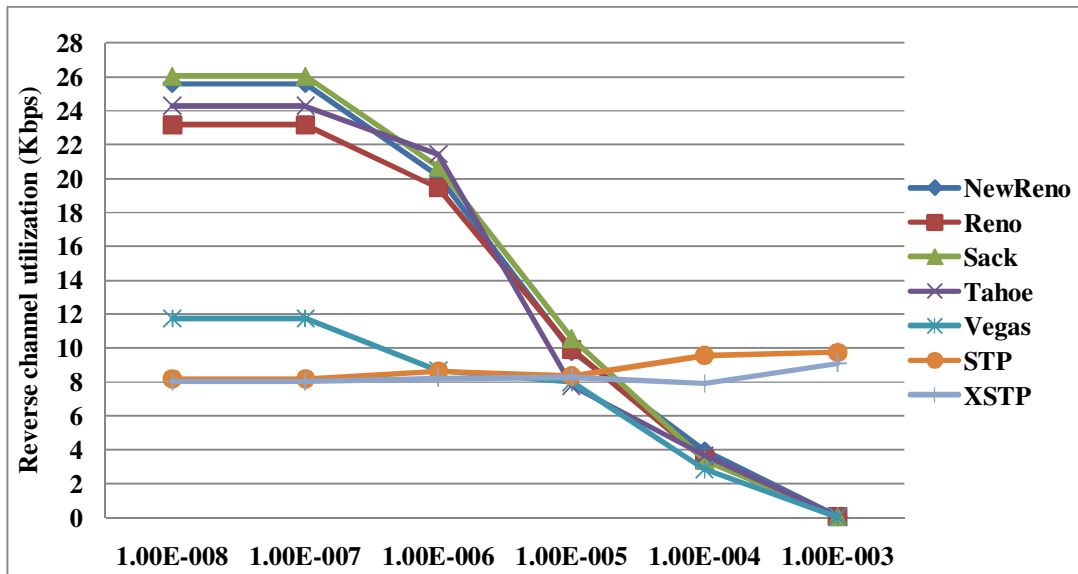


Figure 4.37 – Reverse channel utilization for satellite network model (two-way scenario)

#### 4.3.6 NS2 simulation results for nanosatellite constellation

This chapter presents simulation results for nanosatellite network scenario. Our main interest was to show how protocols behave in high BER environment. Table 4.19 synthesizes the simulation results by pointing out the best performance protocol, the worst performance protocol and TCP clone's best performance in terms of: effective throughput, transmission overhead, channel efficiency and reverse channel utilization.

Scenario		Effective throughput	Transmission overhead	Channel efficiency	Reverse channel utilization
One-way transmission	Best protocol	XSTP 13.5 Kbps, BER=10 <sup>-7</sup> 3.9 Kbps, BER=10 <sup>-4</sup>	XSTP 3.97%, BER=10 <sup>-7</sup> 17.2%, BER=10 <sup>-4</sup>	XSTP 95.5%, BER=10 <sup>-7</sup> 85.32%, BER=10 <sup>-4</sup>	XSTP 0.09 Kbps, BER=10 <sup>-7</sup>
	TCP clone best protocol	Sack 14.4 Kbps, BER=10 <sup>-7</sup> Vegas 1.6 Kbps, BER=10 <sup>-4</sup>	Vegas 4.37%, BER=10 <sup>-7</sup> 19.01%, BER=10 <sup>-4</sup>	Vegas 95.45%, BER=10 <sup>-7</sup>	Reno 0.035 Kbps, BER=10 <sup>-3</sup>
	Worst protocol	Sack 1.13Kbps, BER=10 <sup>-4</sup>	Vegas 84.5%, BER=10 <sup>-3</sup>	Vegas 15.5%, BER=10 <sup>-3</sup>	Sack 0.33 Kbps, BER=10 <sup>-7</sup>
Two-way transmission	Best protocol	STP 13.11Kbps, BER=10 <sup>-7</sup> XSTP 0.63 Kbps, BER=10 <sup>-4</sup>	XSTP 4.32%, BER=10 <sup>-7</sup> 7.95%, BER=10 <sup>-4</sup>	XSTP 95.85%, BER=10 <sup>-7</sup> 89.48%, BER=10 <sup>-3</sup>	XSTP 7.68 Kbps, BER=10 <sup>-7</sup>
	TCP clone best protocol	Sack 12.32 Kbps, BER=10 <sup>-7</sup> NewReno 1.2 Kbps, BER=10 <sup>-4</sup>	Vegas 4.37%, BER=10 <sup>-7</sup> 10.17%, BER=10 <sup>-4</sup>	Vegas 95.81%, BER=10 <sup>-7</sup> Reno 84.16%, BER=10 <sup>-3</sup>	Vegas 11.09 Kbps, BER=10 <sup>-7</sup> 3.014 Kbps, BER=10 <sup>-4</sup>
	Worst protocol	Vegas 5.28 Kbps, BER=10 <sup>-7</sup> Sack 0.98 Kbps, BER=10 <sup>-4</sup>	Vegas 47.43%, BER=10 <sup>-3</sup>	Vegas 60%, BER=10 <sup>-3</sup>	Sack 0.04 Kbps, BER=10 <sup>-3</sup>

Table 4.19 – XSTP performance versus TCP clones performance over nanosatellite network

#### 4.3.6.1 One-way transmission scenario

The effective throughput variation for one-way scenario is plotted in Figure 4.38. We observe that throughput decreases as BER increases, the same variation type as in traditional satellite scenario. XSTP outperforms all TCP clones, by providing the best performance even for high BER conditions. This is mainly due to its probing mechanism. As shown in Figure 4.38, XSTP attained a doubled throughput rate as compared to TCP clones, for high BER conditions ( $10^{-4}$ ). The maximum throughput of XSTP is about 14 Kbps for low BER environment ( $10^{-7}$ ).

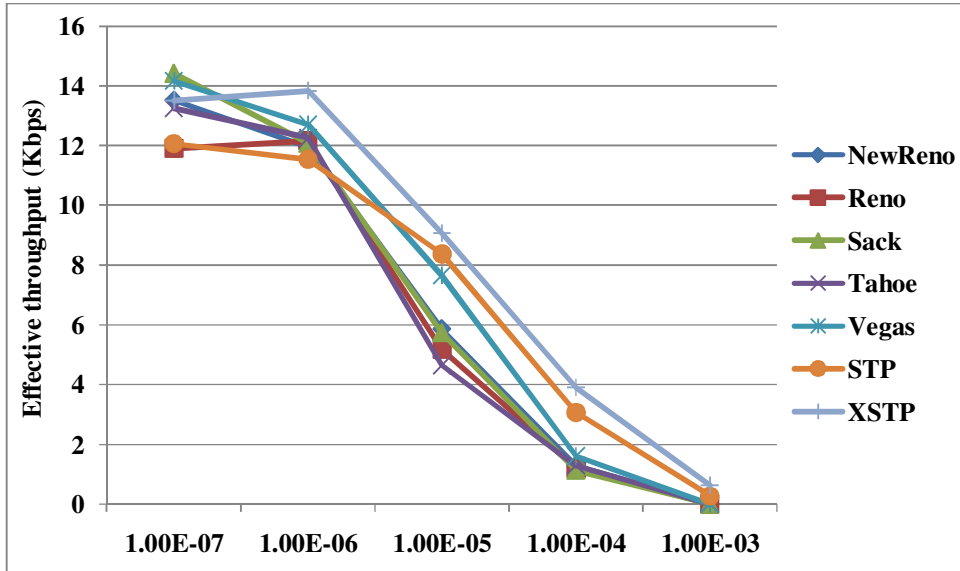


Figure 4.38 – Effective throughput variation for nanosatellite constellation model (one-way scenario)

Figure 4.39 shows transmission overhead variation as a function of BER.

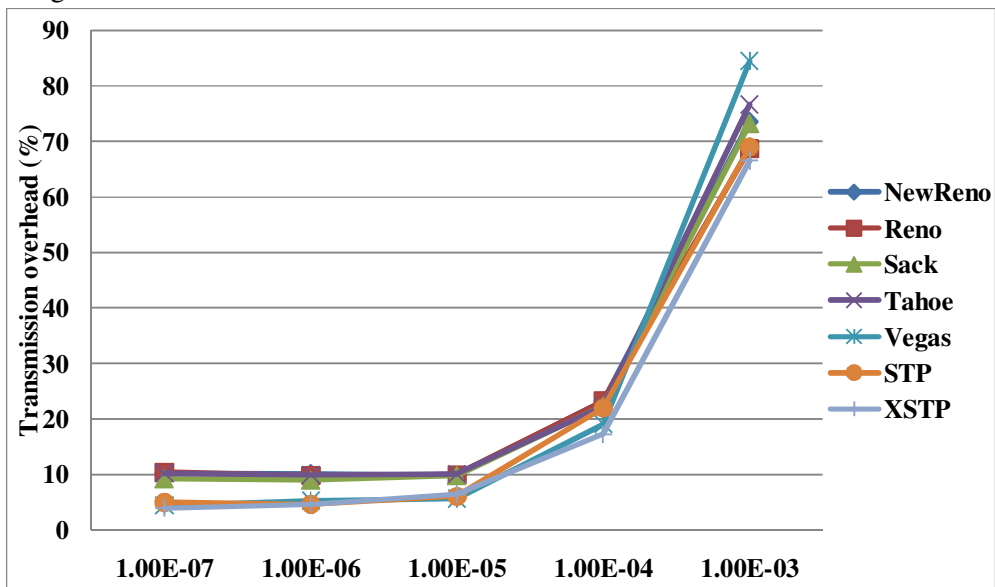


Figure 4.39 – Transmission overhead variation for nanosatellite constellation model (one-way scenario)

By analyzing Eq. 4.2 and Eq. 4.3, we observe that overhead metric is complement to channel efficiency parameter. As a general rule, overhead must be minimized.

According to Figure 4.39, STP and XSTP provide two times less overhead than TCP clones in case of low BER environment. An explanation of this behavior is found in XSTP probing mechanism. During probing cycle, receiver sends one POLL per RTT and stops data transmission in order to avoid data losses. At the end of this cycle and if there is no congestion, sender doesn't reduce its congestion window; thus, it gives user the possibility to send much more data over the network.

TCP Vegas makes an exception by offering a compared overhead as STP and XSTP for low BER.

As for high BER environment ( $10^{-3}$ ), TCP clones and even XSTP provide an overhead higher than 67 % and this need to be reduced.

The overhead is a metric for comparing the scalability of protocols. As seen in Figure 4.39, STP, XSTP and TCP Vegas scale well in case of low BER conditions, as compared to the rest of TCP clones.

Sending more packets into the nanosatellite network (which translates in more overhead), more power is consumed. Therefore, nanosatellite communications have to be based on protocols that provide a minimum level of overhead, by considering low-power resources of nanosatellites. XSTP perform very well in low BER conditions ( $10^{-7} - 10^{-5}$ ), by providing only 5% of overhead, thus being a good candidate for nanosatellite networks. However, we need to find a way to improve its performance for high BER environment.

Nanosatellites have a stringent constraint regarding energy consumption. Consequently, the energy spent for data transmission has to be minimized as much as possible, by providing in the same time efficient telecommunication services.

Channel efficiency metric shows how communication channel is used during data transmission. In case of significant amount of data user, efficiency is closed to 1, which means that channel is well used. Contrary, if efficiency is closed to 0, the channel is not well exploited.

Channel efficiency variation with respect to BER rate is plotted in Figure 4.40. We remark that XSTP has roughly the same performance as STP and Vegas, providing 5% higher efficiency than the other protocols, for low BER conditions. For very high BER environment ( $10^{-3}$ ), STP and XSTP succeed in providing two times more efficiency (33 %) than TCP Vegas which attains the lowest channel efficiency (15.5%).

In conclusion, XSTP can be a good candidate for nanosatellite network because it offers a very good efficiency (95%) in low BER conditions ( $10^{-7}$ – $10^{-5}$ ) and 85% of efficiency in high BER environment ( $10^{-4}$ ). However, we think that an improvement of its probing-mechanism can rise its efficiency level in case of very high BER.

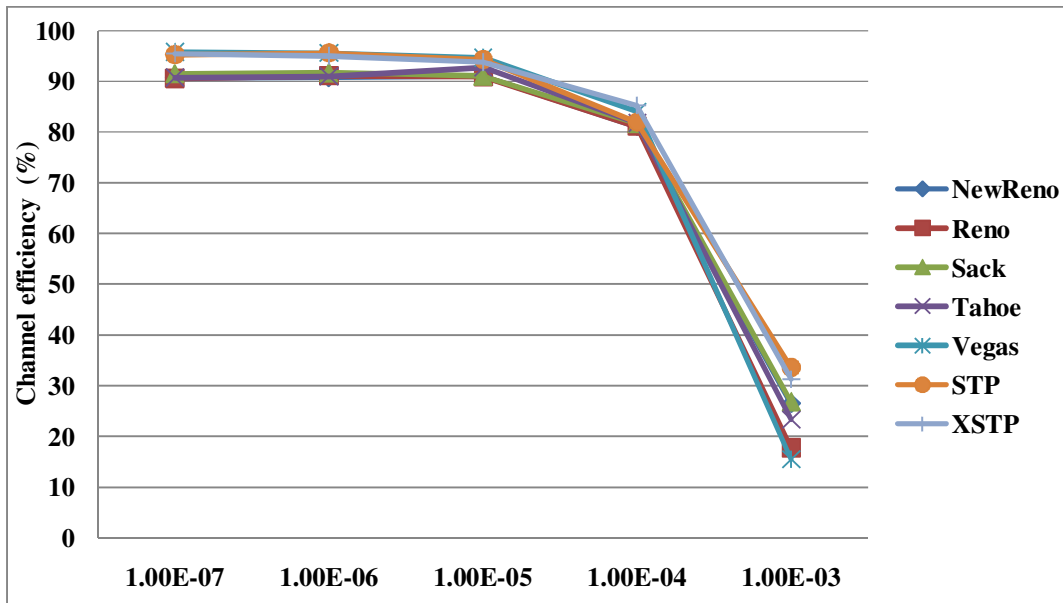


Figure 4.40 – Channel efficiency variation for nanosatellite constellation model (one-way scenario)

Generally, reverse channel is used for ACKs transmission. It is important to mention that reverse channel bandwidth has to be minimized at the very most due to satellite link asymmetry.

As seen in Figure 4.41, XSTP and STP bandwidth for reverse channel increases with BER increasing; this means that XSTP needs a low bandwidth for reverse channel transmissions. Instead, reverse channel bandwidth for TCP clones decreases with BER increasing.

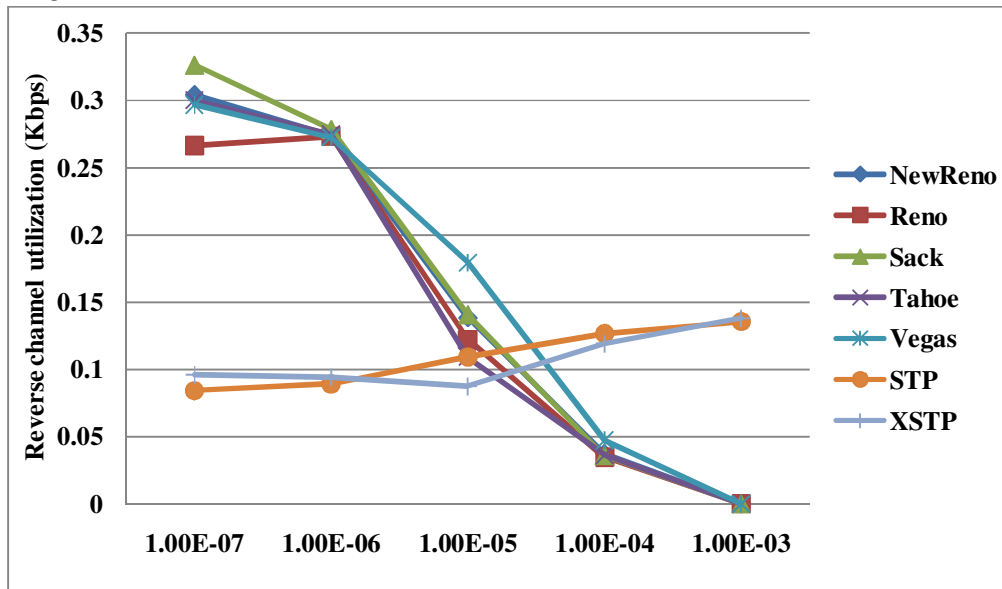


Figure 4.41 – Reverse channel utilization for nanosatellite constellation model (one-way scenario)



This type of variation is explain by the fact that receiver sends one or many ACKs for received data packets. If there are no losses, the reverse channel bandwidth is increasing as many packets are received. Contrary, in high BER conditions, receiver doesn't transmit many ACKs; therefore, reverse channel bandwidth decreases.

Unlike TCP clones, STP and XSTP send STAT and USTAT messages over the reverse channel. When BER is low, receiver sends many small size STAT messages that demand a low reverse channel bandwidth. For high BER, receiver sends many large size USTAT messages that demand a large reverse channel bandwidth.

XSTP needs a lower reverse channel bandwidth than STP because the number of STAT messages transmitted during probing cycle is decreasing as the number of POLL per RTT decreases (1 STAT message per POLL).

In case of STP, the number of POLL per RTT remains unchanged (i.e., 3 POLL per RTT). Because STP doesn't suspend transmission, it sends many USTAT messages even when BER is high.

#### 4.3.6.2 Bidirectional transmission scenario

In this scenario, data transmission is made in both ways (a node is sender and receiver too).

Effective throughput variation as a function of BER is illustrated in Figure 4.42. As compared to one-way scenario, we observe a slightly reduction of effective throughput due to reverse path transmission. STP provides the best performance for low BER conditions, by attaining the same throughput as in one-way scenario. In spite this, all protocols converge to a very poor throughput level when BER rate is very high ( $10^{-3}$ ) because data packet loss probability is significant, so the protocols need more bandwidth and resources to recover from these losses.

We also observed that TCP Vegas is strongly influenced by reverse path transmission, having, even in low BER conditions, a data rate two times less than the other protocols.

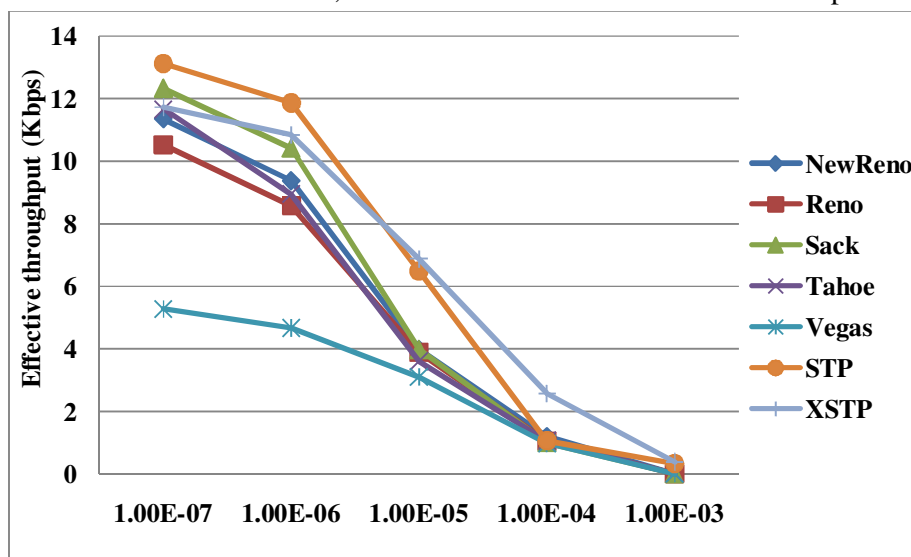


Figure 4.42 – Effective throughput variation for nanosatellite constellation model (two-way scenario)

Transmission overhead variation is plotted in Figure 4.43.

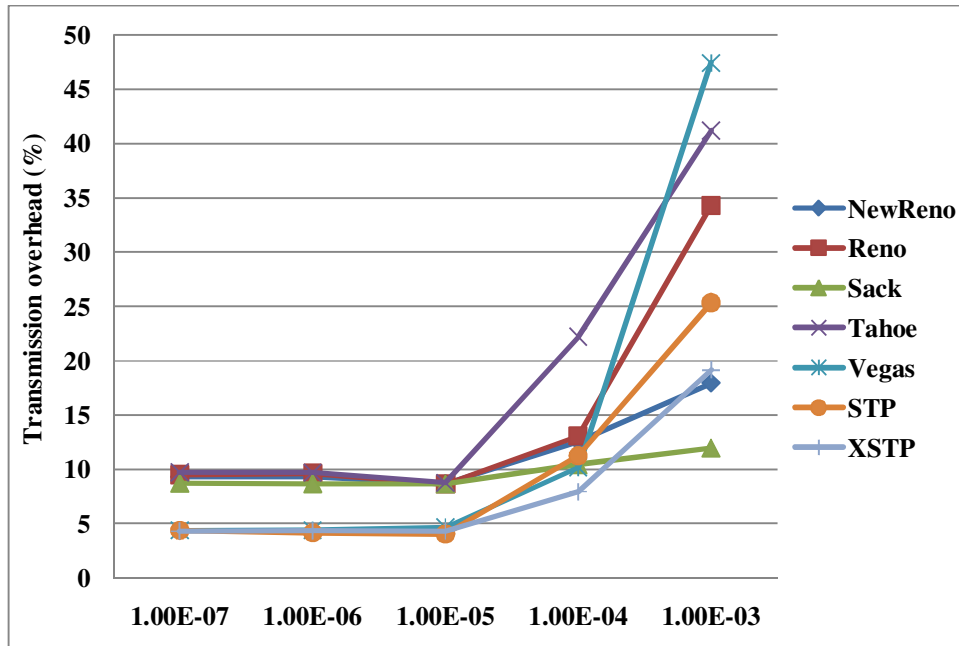


Figure 4.43 – Transmission overhead variation for nanosatellite constellation model (two-way scenario)

XSTP, STP and Vegas achieve two times less overhead than the rest of protocols in low BER conditions, similar to one-way scenario. As compared to one-way, XSTP provides 3 times less overhead (from 67% to 20%) in case of very high BER ( $10^{-3}$ ).

By considering the scalability criterion, we can state that STP, XSTP and TCP Vegas scale well in case of low BER conditions, as compared to the rest of TCP clones.

As for high BER environment ( $10^{-3}$ ), TCP clones and even XSTP provide an overhead higher than 67 % and this need to be reduced.

As mentioned before, overhead metric is a measure to evaluate protocol efficiency in relation to nanosatellite battery power, as sending more packets consumes more power.

Therefore, XSTP performs better as compared to one-way scenario, by providing only 4% of overhead in low BER conditions ( $10^{-7} - 10^{-5}$ ), 8% of overhead for high BER rate ( $10^{-4}$ ) and 20% of overhead in very high BER environment ( $10^{-3}$ ). Therefore, XSTP could successfully be used for communications within nanosatellite networks.

Figure 4.44 shows channel efficiency variation as a function of BER rate. XSTP outperforms all TCP clones and STP, by achieving an efficiency of more that 90 % even in very high BER conditions ( $10^{-3}$ ). This shows that the transmission channel is very well exploited during XSTP-type communications within the nanosatellite network.

As in one-way scenario, TCP Vegas still remains the worst efficient protocol. Interestingly, it is almost 4 times more efficient than in one-way scenario (60% versus 15.5%).

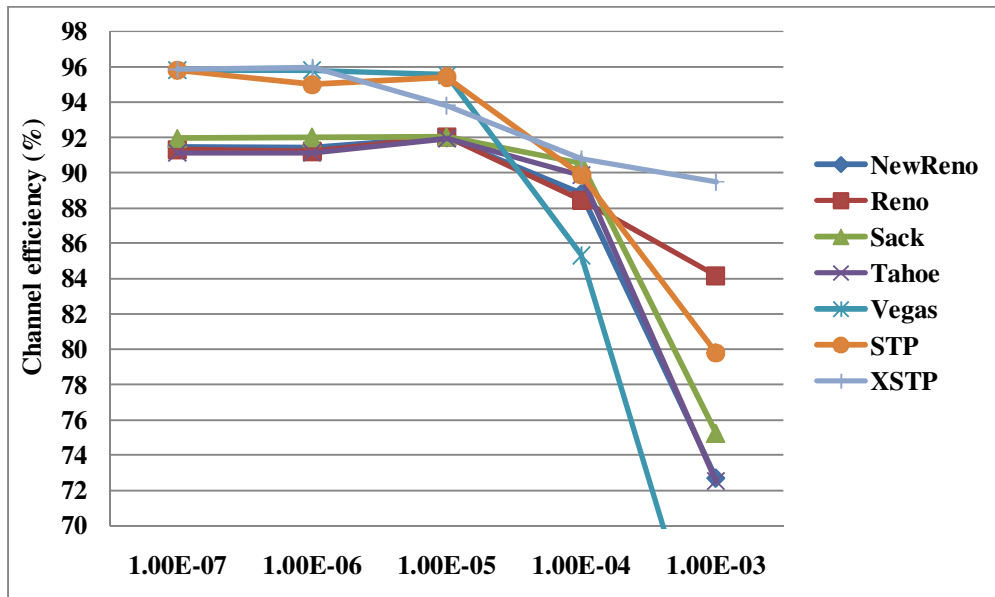


Figure 4.44 – Channel efficiency variation for nanosatellite constellation model (two-way scenario)

Reverse channel utilization as a function of BER is plotted in Figure 4.45. We observe the same variation trend as in one-way scenario: XSTP and STP bandwidth for reverse channel increases with BER increasing; this means that XSTP needs a low bandwidth for reverse channel transmissions. Instead, reverse channel bandwidth for TCP clones decreases with BER increasing. The explanation given for one-way scenario is valid also for two-way scenario.

STP provides an average reverse channel bandwidth of 8.7 Kbps while XSTP achieves a slightly smaller value (7.65 Kbps). Among TCP clones, Vegas uses only 10 Kbps for reverse channel transmission for low BER conditions, which is 2 times and a half less than the rest of TCP clones.

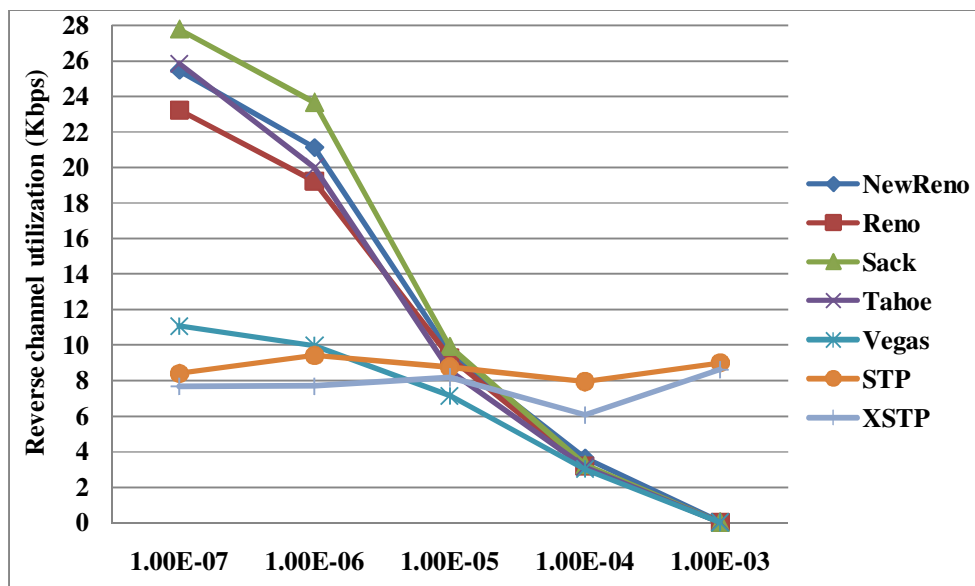


Figure 4.45 – Reverse channel utilization for nanosatellite constellation (two-way scenario)

### 4.3.6.3 Confidence interval for nanosatellite network simulations

This chapter presents the confidence interval of QoS parameters for nanosatellite network simulations in case of one-way transmission scenario.

The confidence interval of a population mean  $\mu$  is expressed by the following formula:

$$\bar{x} \pm z_{\alpha/2} \frac{\sigma}{\sqrt{n}}$$

where:

- $\bar{x}$  is the sample mean
- $n$  is the sample size
- $\sigma$  is the standard deviation
- the level of confidence required is  $(1 - \alpha) \times 100\%$

Substitution of each of the values in the above formula would create the confidence interval required.

The confidence level, expressed as a percentage, is the probability value  $(1-\alpha)$  associated with a confidence interval. In our calculations, we consider two levels of confidence:  $\alpha=0.05$  (95% confidence) and  $\alpha=0.1$  (90% confidence).

If we require a 90% confidence interval then  $z_{\alpha/2} = z_{0.05} = 1.64$ .

If we require a 95% confidence interval then  $z_{\alpha/2} = z_{0.025} = 1.96$ .

In the tables below, we present the confidence intervals for XSTP and STP protocols and for each TCP clone (i.e., New Reno, Reno, Tahoe, Vegas, Sack) for low BER ( $10^{-7}$ ) and high BER ( $10^{-4}$ ) conditions in case of one-way transmission scenario.

<i>Confidence intervals for XSTP protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>13.26 ± 1.61</b>	<b>[11.64; 14.87]</b>	<b>13.26 ± 12%</b>
<b>Channel Efficiency (%)</b>	<b>95.5 ± 0.345</b>	<b>[95.15; 95.84]</b>	<b>95.5 ± 0.36%</b>
<b>Overhead (%)</b>	<b>3.967 ± 1.27</b>	<b>[2.69; 5.24]</b>	<b>3.967 ± 32%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.096 ± 0.0054</b>	<b>[0.09; 0.101]</b>	<b>0.096 ± 6%</b>
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>13.26 ± 1.35</b>	<b>[11.91; 14.61]</b>	<b>13.26 ± 10%</b>
<b>Channel Efficiency (%)</b>	<b>95.5 ± 0.29</b>	<b>[95.21; 95.79]</b>	<b>95.5 ± 0.3%</b>
<b>Overhead (%)</b>	<b>3.967 ± 1.07</b>	<b>[2.9; 5.04]</b>	<b>3.967 ± 27%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.096 ± 0.0045</b>	<b>[0.0915; 0.1005]</b>	<b>0.096 ± 5%</b>

Table 4.20 – Confidence interval for XSTP protocol (BER= $10^{-7}$ )

For example, let's consider the effective throughput metric for low BER conditions. We obtained a mean value of 13.26 with a standard deviation of 1.64.

- If we desire a confidence level of 95%, the corresponding confidence interval is  $\pm 1.61$ . This means that we are 95% certain that the true mean falls into the range from 11.64 to 14.87.

- If we desire a confidence level of 90%, the corresponding confidence interval is  $\pm 1.35$ . This means that we are 90% certain that the true mean falls into the range from 11.91 to 14.61.

The rest of the numerical calculations in terms of confidence interval for the three other QoS parameters can be interpreted in the same manner.

<i>Confidence intervals for XSTP protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
Effective throughput (Kbps)	$3.91 \pm 0.26$	[3.65; 4.17]	$3.91 \pm 7\%$
Channel Efficiency (%)	$85.32 \pm 0.96$	[84.36; 86.28]	$85.32 \pm 1.13\%$
Overhead (%)	$17.21 \pm 1.33$	[15.88; 18.54]	$17.21 \pm 8\%$
Reverse channel bandwidth (Kbps)	$0.1192 \pm 0.0013$	[0.1178; 0.1205]	$0.1192 \pm 1.2\%$
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
Effective throughput (Kbps)	$3.91 \pm 0.22$	[3.69; 4.13]	$3.91 \pm 6\%$
Channel Efficiency (%)	$85.32 \pm 0.81$	[84.51; 86.13]	$85.32 \pm 1\%$
Overhead (%)	$17.21 \pm 1.11$	[16.1; 18.32]	$17.21 \pm 7\%$
Reverse channel bandwidth (Kbps)	$0.1192 \pm 0.0011$	[0.118; 0.1203]	$0.1192 \pm 1\%$

Table 4.21 – Confidence interval for XSTP protocol ( $BER=10^{-4}$ )

<i>Confidence intervals for STP protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
Effective throughput (Kbps)	$12.06 \pm 0.98$	[11.09; 13.05]	$12.06 \pm 8.1\%$
Channel Efficiency (%)	$95.27 \pm 0.36$	[94.92; 95.64]	$95.27 \pm 0.4\%$
Overhead (%)	$4.95 \pm 0.4$	[4.56; 5.36]	$4.95 \pm 8.1\%$
Reverse channel bandwidth (Kbps)	$0.084 \pm 0.0015$	[0.082; 0.085]	$0.084 \pm 1.8\%$
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
Effective throughput (Kbps)	$12.06 \pm 0.82$	[11.25; 12.89]	$12.06 \pm 6.8\%$
Channel Efficiency (%)	$95.27 \pm 0.3$	[94.98; 95.58]	$95.27 \pm 0.3\%$
Overhead (%)	$4.95 \pm 0.33$	[4.63; 5.29]	$4.95 \pm 6.6\%$
Reverse channel bandwidth (Kbps)	$0.084 \pm 0.0013$	[0.082; 0.085]	$0.084 \pm 1.5\%$

Table 4.22 – Confidence interval for STP protocol ( $BER=10^{-7}$ )

<i>Confidence intervals for STP protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
Effective throughput (Kbps)	$3.07 \pm 0.14$	[2.94; 3.22]	$3.07 \pm 4.5\%$
Channel Efficiency (%)	$82 \pm 0.22$	[81.78; 82.22]	$82 \pm 0.27\%$
Overhead (%)	$21.96 \pm 0.32$	[21.64; 22.28]	$21.96 \pm 1.45\%$
Reverse channel bandwidth (Kbps)	$0.126 \pm 0.0004$	[0.1264; 0.1272]	$0.126 \pm 0.3\%$

<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>3.07 ± 0.12</b>	<b>[2.96; 3.2]</b>	<b>3.07 ± 4%</b>
<b>Channel Efficiency (%)</b>	<b>82 ± 0.18</b>	<b>[81.82; 82.18]</b>	<b>82 ± 0.22%</b>
<b>Overhead (%)</b>	<b>21.96 ± 0.27</b>	<b>[21.69; 22.23]</b>	<b>21.96 ± 1.23%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.126 ± 0.0003</b>	<b>[0.1256; 0.1263]</b>	<b>0.126 ± 0.24%</b>

Table 4.23 – Confidence interval for STP protocol ( $BER=10^{-4}$ )

<b>Confidence intervals for NewReno protocol for low BER conditions</b>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>13.51 ± 0.9</b>	<b>[12.62; 14.4]</b>	<b>13.51 ± 7%</b>
<b>Channel Efficiency (%)</b>	<b>90.75 ± 0.36</b>	<b>[90.39; 91.11]</b>	<b>90.75 ± 0.4%</b>
<b>Overhead (%)</b>	<b>10.19 ± 0.43</b>	<b>[9.76; 10.62]</b>	<b>10.19 ± 4%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.3 ± 0.02</b>	<b>[0.28; 0.32]</b>	<b>0.3 ± 7%</b>
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>13.51 ± 0.75</b>	<b>[12.76; 14.26]</b>	<b>13.51 ± 6%</b>
<b>Channel Efficiency (%)</b>	<b>90.75 ± 0.3</b>	<b>[90.45; 91.05]</b>	<b>90.75 ± 0.3%</b>
<b>Overhead (%)</b>	<b>10.19 ± 0.36</b>	<b>[9.83; 10.55]</b>	<b>10.19 ± 3.5%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.3 ± 0.02</b>	<b>[0.28; 0.32]</b>	<b>0.3 ± 7%</b>

Table 4.24 – Confidence interval for NewReno protocol ( $BER=10^{-7}$ )

<b>Confidence intervals for NewReno protocol for high BER conditions</b>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>1.28 ± 0.07</b>	<b>[1.22; 1.36]</b>	<b>1.28 ± 5.5%</b>
<b>Channel Efficiency (%)</b>	<b>81.17 ± 0.7</b>	<b>[80.48; 81.86]</b>	<b>81.17 ± 0.86%</b>
<b>Overhead (%)</b>	<b>23.2 ± 1.04</b>	<b>[22.16; 24.24]</b>	<b>23.2 ± 4.5%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.037 ± 0.002</b>	<b>[0.034; 0.039]</b>	<b>0.037 ± 5.4%</b>
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>1.28 ± 0.06</b>	<b>[1.23; 1.35]</b>	<b>1.28 ± 4.7%</b>
<b>Channel Efficiency (%)</b>	<b>81.17 ± 0.58</b>	<b>[80.59; 81.75]</b>	<b>81.17 ± 0.7%</b>
<b>Overhead (%)</b>	<b>23.2 ± 0.87</b>	<b>[22.33; 24.07]</b>	<b>23.2 ± 3.75%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.037 ± 0.0018</b>	<b>[0.0352; 0.0388]</b>	<b>0.037 ± 4.8%</b>

Table 4.25 – Confidence interval for NewReno protocol ( $BER=10^{-4}$ )

<i>Confidence intervals for Reno protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	11.91 ± 1.51	[10.4; 13.42]	11.91 ± 13%
Channel Efficiency (%)	90.6 ± 0.51	[90.09; 91.11]	90.6 ± 0.5%
Overhead (%)	10.37 ± 0.62	[9.75; 11]	10.37 ± 6%
Reverse channel bandwidth (Kbps)	0.266 ± 0.03	[0.24; 0.3]	0.266 ± 11%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	11.91 ± 1.27	[10.64; 13.18]	11.91 ± 11%
Channel Efficiency (%)	90.6 ± 0.43	[90.17; 91.03]	90.6 ± 0.47%
Overhead (%)	10.37 ± 0.52	[9.85; 10.89]	10.37 ± 5%
Reverse channel bandwidth (Kbps)	0.266 ± 0.03	[0.24; 0.3]	0.266 ± 11%

Table 4.26 – Confidence interval for Reno protocol ( $BER=10^{-7}$ )

<i>Confidence intervals for Reno protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	1.2 ± 0.09	[1.12; 1.3]	1.2 ± 7.5%
Channel Efficiency (%)	81.14 ± 1.16	[80; 82.3]	81.14 ± 1.4%
Overhead (%)	23.26 ± 1.76	[79.38; 82.9]	23.26 ± 7.5%
Reverse channel bandwidth (Kbps)	0.035 ± 0.0017	[0.03311; 0.3664]	0.035 ± 5%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	1.2 ± 0.08	[1.13; 1.29]	1.2 ± 7.5%
Channel Efficiency (%)	81.14 ± 1	[80.16; 82.12]	81.14 ± 1.4%
Overhead (%)	23.26 ± 1.5	[21.78; 24.74]	23.26 ± 7.5%
Reverse channel bandwidth (Kbps)	0.035 ± 0.0015	[0.033; 0.036]	0.035 ± 5%

Table 4.27 – Confidence interval for Reno protocol ( $BER=10^{-4}$ )

<i>Confidence intervals for Tahoe protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	13.51 ± 0.48	[13.03; 14]	13.51 ± 3.5%
Channel Efficiency (%)	90.74 ± 0.12	[90.62; 90.86]	90.74 ± 0.13%
Overhead (%)	10.19 ± 0.15	[10.05; 10.35]	10.19 ± 1.5%
Reverse channel bandwidth (Kbps)	0.3 ± 0.01	[0.29; 0.31]	0.3 ± 3.3%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	<b>Confidence interval</b>		
Effective throughput (Kbps)	13.51 ± 0.4	[13.11; 13.91]	13.51 ± 3%
Channel Efficiency (%)	90.74 ± 0.1	[90.64; 90.84]	90.74 ± 0.1%
Overhead (%)	10.19 ± 0.12	[10.07; 10.31]	10.19 ± 1.1%
Reverse channel bandwidth (Kbps)	0.3 ± 0.01	[0.29; 0.31]	0.3 ± 3.3%

Table 4.28 – Confidence interval for Tahoe protocol ( $BER=10^{-7}$ )

<i>Confidence intervals for Tahoe protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	1.29 ± 0.09	[1.2; 1.39]	1.29 ± 7%
Channel Efficiency (%)	81.83 ± 0.88	[80.95; 82.71]	81.83 ± 1%
Overhead (%)	22.2 ± 1.31	[20.9; 23.5]	22.2 ± 6%
Reverse channel bandwidth (Kbps)	0.036 ± 0.002	[0.034; 0.038]	0.036 ± 5.5%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	1.29 ± 0.08	[1.21; 1.38]	1.29 ± 6%
Channel Efficiency (%)	81.83 ± 0.74	[81.09; 82.57]	81.83 ± 0.9%
Overhead (%)	22.2 ± 1.1	[21.1; 23.3]	22.2 ± 5%
Reverse channel bandwidth (Kbps)	0.036 ± 0.0017	[0.034; 0.037]	0.036 ± 4.7%

Table 4.29 – Confidence interval for Tahoe protocol ( $BER=10^{-4}$ )

<i>Confidence intervals for Vegas protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	14.16 ± 0.66	[13.5; 14.82]	14.16 ± 4.6%
Channel Efficiency (%)	95.81 ± 0.03	[95.78; 95.84]	95.81 ± 0.03%
Overhead (%)	4.37 ± 0.04	[4.33; 4.41]	4.37 ± 1%
Reverse channel bandwidth (Kbps)	0.29 ± 0.01	[0.29; 0.31]	0.29 ± 3.5%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	14.16 ± 0.55	[13.61; 14.71]	14.16 ± 3.8%
Channel Efficiency (%)	95.81 ± 0.03	[95.78; 95.84]	95.81 ± 0.03%
Overhead (%)	4.37 ± 0.03	[4.34; 4.4]	4.37 ± 0.7%
Reverse channel bandwidth (Kbps)	0.29 ± 0.01	[0.29; 0.31]	0.29 ± 3.5%

Table 4.30 – Confidence interval for Vegas protocol ( $BER=10^{-7}$ )

<i>Confidence intervals for Vegas protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	1.61 ± 0.34	[1.27; 1.95]	1.61 ± 21%
Channel Efficiency (%)	84.03 ± 1.14	[82.9; 85.17]	84.03 ± 1.3%
Overhead (%)	19.01 ± 1.6	[17.42; 20.6]	19.01 ± 8.5%
Reverse channel bandwidth (Kbps)	0.047 ± 0.01	[0.04; 0.06]	0.047 ± 21%
<b>alpha = 0.1 → 90% confidence</b>			
QoS performance metric	Confidence interval		
Effective throughput (Kbps)	1.61 ± 0.28	[1.33; 1.89]	1.61 ± 17%
Channel Efficiency (%)	84.03 ± 0.95	[93.09; 85]	84.03 ± 1.1%
Overhead (%)	19.01 ± 1.3	[17.68; 20.34]	19.01 ± 7%
Reverse channel bandwidth (Kbps)	0.047 ± 0.01	[0.04; 0.06]	0.047 ± 21%

Table 4.31 – Confidence interval for Vegas protocol ( $BER=10^{-4}$ )



<i>Confidence intervals for Sack protocol for low BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>14.42 ± 1.35</b>	<b>[13.07; 15.77]</b>	<b>14.42 ± 9.4%</b>
<b>Channel Efficiency (%)</b>	<b>91.54 ± 0.15</b>	<b>[91.4; 91.7]</b>	<b>91.54 ± 0.16%</b>
<b>Overhead (%)</b>	<b>9.24 ± 0.18</b>	<b>[9.07; 9.43]</b>	<b>9.24 ± 2%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.33 ± 0.03</b>	<b>[0.3; 0.36]</b>	<b>0.33 ± 9.1%</b>
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>14.42 ± 1.14</b>	<b>[13.28; 15.56]</b>	<b>14.42 ± 8%</b>
<b>Channel Efficiency (%)</b>	<b>91.54 ± 0.13</b>	<b>[91.41; 91.67]</b>	<b>91.54 ± 0.14%</b>
<b>Overhead (%)</b>	<b>9.24 ± 0.15</b>	<b>[9.09; 9.39]</b>	<b>9.24 ± 1.6%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.33 ± 0.02</b>	<b>[0.31; 0.35]</b>	<b>0.33 ± 6%</b>

Table 4.32 – Confidence interval for Sack protocol ( $BER=10^{-7}$ )

<i>Confidence intervals for Sack protocol for high BER conditions</i>			
<b>alpha = 0.05 → 95% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>1.135 ± 0.06</b>	<b>[1.08; 1.2]</b>	<b>1.135 ± 5.3%</b>
<b>Channel Efficiency (%)</b>	<b>81.74 ± 1.05</b>	<b>[80.7; 82.8]</b>	<b>81.74 ± 1.3%</b>
<b>Overhead (%)</b>	<b>22.35 ± 1.57</b>	<b>[20.78; 23.92]</b>	<b>22.35 ± 7%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.036 ± 0.0015</b>	<b>[0.0344; 0.0375]</b>	<b>0.036 ± 4%</b>
<b>alpha = 0.1 → 90% confidence</b>			
<b>QoS performance metric</b>	<b>Confidence interval</b>		
<b>Effective throughput (Kbps)</b>	<b>1.135 ± 0.05</b>	<b>[1.09; 1.19]</b>	<b>1.135 ± 4.4%</b>
<b>Channel Efficiency (%)</b>	<b>81.74 ± 0.88</b>	<b>[80.86; 82.62]</b>	<b>81.74 ± 1.1%</b>
<b>Overhead (%)</b>	<b>22.35 ± 1.31</b>	<b>[21.04; 23.66]</b>	<b>22.35 ± 5.9%</b>
<b>Reverse channel bandwidth (Kbps)</b>	<b>0.036 ± 0.0013</b>	<b>[0.0346; 0.0373]</b>	<b>0.036 ± 3.6%</b>

Table 4.33 – Confidence interval for Sack protocol ( $BER=10^{-4}$ )

## 4.4 XSTP performance comparison: satellite network versus nanosatellite network

This chapter presents a comparison study between satellite network and nanosatellite network in case of XSTP-type communication scenarios.

Table 4.34 presents the results of the three QoS performance metrics (i.e., effective throughput, transmission overhead, channel efficiency) for low BER conditions ( $10^{-7}$ ), high BER ( $10^{-4}$ ) and very high BER environment ( $10^{-3}$ ).

Below, we made some useful observations by considering the results for one-way scenario and two-way scenario respectively.

		Effective throughput	Transmission overhead	Channel efficiency
Satellite network	One-way scenario	1402 Kbps, BER= $10^{-7}$	3.63%, BER= $10^{-7}$	96.37%, BER= $10^{-7}$
		392 Kbps, BER= $10^{-4}$	13.82%, BER= $10^{-4}$	86.18%, BER= $10^{-4}$
		69 Kbps, BER= $10^{-3}$	66.36%, BER= $10^{-3}$	33.64%, BER= $10^{-3}$
	Two-way scenario	1266 Kbps, BER= $10^{-7}$	4.2%, BER= $10^{-7}$	95.8%, BER= $10^{-7}$
		234 Kbps, BER= $10^{-4}$	6.6%, BER= $10^{-4}$	93.41%, BER= $10^{-4}$
		43 Kbps, BER= $10^{-3}$	21.7%, BER= $10^{-3}$	78.3%, BER= $10^{-3}$
Nanosatellite network	One-way scenario	13.5 Kbps, BER= $10^{-7}$	3.96%, BER= $10^{-7}$	95.5%, BER= $10^{-7}$
		3.9 Kbps, BER= $10^{-4}$	17.21%, BER= $10^{-4}$	85.32%, BER= $10^{-4}$
		0.64 Kbps, BER= $10^{-3}$	66.5%, BER= $10^{-3}$	31.28%, BER= $10^{-3}$
	Two-way scenario	11.73 Kbps, BER= $10^{-7}$	4.32%, BER= $10^{-7}$	95.85%, BER= $10^{-7}$
		2.57 Kbps, BER= $10^{-4}$	7.95%, BER= $10^{-4}$	90.77%, BER= $10^{-4}$
		0.4 Kbps, BER= $10^{-3}$	19.16%, BER= $10^{-3}$	89.5%, BER= $10^{-3}$

Table 4.34 – XSTP performance comparison table: satellite network versus nanosatellite network

### 4.4.1 One-way scenario

First of all, we observe a significant difference between the satellite network throughput and nanosatellite network throughput provided in all BER conditions. This is due to the high capacity of satellite network, designed to support uplink rates of 2 Mbps and downlink rates up to 64 Mbps. In contrast, nanosatellite network provides only 32 Kbps for uplink and maximum 1 Mbps for downlink.

Secondly, both networks roughly provide the same transmission overhead for each of BER level previously defined. The overhead is a metric for comparing the scalability of protocols. As Table 4.34 results shows, XSTP scales well in case of low BER conditions but its performance in very high BER environment need to be improved.

Thirdly, both networks have comparative results in terms of channel efficiency for each category of BER conditions. XSTP protocol offers a good performance (96%) in low BER conditions and even for high BER rates (86%), which means that the transmission channel is very well used during data transmissions. However, the channel efficiency attains

a low level in very high BER conditions, being 3 times less than the efficiency level obtained in low BER environment.

#### 4.4.2 Two-way scenario

As regards of effective throughput, we observe a big difference between satellite network and nanosatellite network. The same explanation as in one-way scenario is valid here.

In terms of transmission overhead, both networks have the same performance in low BER conditions. However, we remark that nanosatellite network provides a lower overhead in high and very high conditions, as compared to satellite network. Though, the performance of both networks in very high BER conditions remains an issue that need to be solved.

It is important to mention here that transmission overhead is a measure to evaluate protocol efficiency in relation to nanosatellite battery power, as sending more packets consumes more power. Furthermore, sending more data increases the probability of packet collision and can delay data packets in the queues. In this regard, our simulations demonstrate that XSTP is an ideal candidate for nanosatellite networks because it considers the limited power resources of nanosatellites.

As for channel efficiency, both networks have comparable performance in low BER and high BER conditions. Interestingly, the nanosatellite network provides a better channel efficiency (almost 90%) in very high BER conditions as compared to satellite network. This means that the transmission channel is better exploited during nanosatellite communications. This is a further reason to consider XSTP protocol as a good solution for nanosatellite telecommunications.

### 4.5 Summary

This chapter yielded some very interesting results. Firstly, the coverage parameters and performance indicators of NanoDREAM, NanoICE and NanoSPHERE constellations were presented and discussed. Then, these constellations were evaluated with respect to coverage criterion, using SaVi simulator.

According to our results, a NanoDREAM constellation of 9 nanosatellites, placed on a single equatorial plane at 1500 km of altitude and having an elevation angle of 15° provides the best coverage of Salar de Uyuni Desert. Also, this constellation is design such as the number of nanosatellites is minimized.

Moreover, we have shown that a NanoICE constellation of 15 nanosatellites, placed on a polar orbit at 700 km of altitude and having a minimum elevation angle of 10° is the best configuration that could provide efficient communication services for the Polar Regions scientific community.

In the context of a high demand of telecommunication services among various industrial companies in charge of mineral resources exploitation, we identified that a NanoSPHERE constellation of 45 nanosatellites disposed on 5 orbital planes, each plane

inclined at  $65^\circ$  with respect to equatorial plane, and having 9 nanosatellites per plane at 1500 km of altitude, is the best constellation to provide global coverage.

Secondly, the ground segment architecture, proposed for Salar de Uyuni mission, is tested via computer simulations in OPNET modeler. Our results have shown that the ground segment architecture could support telecommunications services via a nanosatellite network.

Thirdly, the NS2 simulation results concerning XSTP performance over satellite networks and nanosatellite networks are described and analyzed. Also, the simulation scenarios, the XSTP implementation solution and the networks topologies are presented. NS2 simulations were conducted for two types of scenarios (i.e., one-way scenario, where transmission channels are symmetrical and bidirectional scenario, when transmission is made in both ways). For each type of network, XSTP performance was evaluated based on four QoS metrics: effective throughput, overhead, channel efficiency and reverse channel utilization.

One achievement of this chapter is the comparison between satellite network and nanosatellite network in terms of XSTP performance. This analysis has shown that XSTP could be a good transport protocol for nanosatellite telecommunications, since it considers the limited power resources of nanosatellites. XSTP protocol provides a better channel efficiency and lower transmission overhead in very high BER conditions as compared to satellite network.

The next chapter will conclude this thesis and will point out future research directions in nanosatellite telecommunication field.



# CHAPTER 5

## Chapitre 5. CONCLUSIONS ET PERSPECTIVES

Ce chapitre récapitule les conclusions résultant de ces travaux de recherche. Les contributions de la thèse ainsi que les perspectives pour étendre les travaux de recherche dans le domaine de nano-satellites sont proposées.

### Sommaire des résultats de la thèse

Ce travail de recherche a été plus difficile qu'attendu, en raison du manque ou très peu d'études disponibles à ce jour dans le domaine de constellations de nano-satellites. Cependant, les caractéristiques de réseaux de nano-satellites ont été examinées en détail. La thèse propose également des nouveaux modèles de constellations de nano-satellites, des méthodes pour évaluer leurs performances, des nouvelles approches de routage et de la Qualité de Service pour les réseaux de nano-satellites.

En outre, ces recherches font étendre la base de connaissance de réseaux de nano-satellites, en développant des modèles innovants de constellations de nano-satellites, en identifiant un protocole de transport pour les télécommunications par nano-satellites et en proposant de nouvelles approches pour implémenter, de façon efficace, la QoS dans les réseaux de nano-satellites.

Cette thèse a un double but : la proposition des modèles innovants de constellations de nano-satellites et des nouvelles approches de routage pour les réseaux de nano-satellites. Pour réaliser ce but, nous avons utilisé l'approche suivante.

Dans un premier temps, nous avons fait une introduction dans le domaine de petits satellites, en définissant des concepts comme le nano-satellite, le vol en formation, le *cluster*, la constellation. Aussi, les défis de systèmes nano-satellites sont soulignés avec quelques aspects complémentaires de satellites conventionnels et de petits satellites. Ensuite, les avantages et les inconvénients de petits satellites par rapport aux satellites classiques sont présentés. Nous avons aussi passé en revue la littérature pour déterminer les plus importantes applications de nano-satellites. Pour identifier la tendance dans le domaine de lancement de nano-satellites, nous avons réalisé une analyse de lancement de nano-satellites dans la période 2004 – mi2007. Cette analyse montre que dans l'avenir, les nano-satellites accéléreront l'exploration spatiale qui entraîne aussi une augmentation significative de lancements de nano-satellites et la conception des petits lanceurs.

D'autre part, l'évolution de la technologie multimédia et l'intérêt commercial des opérateurs nano-satellites futurs pour pénétrer le marché de télécommunications, en offrant, au grand public, des services de télécommunications de haute qualité et bon marché, feront que l'aspect Qualité de Service soit très important dans les futures constellations de nano-satellites. Pour cette raison, nous avons proposé plusieurs approches pour implémenter la Qualité de Service dans les réseaux de nano-satellites.

Dans un deuxième temps, nous avons examiné d'autres types de réseaux (i.e., les réseaux de capteurs, les réseaux Ad hoc, les réseaux de satellites conventionnels) à la recherche de nouvelles idées qui pourraient être appliquées aux réseaux de nano-satellites.

Cette thèse propose et analyse trois modèles de constellations de nano-satellites, dénommés NanoDREAM, NanoICE, NanoSPHERE, qui fournissent des services de télécommunications aux régions éloignées. Le modèle NanoDREAM est conçu pour le Désert Salar de Uyuni de la Bolivie, une région qui détient 70% de la réserve mondiale de lithium. La mission d'exploitation du lithium en Bolivie a reçu une attention significative, en considérant la nouvelle politique d'énergie et les futures applications envisagées pour la réduction des émissions de CO<sub>2</sub> au niveau mondial. Aussi, nous avons proposé une architecture pour le segment terrestre basée sur la technologie sans fil. Cette architecture a été déployée sur la zone d'exploitation du Désert Salar de Uyuni. Le modèle NanoICE est destiné pour les Régions Polaires, pour satisfaire les besoins de télécommunications de la communauté scientifique. Le modèle NanoSPHERE est conçu pour fournir une couverture globale de la Terre dans le contexte d'un marché de télécommunications robuste. Ces modèles ont été développés analytiquement et mis ensuite en œuvre dans le simulateur SaVi afin d'identifier la meilleure constellation qui satisfait les requis de la mission en termes de couverture, en réduisant au minimum le nombre de nano-satellites de la constellation.

De plus, cette thèse s'est concentrée sur l'évaluation de la capacité des constellations de nano-satellites à fournir des services de télécommunications, en mesurant les délais de propagation à travers les réseaux nano-satellites simulés. Ainsi, nous avons calculé la quantité de données transmise chaque fois qu'un nano-satellite passe au-dessus d'une station terrestre.

En outre, nous avons proposé une architecture de segment terrestre pour la mission d'exploitation du désert Salar de Uyuni. Ainsi, nous proposons de déployer un réseau maillé sans fil sur la zone d'exploitation du lithium pour connecter tous les bâtiments facilement et efficacement en utilisant une technologie peu coûteuse. Les simulations OPNET ont montré que ce réseau Ad hoc est adapté pour des télécommunications via un réseau de nano-satellites, en fournissant une bande passante effective supérieure à la liaison ascendante et descendante d'un nano-satellite.

Nous avons aussi étudié les performances des protocoles de transport dans les réseaux nano-satellites. Le protocole de transport XSTP a été identifié comme un candidat possible pour les réseaux de nano-satellites, basé sur une étude sur le routage dans les réseaux de satellites conventionnels. Le protocole XSTP a alors été implémenté dans le simulateur NS2. Les scénarios unidirectionnel et bidirectionnel ont fourni la base de l'évaluation du protocole XSTP sur un réseau de satellite et sur un réseau de nano-satellite. Comme l'aspect Qualité de Service est un point important de cette thèse, nous avons défini plusieurs paramètres de performances, comme la bande passante effective, l'*overhead*, l'efficacité du canal et la bande passante nécessaire pour la transmission en sens inverse. Ainsi, les performances du protocole XSTP sont évaluées en ce qui concerne ces paramètres de performances de QoS et pour chaque type de réseau (i.e., satellitaire, nano-satellitaire). Nos simulations ont montré que le protocole XSTP a atteint les meilleures performances en termes de bande passante effective, la meilleure efficacité du canal et un *overhead* plus bas que les clones TCP.

Une analyse intéressante est la comparaison des performances du protocole XSTP entre un réseau de satellites traditionnels et un réseau de nano-satellites. Cette analyse a montré que le protocole XSTP pourrait être utilisé avec succès dans les réseaux de nano-satellites pour les raisons suivantes. Le protocole XSTP atteint une meilleure efficacité



(presque 90 %) dans des conditions de haut taux d'erreurs pour les réseaux de nano-satellites par rapport aux réseaux de satellites. Cela signifie que le canal de transmission est mieux exploité pendant les communications nano-satellitaires. Ainsi, le réseau de nano-satellites fournit un *overhead* inférieur par rapport au réseau de satellites conventionnels, dans un environnement caractérisé par haut et très haut taux d'erreurs. Cependant, les performances du protocole XSTP dans des conditions de très haut taux d'erreurs reste un problème qui doit être résolu.

En considérant les propositions faites dans cette thèse, nous pouvons conclure que les futures constellations de nano-satellites pourraient profiter aux trois modèles de constellation décrits dans cette thèse. De plus, nous avons démontré que le protocole de transport XSTP est un bon candidat pour les réseaux de communication par nano-satellites.

## Les contributions de la thèse

Cette thèse couvre deux champs d'études : la conception de constellation de nano-satellites et le routage dans les réseaux de nano-satellites en orbite basse. Les contributions spécifiques de cette thèse sont les suivantes:

- 1) Proposer trois modèles de constellations de nano-satellites, spécifiquement conçus pour fournir des services de télécommunications dans des régions éloignées. Une mission innovatrice a été proposée pour chacun d'entre eux :
  - le modèle NanoDREAM conçu pour le Désert de Salar de Uyuni en Bolivie ;
  - le modèle NanoICE destiné aux Régions Polaires, afin d'assurer les besoins en termes de télécommunications de la communauté scientifique d'Antarctique et d'Arctique ;
  - le modèle NanoSPHERE conçu pour fournir une couverture globale de la Terre, dans l'hypothèse d'une demande significative de services de télécommunications de sociétés industrielles étant responsables de l'exploitation de ressources minières dans plusieurs régions de la Terre.
- 2) Proposer une méthode pour calculer le nombre de nano-satellites nécessaires pour couvrir une région spécifique de la Terre.
- 3) Proposer une méthode basée sur le modèle de Markov pour évaluer les performances des constellations de nano-satellites.
- 4) Proposer une architecture de segment terrestre basée sur la technologie sans fil. Comme nos simulations l'ont montré, cette architecture pourrait fournir des services de télécommunications via un réseau nano-satellitaire.
- 5) Introduire les premières idées et formuler plusieurs questions sur la QoS dans les réseaux de nano-satellites, sur laquelle il n'y a eu aucune recherche précédente. Les défis de la QoS dans les réseaux de nano-satellites ont été identifiés et nous avons proposé plusieurs approches afin d'implémenter la QoS dans ceux-ci.
- 6) Proposer de nouvelles approches de routage pour les réseaux nano-satellitaires, en étudiant d'autres types de réseaux (i.e., les réseaux de capteurs, les réseaux Ad hoc) qui pourraient fournir des idées intéressantes et innovatrices qui seraient appliquées aux réseaux nano-satellitaires.

- 7) Identifier le protocole XSTP comme un candidat possible pour les réseaux de nano-satellites, en se basant sur une étude sur le routage dans les réseaux de satellites classiques.
- 8) Développer et implémenter deux nouveaux modules (STP, XSTP) dans le simulateur NS2 afin d'évaluer les performances de ces protocoles à travers les réseaux de satellites et les réseaux nano-satellites.
- 9) Conduire des études de performances, à travers des simulations et des analyses, pour évaluer les performances du protocole XSTP sur des réseaux de satellites traditionnels et des réseaux de nano-satellites.

## Perspectives

Tandis que les méthodes, les modèles et les approches de routage et de la QoS proposés dans cette thèse font étendre les connaissances du domaine de nano-satellites, les extensions de ce travail de recherche peuvent fournir d'autres avantages. Dans cet esprit, nous recommandons les perspectives suivantes :

Puisque les trois modèles de constellations nano-satellites (i.e., NanoDREAM, NanoICE et NanoSPHERE) ont été développés en considérant plusieurs hypothèses, des modèles plus complexes devront être considérés qui tiennent compte des perturbations qui agissent sur les nano-satellites. Notre but était de proposer des modèles simples qui devraient être des modèles de base pour la conception de futures constellations de nano-satellites.

A notre connaissance, il n'y a actuellement aucun outil de simulation spécifiquement conçu pour des constellations de nano-satellites. Pour cette raison, développer des outils de simulations, basés sur l'approche *open-source*, pour la conception des constellations de nano-satellites est un défi adressé à la communauté du logiciel libre. Nous pensons aussi qu'en rendant disponible, de façon libre, les implémentations de protocoles, cela permettra d'ajouter des améliorations substantielles aux protocoles. Le présent travail de recherche inclut aussi de nouvelles implémentations logicielles des protocoles de transport STP et XSTP dans le simulateur NS2 pour évaluer leurs performances sur les réseaux de satellites classiques et de nano-satellites.

Malgré tout, le protocole XSTP n'est pas parfait. Pour cette raison, nous proposons dans cette thèse, quelques perspectives de recherche futures. Nous avons observé que l'*overhead* est significatif dans des conditions de très haut taux d'erreurs ( $10^{-3}$ ) et devrait être réduit. Aussi, au niveau du mécanisme de *probing*, le principe de décision doit être amélioré pour distinguer les erreurs liées à la congestion du réseau et d'autres types d'erreurs qui pourraient être trouvées dans les réseaux de nano-satellites. Un autre aspect important est le niveau d'énergie dépensée pendant le cycle de *probing*. Une perspective intéressante serait de trouver une méthode pour mesurer et évaluer quantitativement cette énergie. De plus, une évaluation des performances du protocole XSTP en considérant des paramètres de performances de la QoS et des scénarios de test plus complexes pourrait être une direction de recherche intéressante.

D'autres études futures pourraient être dirigées vers les performances du protocole XSTP sur d'autres types de topologies (e.g., des constellations de type *Flower*, des *clusters*,

des constellations hybrides composées des satellites classiques et de nano-satellites). Une autre perspective est une étude de comparaison entre le mécanisme de *probing* du protocole XSTP et le mécanisme du protocole TCP. Cette comparaison pourrait montrer le mécanisme le plus efficace en termes d'adaptation aux différents types d'erreurs des liaisons satellitaires. De plus, le mécanisme de *probing* pourrait être étudié dans un contexte de communications sans fil ou dans un domaine similaire caractérisé par des différents types d'erreurs de communications.

Cette thèse a abordé deux sujets fondamentaux sur les réseaux de nano-satellites : le routage et la Qualité de Service. Nous avons démontré que le protocole XSTP, initialement conçu pour des réseaux de satellites traditionnels, pourra être utilisé dans des réseaux de nano-satellites. Les travaux futurs pourront se concentrer sur une étude détaillée d'autres protocoles de réseau de satellites traditionnels, en utilisant des techniques d'analyse et des simulations.

De plus, une étude sur les simulateurs de réseau actuels pourrait montrer si ces outils pourraient être adaptés afin de réaliser des simulations de réseaux nano-satellitaires.

Des travaux futurs sont aussi nécessaires pour développer des protocoles spécifiquement conçus pour les réseaux de nano-satellites et qui prennent en considération les ressources très limitées des nano-satellites. Les premiers pas ont déjà été faits par un groupe d'étudiants de l'Université d'Aalborg [68] en 2008 qui a développé, le protocole CSP (*CubeSat Space Protocol* [69]) – un protocole de la couche réseau conçu pour les CubeSats.

A notre connaissance, il n'y a aucune topologie spécifiquement conçue pour des réseaux de nano-satellite. Donc, les topologies de réseaux de satellites traditionnels (i.e., Maillé, Étoile, Hybride) devraient être examinées pour voir si elles sont adaptées aux réseaux de nano-satellites ou si de nouvelles topologies sont nécessaires.

Nous avons identifié dans cette thèse les contraintes principales en termes de QoS pour les réseaux de nano-satellites. En outre, nous proposons plusieurs directions de recherche afin d'implémenter la QoS dans l'environnement nano-satellitaire :

- 1) Développer des outils qui permettent aux utilisateurs une utilisation efficace des ressources du réseau de nano-satellites; aussi, ces outils peuvent montrer les ressources utilisées par le réseau de nano-satellites à un instant  $t$  et la priorité de chaque type de trafic.
- 2) Développer des technologies de QoS dans des réseaux de nano-satellites afin de fournir des services multimédia.
- 3) Développer des méthodes spécifiques pour identifier le type de trafic transmis à travers un réseau nano-satellitaire. Par exemple, la classification est une méthode pour fournir un service préférentiel à un certain type de trafic.
- 4) Développer des techniques pour éviter la congestion du réseau afin de pouvoir contrôler la charge du réseau nano-satellitaire sur certains segments de réseau. Ainsi, la congestion du réseau pourra être prévue et évitée avant que cela ne devienne un problème. Si la congestion commence à augmenter, les paquets seront refusés, ce qui conduira à un ralentissement de transmission de données au nœud source.
- 5) Développer des techniques de gestion de la congestion afin de contrôler la congestion avant qu'elle ne se produise. Les outils de gestion de la congestion permettent de monter la priorité d'un trafic en utilisant des méthodes de *queuing* et *servicing queues*.

- 6) Développer des techniques de *traffic shaping* et de *policing* pour les réseaux de nano-satellites. Le *traffic shaping* offre un moyen de contrôler le volume du trafic en train d'être envoyé à un réseau pendant une période donnée et le débit maximal auquel le trafic peut être envoyé. Cependant, le *traffic shaping* se fait toujours en retardant certains paquets (sans aucune perte).
- 7) Définir des niveaux de QoS de bout en bout qui se réfèrent à la capacité du réseau de nano-satellites à fournir des services nécessaires à certains trafics. Chaque service fourni par le réseau nano-satellitaire devrait avoir un certain niveau de priorité sur la QoS qui décrit comment le service doit être limité en termes de bande passante, délai, gigue et pertes. Puisque les niveaux de QoS (i.e., *Best effort*, *Differentiated service* et *Guaranteed service*) sont appropriés seulement aux réseaux IP terrestres, d'autres niveaux de QoS doivent être développés pour les réseaux de nano-satellites. Nous pensons qu'un bon point de départ serait d'étudier si ces niveaux de QoS peuvent être appliqués ou adaptés aux réseaux de nano-satellites. Si cette étude montre qu'ils ne sont pas appropriés aux réseaux de nano-satellites, d'autres types de niveaux doivent être proposés.

Pour conclure, nous considérons que les techniques de QoS peuvent fournir une importante valeur ajoutée aux services fournis par les réseaux de nano-satellites. En utilisant ces mécanismes, nous espérons que le trafic peut être contrôlé et les ressources des réseaux de nano-satellites pourraient être utilisées efficacement.

## 5 CONCLUSION AND FUTURE WORK

This chapter summarizes the conclusions resulting from this research work. Moreover, the contributions of this thesis and specific recommendations to further develop and extend this work are pointed.

### 5.1 Summary of research work

This work has been more difficult than expected, due to the lack of prior work in the nanosatellite constellation field, and this has prevented the early creation of realistic simulations. However, the features of nanosatellites network have been investigated in depth, and the resulting models and QoS concepts appear to be novel and not discussed in prior literature.

Furthermore, this research work has extended the knowledge base of nanosatellite networks, by developing a novel set of nanosatellite constellation models, by identifying candidate protocols for nanosatellite telecommunications and by proposing new approaches for an efficient QoS provisioning in nanosatellite networks.

The goal of this thesis is two-fold: proposing innovative nanosatellite constellation models and new routing approaches for nanosatellite network telecommunications. For achieving this goal, we used the following research approach.

Firstly, an introduction into small satellite field is made, by defining concepts such as nanosatellite, formation flying, cluster, and constellation. Also, the challenges of nanosatellite systems are emphasized along with some complementary aspects of large and small satellites. Then, the advantages and disadvantages of small satellites over conventional satellites are underlined. We also reviewed the literature to determine nanosatellite applications that need more attention. Since small satellite domain has imposed itself as a particular field in the last two decades, we found important to point out the results of an analysis of nanosatellite launches in the period 2004-mid 2007. This gives us an idea of the future trend in the nanosatellite launching field.

Moreover, the telecommunication framework of nanosatellite networks is presented and discussed along with QoS challenges. The evolution of multimedia technology and the commercial interest of future small satellite operators to reach widely public applications will make QoS in nanosatellite networks an area of great interest. For this reason, we proposed several approaches in order to develop and implement QoS mechanisms into nanosatellite networks.

Secondly, we survey other fields (i.e., sensor networks, Ad hoc networks, satellite networks) in search of new ideas that might be applied to nanosatellite networks. Thus, new routing approaches were proposed and a transport protocol candidate (XSTP – eXtended Satellite Transport Protocol) for nanosatellite networks was identified.

Thirdly, three mathematical models were developed by considering some basic rules of constellation design. In order to evaluate nanosatellite constellation in terms of coverage, SaVi simulator was used. SaVi modeler allows satellite orbits and coverage simulations, in two and three dimensions.

The first model, named NanoDREAM (**N**anosatellite constellation for **D**esert **R**egion **E**xploit**A**tion and **M**onitoring), is intended to deploy a LEO, sun-synchronous nanosatellite constellation that provides telecommunications services (e.g., voice, SMS and images) for an industrial company in charge of lithium resources exploitation in Salar de Uyuni Desert. It is important to mention that this nanosatellite system can be applied to any similar remote area of the Earth. Three groups of six configurations each of NanoDREAM constellations were analyzed, each group corresponding to one of the three altitudes considered in this study: 800 km, 1000 km and 1500 km. All these configurations were analyzed based on “round-trip propagation delay” criterion, pointing out the “best case” solution and “worst case” solution in terms of propagation delay.

Among all 18 configurations, four NanoDREAM-type constellations were selected and implemented in SaVi simulator. Then, these four constellations were analyzed based on the coverage criterion. Thus, we identified the best constellation which responds to our mission objectives (i.e., minimizing the number of nanosatellites and maximizing the coverage). It is a nanosatellite constellation of 9 nanosatellites, all disposed on a single equatorial orbital plane at 1500 km of altitude and having a minimum elevation angle of 15°. Thus, this constellation provides a coverage band between 0° and 22° S latitude, including also Salar de Uyuni Desert.

The second model, named NanoICE (**N**anosatellite **I**nnovative **C**onst**E**llation), designed to provide the best coverage performance at high latitudes (70 °- 90 ° N latitude and 70 °- 90° S latitude). The Poles turn out to be the only geographic region where continuous coverage may be achieved soon. Polar Regions are the primary service areas for conducting scientific research in various domains, such as understanding the climate changing, monitoring the ozone layer, investigating the impact of solar wind on satellite electronics, earth-mapping, earth observation, weather monitoring. NanoICE is aimed to meet the voice and data transfer needs of the entire Antarctic community. NanoICE system supports the remote monitoring of scientific experiments, the data transfer, and enables scientists to communicate with their colleagues around the world. It was shown that a NanoICE constellation of 15 nanosatellites placed on a sun-synchronous orbit at 700 km of altitude and having an elevation angle of 10° could provide telecommunication services to Polar Regions scientific community.

The last model, named NanoSPHERE, is based on Walker-type method and it is intended to provide global coverage. This model was envisaged in the context of a robust nanosatellite telecommunications market, where many nanosatellite operators are in competition. With more operators, the competition is more severe and market penetration is faster. Initially, only a portion of the full NanoSPHERE constellation is deployed to provide coverage only for a specific remote region. Thus, the nanosatellite operator could begin early revenue operations while the remaining orbital planes are progressively populated with nanosatellites. The extension of coverage area is justified by the growing demand of telecommunications services in other remote regions of the Earth, exploited for their mineral resources wealth. Our simulations showed that a NanoSPHERE constellation of 45 nanosatellites with 9 nanosatellites evenly distributed in 5 orbital planes could provide the highest degree of coverage at the mid-latitudes. Moreover, NanoSPHERE constellation

neglects polar coverage, NanoICE model being specifically designed for polar region coverage.

These models were developed analytically and then implemented in SaVi and NS2 simulators. Based upon these models, several parameters of nanosatellite constellations were calculated, such as the number of nanosatellites, the maximum time in view, and the coverage parameters (i.e., antenna footprint, coverage rate, access area, access rate).

In examining nanosatellite constellations in terms of their capability of providing telecommunication services, this thesis has focused on measuring propagation delays across simulated constellation networks, between ground terminals as endpoints. Also, the amount of data transmitted on each nanosatellite pass over a ground station has been assessed as a way of characterizing the perceived performance of the constellation.

Furthermore, a ground segment architecture was proposed for Salar de Uyuni exploitation mission. We propose to deploy a wireless mesh network over the lithium exploitation area in order to easily, effectively and wirelessly connect all the buildings using inexpensive technology. The OPNET simulations showed that this Ad hoc network is suited for telecommunications via nanosatellite network, by providing an effective throughput superior to nanosatellite uplink and downlink rates.

We have also studied, through analysis and simulations, the performance of transport protocols in nanosatellite networks. XSTP transport protocol was identified as a possible candidate for nanosatellite network, based on a survey of routing mechanisms in conventional satellite networks. Then, XSTP protocol was implemented in NS2 simulator. One-way scenario and two-way scenarios provided the basis for the XSTP protocol assessment over satellite network and nanosatellite network respectively. Since QoS aspect is an important focus of this thesis, we defined in this chapter several QoS performance metrics, such as effective throughput, transmission overhead, channel efficiency and reverse channel utilization. Thus, the XSTP performance is assessed with respect to these QoS metrics and for every type of network (i.e., satellite, nanosatellite). Our simulations showed that XSTP attained higher effective throughput, much lower overhead, and better channel efficiency as compare to TCP clones.

A special emphasis is placed on the comparison between satellite network and nanosatellite network with respect to XSTP performance. This analysis has shown that XSTP could be a good transport protocol for nanosatellite telecommunications for the following reasons. The nanosatellite network provides a better channel efficiency (almost 90%) in very high bit error rate conditions as compared to satellite network. This means that the transmission channel is better exploited during nanosatellite communications. Also, the nanosatellite network provides a lower overhead in high and very high conditions, as compared to satellite network. However, its performance in very high BER environment remains an issue that need to be solved.

From this research work, we can conclude that future nanosatellite constellations could benefit from the three constellation models described in this thesis. Moreover, we have demonstrated that XSTP transport protocol is good candidate to be considered for nanosatellite communications networks.

## 5.2 Thesis contributions

This thesis is a joint of nanosatellite constellation design and routing in LEO nanosatellite networks. The following specific thesis contributions can be identified:

- 1) Proposing three nanosatellite constellation models, specifically designed to provide telecommunications services in remote regions. Thereby, an innovative mission has been envisaged for each of them:
  - NanoDREAM model is designed for Bolivia's Salar de Uyuni Desert, where an industrial company in charge of lithium exploitation, since this region detains 70% of the global lithium reserve;
  - NanoICE model is intended for Polar Regions, in order to meet the voice and data transfer needs of the entire Antarctic and Arctic scientific community;
  - NanoSPHERE is aimed to provide global coverage in the context of a robust telecommunications market and assuming a significant demand of telecommunications services from different industrial companies in charge of mineral resources exploitation in many regions of the Earth.
- 2) Proposing a methodology for calculating the number of nanosatellites in the constellation.
- 3) Proposing a Markov modeling method for evaluating the performance of nanosatellite constellations.
- 4) Proposing a ground segment architecture based on wireless technology. As our simulations shown, this architecture could support telecommunications services via a nanosatellite network.
- 5) Introducing the first ideas and pointing out several questions on "QoS in nanosatellite networks" topic, on which there has been no previous research work. QoS challenges of nanosatellite networks have been identified and several approaches for an efficient QoS provisioning in nanosatellite networks have been proposed.
- 6) Proposing new routing approaches for nanosatellite networks, by exploring other network fields (i.e., sensor, Ad hoc) that could provide interesting and innovative ideas that would be applied to nanosatellite networks.
- 7) Identifying XSTP as a possible candidate for nanosatellite network, based on a survey of routing mechanisms in conventional satellite networks.
- 8) Developing and implementing two new modules (STP, XSTP) in NS2 simulator in order to evaluate the performance of these protocols across satellite networks and nanosatellite networks respectively.
- 9) Carrying out performance studies, throughout simulations and analysis, in order to evaluate XSTP performance over traditional satellite networks and nanosatellite networks respectively.



### 5.3 Future work

While the current methodology and models provide insight into both the nanosatellite constellation design and nanosatellite protocol design problems, extensions of this work may provide even more benefit. It is recommended that the following areas be investigated.

Since the three models (i.e., NanoDREAM, NanoICE and NanoSPHERE) were developed by considering several assumptions, more complex models should be considered for taking into account the perturbations effects that act on nanosatellites. It is evident that there are a lot of parameters and design choices to consider when designing a nanosatellite constellation. Our aim was to propose low-complexity models that should be the basic models for future nanosatellite constellation designs.

From our knowledge, there is a little research on developing simulation tools specifically designed for nanosatellite constellations. For example, a research team from The Institute of Astronautics of the Technische Universitaet Muenchen has developed a simulator called DySyS [123], to model a small satellite project with respect to the system composition and dynamic behavior. We consider that developing nanosatellite constellation modelers based on open-source approach is a challenge addressed to open-source community.

We also think that making protocols software implementations available to research community will allow substantial protocols improvements, by adding an innovative dimension to them. The present work has involved new software implementations of STP and XSTP protocols in NS2 simulator in order to evaluate protocols performance over satellite and nanosatellite networks.

In spite of all performances previously discussed, XSTP protocol is not perfect. For this reason, we propose here some future research guidelines. We observed that transmission overhead on the return channel is significant in very high BER conditions ( $10^{-3}$ ) and this need to be reduced. Also, at the probing mechanism level, the decision principle needs to be improved in order to discriminate between congestion and other types of errors that might be found in nanosatellite networks. Another important aspect is the energy level spent during probing cycle. An interesting research will be to find how can we measure and quantify this energy. Moreover, an assessment of XSTP performance by considering more complex QoS metrics and scenarios could be an interesting research direction.

Other future studies could be directed towards XSTP performance over other types of topologies (i.e., Flower constellation, clusters, hybrid constellation – conventional satellites and nanosatellites). Another proposal is a comparison study between XSTP probing and TCP probing mechanisms, considering that both protocols can be configured with similar set of parameters as in our survey. This comparison might show the most effective mechanism in terms of adaptation to various satellite links errors. Finally, probing mechanism could be studied in wireless communication context or in a similar domain characterized by various types of communications errors.

This thesis has addressed two fundamental topics of nanosatellite networks: “routing in nanosatellite networks” and “QoS provisioning in nanosatellite networks” in Chapter 2.

We demonstrated in this thesis that XSTP protocol, initially designed for traditional satellite networks, could be a used in nanosatellite networks. Further work could be

concentrated on an in depth study of other traditional satellite network protocols, using simulations and analysis techniques.

Moreover, a study of the present network simulators might show if these tools could be adapted for performing nanosatellite network simulations.

Future work is also needed to develop dedicated protocols for nanosatellite networks that take into consideration the very limited resources of nanosatellites. Some first steps have already been made by a group of students from Aalborg University [119] in 2008 that developed the CubeSat Space Protocol (CSP) [120] – a small network-layer delivery protocol designed for CubeSats.

From our knowledge, there are no topologies specifically designed for nanosatellite networks. Therefore, the topologies of satellite networks (i.e. Mesh, Star, Hybrid) should be investigated in order to see if they are suited for nanosatellite networks or new topologies are needed.

We identified in this work the main constraints in terms of QoS for nanosatellite networks. Furthermore, we propose the following research directions for an efficient QoS provisioning in nanosatellite environment:

- 1) Developing tools that allow an efficient use of nanosatellite network resources; also, these tools can show the resources used by nanosatellite network at a certain moment and the priority of each type of traffic.
- 2) Developing QoS technologies in nanosatellite networks in order to accommodate multimedia services needed in the near future.
- 3) Developing specific methods for identifying the type of traffic carried by nanosatellite network. Classification is the first step for providing preferential service to a certain type of flow.
- 4) Developing congestion-avoidance techniques in order to monitor nanosatellite network traffic loads at certain points in the network, in an effort to anticipate and avoid congestion before it becomes a problem. If the congestion begins to increase, packets are discarded, leading to a slowing down of data transmission at the source node, as a result of the early dropped traffic detection.
- 5) Developing congestion-management techniques that operate to control congestion after it occurs. Congestion-management tools allow raising the priority of a flow by queuing and servicing queues in different ways. Congestion-avoidance and congestion-management are opposed mechanisms.
- 6) Developing traffic shaping and policing techniques for nanosatellite networks. Fundamentally, QoS provides priority either by raising the priority of one flow or by limiting the priority of another. Policing and shaping provide priority to a flow by limiting the throughput of other flows.
- 7) Defining End-to-End QoS levels that refer to the capability of the nanosatellite network to deliver the service needed by specific traffic from edge to edge. Every service delivered by nanosatellite network should have a certain level of QoS strictness which describes how tightly the service can be bound by specific bandwidth, delay, jitter, and loss characteristics. Since the QoS levels (i.e., Best effort, Differentiated service and Guaranteed service) are relevant only to terrestrial IP networks, other QoS levels need to be developed for nanosatellite networks. We think

that a good starting point is to investigate if these End-to-End QoS levels can be applied or adapted to nanosatellite networks and how can these levels could be implemented. If they are not suited for nanosatellite networks, other types of levels need to be defined.

In conclusion, we consider that QoS techniques can provide powerful value added service for nanosatellite networks. By using those mechanisms, we hope that the user traffic can be controlled and the nanosatellite network resources could be used efficiently.



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## List of my publications

### Articles:

- ✓ Maria-Mihaela Burlacu, Hacene Zidani, Joséphine Kohlenberg, Pascal Lorenz – “*Performance Study of eXtended Satellite Transport Protocol over a satellite network*”, Proceedings Book of SPACOMM 2010 – The Second International Conference on Advances in Satellite and Space Communications, June 13-19, 2010, Glyfada/Athens, Greece, ISBN: 978-0-7695-4067-2
- ✓ Bogdan Mocanu, Maria-Mihaela Burlacu, Joséphine Kohlenberg, Mahendiran Prathaban, Ruxandra Tapu, Pascal Lorenz – “*Determining Optimal Orbital Path of a Nanosatellite for Efficient Exploitation of the Solar Energy Captured*”, Proceedings Book of SPACOMM 2009 – The First International Conference on Advances in Satellite and Space Communications, July 20-25, 2009, Colmar, France, ISBN 978-0-7695-3694-1
- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg – “*An analysis of the nanosatellites launches between 2004 and 2007*”, Proceedings Book of The Third International Conference on Systems and Networks Communications Conference, October, 26 – 31, 2008, Sliema, Malta, ISBN 978-0-7695-3371-1
- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg, Mahendiran Prathaban – “*SIMOBIZ– Simulation tool to study the impact of small satellites in mobile market*”, Proceedings Book of The 4S Symposium - Small Satellites Systems and Services, May 26 - 30, 2008, Rhodes, Greece, ESA SP-660, ISBN 978-92-9221-224-7

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- ✓ Maria-Mihaela Burlacu, Pascal Lorenz, Joséphine Kohlenberg – “*Performance Comparative Study of eXtended Satellite Transport Protocol over Traditional Satellites Networks and Nanosatellite Constellations*”, International Journal On Advances in Telecommunications, ISSN: 1942-2601 (To be published in December 2010)
- ✓ Maria-Mihaela Burlacu, Pascal Lorenz – “*A survey of small satellites domain: challenges, applications and communications key issues*”, Published on September 24<sup>th</sup>, 2010 in ICaST Magazine:  
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- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg - “*A study concerning nanosatellite systems*”, Télécom&Management SudParis, 08006-RST 2008, ISSN 0183-0570

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- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg, Pascal Lorenz – “*Architectures et Performances des Réseaux Nano-satellites*”, Journée des Ecoles Doctorales de l’Université de Haute Alsace, June 3<sup>rd</sup>, 2010, Faculté des Sciences et Techniques, Mulhouse, France
- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg, Pascal Lorenz – “*Architectures et Performances des Réseaux Nano-satellites*”, Doctoriales d’Alsace 2009, November 14-19, 2009, Mittelwihr, France
- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg, Mahendiran Prathaban, Pascal Lorenz:
  - “*From Terrestrial Sensor Networks Routing to Routing in Nanosatellites Constellations*”
  - “*Mobility Aware Routing in Ad-Hoc Nanosatellites Networks*”Wireless Sensor Networks for Space Applications Workshop (WiSens4Space 2009), organized by European Space Agency, October 1-2, 2009, Santorini, Greece
- ✓ Maria-Mihaela Burlacu, Joséphine Kohlenberg – “*MEDUSA - Etudes Marketing, Economiques et Techniques pour le Développement des Applications Utilisant les Nano Satellites*”, 4<sup>th</sup> PERSEUS Workshop, February 5-7, 2009, Musée de l’Air et de l’Espace, Le Bourget, France