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Boris Tiomela Jou

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Par

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Performance enhancement and evaluation frameworks for integrated 5G satellite networks

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"Enjoy the journey as much as the destination." – Marshall Sylver

"First we must discern what we want, then we must have the courage to say it, and finally we must have the energy to do it." – Georges Clemenceau

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Dedication

In the loving memory of my ancestors and particularly my late father Michel Tiomela (père Cocodious) who were my guiding light, great source of inspiration, kindness, and sharing. I dedicate my research work to them, to him. May they rest in Peace

SOMMAIRE EN FRANÇAIS

Ce manuscrit est réalisé dans le cadre d'un doctorat par validation des acquis de l'expérience.

Les travaux présentés dans ce manuscrit retracent les contributions les plus significatives de mon parcours de recherche au cours des dix dernières années.

Ces travaux ont comme fil conducteur l'amélioration des performances de systèmes de communication par satellite (SatCom) pour répondre aux besoins croissant de connectivité. Cette thématique est abordée sous différents angles, allant de la définition et la sélection de critères et indicateurs de performances (KPI), aux techniques d'évaluation et d'amélioration de certains de ces critères, et à l'évaluation de leur efficacité pour une interconnexion efficace avec les systèmes terrestres dans un contexte 5G.

Le chapitre « Chapter 2 » aborde l'état de l'art et l'évolution des systèmes SatCom. Les critères de performances y sont revus suivant les principales caractéristiques et contraintes des systèmes d'accès large bande par satellite. Les critères retenus sont : la zone de couverture, la latence et la capacité en termes de bande passante et de débit.

L'amélioration de la zone de couverture peut se traduire par son extension et par la définition d'un niveau minimal de performance : puissance d'émission du satellite pour le lien descendant et gain de réception satellite pour le lien montant. Ces éléments peuvent être améliorés grâce à de nouvelles techniques d'amplifications, permettant de rediriger la puissance vers des zones spécifiques. Mais c'est surtout à travers les techniques d'antennes actives, permettant une reconfiguration numérique, plus dynamique de la zone de couverture, comparée à un re-pointage d'une antenne standard.

La latence quant à elle est améliorée par l'adoption des orbites basses, passant ainsi d'environ 500 ms en orbite géostationnaire à quelques dizaines de ms en orbite basse selon les systèmes.

La capacité en termes de bande passante et de débit reste le critère principal d'optimisation dans les systèmes SatCom et mobilise ainsi une part considérable de la recherche depuis des décennies. Les techniques de réutilisation de fréquences, avec des spots de plus en plus petits et proches, ont permis d'augmenter considérablement la capacité des satellites cette dernière décennie, leur permettant de passer de quelques dizaines de Gbps pour un satellite, à plusieurs centaines de Gbps, voire 1 Tbps.

La capacité disponible n'est toutefois pas encore suffisante pour répondre au besoin croissant de connectivité, notamment dans le contexte de nouveaux cas d'usages d'intégration de systèmes satellites et terrestres. De plus, cette capacité n'est parfois pas répartie de façon optimale pour être toujours en phase avec un besoin qui peut être dynamique (ex. connectivité maritime ou aérienne). Il y a donc un besoin croissant de flexibilité.

Mes travaux sur l'estimation précise de cette capacité et quelques techniques d'optimisation et l'intégration aux systèmes terrestres sont ceux choisis pour être davantage développés dans ce manuscrit.

Le chapitre « Chapter 3 » aborde deux techniques permettant d'améliorer les performances d'un système SatCom de différentes manières. La première concerne les techniques de compensation de produits d'intermodulation et l'optimisation du point d'opération d'un amplificateur de puissance d'un satellite alors que la deuxième, sur les formes d'onde, concerne la modulation à phase continue (CPM).

La modulation à phase continue consiste en une modulation continue de la phase avec un effet de mémoire, le symbole transmis à un instant dépendant d'un ou de plusieurs symboles transmis avant lui (en fonction de la taille de la mémoire). La technique est proposée dans le standard DVB-RCS2, mais à l'époque de l'étude il ne comportait aucune indication sur les techniques d'implémentation. Les travaux menés ont permis de proposer une implémentation du modulateur suivant la décomposition de Rimoldi. Dans un contexte de réalisation d'un terminal à très bas coût, cette décomposition qui a été retenue est la base d'un design et d'une implémentation sur un FPGA. Les performances d'un tel système se sont montrées cependant insuffisantes ou inadaptées pour les systèmes haut débit SatCom et la technologie n'a pas rencontré de succès. Elle est aujourd'hui proposée comme option sur certains terminaux, mais presque pas utilisée dans la pratique.

Les techniques de compensation de produits d'intermodulation viennent du besoin d'utiliser de manière plus efficace les amplificateurs de puissance des satellites, notamment par le fait que leur bande passante s'est accrue et qu'ils sont de plus en plus utilisés en mode multi-porteuses. Or dans ce mode, les produits d'intermodulation sont importants et obligent à utiliser les amplificateurs à une efficacité bien moins importante (parfois plus de 3dB). Les techniques de pré-distorsion permettent de réduire ces produits d'intermodulation et ainsi de faire fonctionner l'amplificateur de manière plus efficace (point de fonctionnement plus proche de son point de saturation). Cependant, il est difficile de définir de manière précise ce point de fonctionnement de manière optimale. Les techniques précédentes se basant sur une estimation du PAPR qui s'avère assez imprécise. La proposition décrite consiste à utiliser d'autres critères pour déterminer ce point optimal : l'estimation de marge du lien et le ratio d'erreur de trames. La recherche de ce point d'opération est effectuée en deux étapes, une recherche grossière, puis une recherche fine en utilisant un algorithme de maximisation d'une fonction convexe et un autre de type « recherche racine » (i.e. valeur pour laquelle la fonction est égale à zéro).

Avec la technique opérationnelle choisie, l'amélioration de débit grâce à la pré-distorsion atteint 10%, autant lors des tests en laboratoire que sur satellite.

Le chapitre « Chapter 4 » traite de la question contemporaine de l'intégration satellite/terrestre dans un contexte 5G. Le sujet étant assez récent et très peu étudié, tant le champ de recherche est vaste. Les sujets principaux abordés sont la spécification des cas d'utilisation et de la chaîne de la valeur, puis la spécification

des architectures de systèmes intégrés pour le support de la qualité de service et de la livraison de contenus en bordure de réseau.

Deux catégories de cas d'utilisation du satellite dans un réseau 5G ont été définies : l'accès direct depuis un terminal satellite au système 5G ou l'utilisation du lien satellite pour faire du backhaul. La suite de l'analyse a été faite pour cette seconde catégorie. La chaîne de la valeur de l'industrie des satellites est revue avec une proposition d'un rôle de broker (dealer) de capacité satellite dont l'interfaçage avec les différents opérateurs de satellites demanderont flexibilité et allocation dynamique de capacité.

Une architecture générique de backhaul satellite pour un réseau 5G est proposée, avec une identification des fonctions d'interfaçage nécessaires entre les deux systèmes. Les différentes options identifiées pour un tel usage sont regroupées en deux familles : la première se base sur le principe de nœud de relai, permettant à un terminal satellite de servir de point d'accès pour plusieurs terminaux non-satellite. La seconde se base sur un principe plus mature de satellites en réseau de transport, avec une interface de management avec les systèmes 5G.

Sur la base de ce réseau de transport, je propose une fonction d'interfaçage entre le réseau satellite et le système 5G sur le plan utilisateur. Celle-ci sera notamment chargée d'effectuer une correspondance entre les contraintes liées à l'indicateur de qualité de service d'un flux venant du réseau 5G (5QI) et l'allocation de ressources au niveau du satellite.

Enfin, le système satellite étant le candidat idéal pour effectuer du multicast sur une large zone de couverture, une architecture pour la livraison de contenus populaires en bordure de réseau 5G est proposée. Les procédures permettant la gestion d'une requête de contenu par un utilisateur en cas de présence d'un lien satellite et d'un serveur local de contenu sont proposées et revues dans le cadre des travaux de normalisation 5G au 3GPP.

Le chapitre « Chapter 5 » concerne mes travaux les plus récents sur la gestion des ressources dans des réseaux satellites, notamment ceux dédiés à la connectivité de plateforme mobile (maritime, aéronautique).

La ressource satellite est rare et chère, et le système est dynamique, dû aux mouvements des terminaux et à la variation des éléments pouvant perturber la qualité de la liaison satellite. Une estimation précise et continue de la performance de chaque réseau est donc essentielle pour l'optimisation continue de cette capacité tout au long de la vie du système.

Un cadre d'estimation de performance (appelé MAPAN) est donc proposé, avec la définition de trois types de performances : la performance planifiée (ou escomptée précédemment) avant l'activation du réseau, la performance actuelle (effectivement mesurée) et la performance prédite (escomptée dans le futur), après application des modifications à venir.

Ce cadre est ensuite appliqué avec la capacité en termes de débit comme critère de performance. La capacité planifiée est ainsi estimée suivant une proposition d'un terminal de référence placé au centre du beam (car à ce stade le réseau n'existe pas encore), auquel est appliquée une certaine marge en fonction du type de beam. Les

marges proposées ont été déterminées de façon empirique. La capacité actuelle est estimée sur la base de performance de terminaux actuellement dans le réseau. Enfin la capacité prédite est calculée sur la base de bilans de liaison à la demande, avec les paramètres actuels et futurs du réseau.

Un concept d'opérations est ensuite défini en se basant sur le cadre de travail MAPAN et en ajoutant un nouveau paramètre qui est la capacité commercialisable. Celle-ci est ajustée au gré des évènements et modifications des différents types de capacités définis précédemment. Cette approche permet aussi l'identification d'une potentielle sous-performance d'un réseau et ainsi d'initier une enquête sur sa source et éventuellement des actions correctrices.

En conclusion, les travaux abordés dans ce manuscrit balayent un large spectre de recherche dans le domaine des télécommunications par satellite. Ils gardent comme ligne de conduite l'optimisation du débit offert par les systèmes SatCom et son utilisation pour l'amélioration de systèmes terrestres.

Les perspectives sont toutes aussi nombreuses, comme évoqué dans le chapitre « Chapter 6 ». Elles s'articulent essentiellement autour de la question de la flexibilité, autant dans l'allocation des ressources que dans la zone de service. Parmi les thématiques d'intérêt, l'une des plus prometteuses est l'utilisation de l'apprentissage machine et de l'intelligence artificielle pour des estimations plus précises de la capacité, la comparaison avec les performances attendues et l'ajustement des ressources allouées.

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym / Abbreviation	Definition
5G PPP	5G Infrastructure Public Private Partnership
5QI	5G system Quality of service Identifier
ACI	Adjacent Channel Interference
ACM	Adaptive Coding and Modulation
AF	Application Function
AI	Artificial Intelligence
AM/AM	Amplitude Modulation-to-Amplitude Modulation conversion
AM/PM	Amplitude Modulation-to-Phase Modulation conversion
AN	Access Network
API	Application Programming Interface
APSK	Amplitude and Phase Shift Keying
ASI	Adjacent Satellite Interference
BE	Beam Edge
BFN	Beam Forming Network
BP	Beak Peak
BSS	Broadcasting Satellite Service
BUC	Block Up Converter
BW	Bandwidth
C&SP	Connectivity and service providers
CAPEX	Capital expenditure
CC-CPM	Turbo Coding and Linear Modulation
CCI	Co-Channel Interference
CDF	Cumulative Distribution Function
CIR	Committed Information Rate
CIR	Carrier to Interference Ratio
CN	Core Network
CNIR	Carrier to Noise and Interference Ratio
CNR or C/N	Carrier over Noise ratio
CoD or C/D	Carrier over distortion ratio
CoND	Carrier over Noise and Distortion ratio
CONOPS	Concept of operations
CPE	Continuous Phase Encoder
CPM	Continuous Phase Modulation
CS	Carrier Spacing
CSIM	Satellite Channel Emulator
DAC	Digital to Analog Converter
DN	Data Network
DPD	Digital Predistortion
DVB	Digital video Broadcasting
EHF	Extremely High Frequency

EIRP	Equivalent /Effective Isotropic Radiated Power
eMBB	enhanced Mobile Broadband
ESA	European Space Agency
EsNo	Energy per symbol to noise density ratio
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
FEC	Forward Error Correction
FER	Frame Error Rate
FPGA	Field Programmable Gate Arrays
FSL	Free Space Losses
FSS	Fixed satellite service
GEO	Geostationary Earth Orbit
GIBO	Global IBO
gNB	gNodeB
GW	Gateway
GWe	GW emulator
HARQ	Hybrid Automatic Repeat reQuest
HPA	High Power Amplifier
HTS	High Throughput Satellite
I	In-phase component of a signal
IAB	Integrated Access and Backhaul
IBO	Input Back-Off
ICSSC	International Communications Satellite Systems Conference
IET	Institution of Engineering and Technology
IMD	Inter-Modulation Distortions
IMT	Interference Mitigation Technique
IMUX	Input Multiplexer
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union - Radiocommunication
KPI	Key Performance Indicator
LEO	Low Earth Orbit
LM	Link Margin
LSB	Least Significant Bit
LTE	Long Term Evolution
LUT	Look-up Table
M&C	Monitoring and Control
MCPRED	Multi-Carrier Predistortion
MEC	Multi-Access Edge Computing
MEO	Medium Earth Orbit
MIR	Maximum Information Rate
ML	Machine Learning
MM	Memoryless Modulator
mMTC	Massive Machine-Type Communications
MNO	Mobile Network Operator

Modcod	Modulation and Coding
MSB	Most Significant Bit
MSE	Mean Square Error
MSS	Mobile satellite service
N3IWF	Non-3GPP interworking function
NCR	Network Clock Recovery
NF	Network Function
NFV	Network Function Virtualization
NISI	Nonlinear Inter-Symbol Interference
NMS	Network Management System
NR	5G New Radio
OBO	Output Back-Off
OMUX	Output Multiplexer
OOP	Optimal Operation Point
OPEX	Operational expenditure
PAPR	Peak to Average Power Ratio
PDU	Packet Data Unit
PEP	Performance Enhancing Proxy
PIR	Peak Information Rate
PSTN	Public Switched Telephone Network
Q	Quadrature component of a signal
QEF	Quasi Error Free
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RCS	Return Channel by Satellite
RF	Radio Frequency
RTT	Round-trip Time
Rx	Receive (Receiver)
SatCom	Satellite Communication
SatNet	Satellite communication network
SCPC	Single Channel Per Carrier
SDN	Software Defined Network
SE	Spectral Efficiency
SIC	Successive Interference Cancellation
SISO	Soft In Soft Out
SLA	Service Level Agreement
SMF	Session Management Function
SNO	Satellite Network Operator
SNR	Signal to Noise Ratio
SoC	System on Chip
SR	Symbol Rate
TC-LM	Convolutional Coding and Continuous Phase Modulation
TCP	Transport Control Protocol
TD	Total Degradation

TMTC	Tracking, Monitoring, Telemetry, Command
TN	Transport Network
TRL	Technical Readiness Level
TSSS	Traffic Switching, Splitting and Steering
TWTA	Travelling Wave Tube Amplifier
Tx	Transmit (Transmitter)
UE	User Equipment
UL CL	Uplink Classifier
ULPC (UPC)	Uplink Power Control
UPF	User Plane Function
URLLC	Ultra-Reliable, Low-Latency Communications
UT	User Terminal
UW	Unique Word
VAE	Validation des Acquis de l'Expérience
VHTS	Very HTS
VSAT	Very Small Aperture Terminal

SUMMARY

This PhD thesis is an insight in some of my research activities in the approximately past ten years. It is written in the context of a PhD by validation of acquired experience (PhD by VAE).

The first part of this process presents my career evolution.

The second part of this process provides an overview of all my research activities.

The third part of this process focuses on my other activities, not related to research.

This thesis is the last part of this process and it aims to provide further analysis on some of my main research activities.

Chapter 1. INTRODUCTION

1.1 SATELLITE COMMUNICATION SYSTEM OVERVIEW

A communication satellite is an artificial satellite dedicated to telecommunication services. It receives a communication signal from a transmitter on the Earth or from another satellite, eventually performs on-board signal processing, and signal amplification before transmitting to a receiver on the Earth or to another satellite. A communication satellite differs from other types of satellites mainly by the fact that its payload is a communication payload in charge of processing the signal. It is different from satellites for observation and science, and it does not necessarily embed sensors, telescopes, and other instruments.

The signal transmitted through a communication payload can aim to transport three principal services: voice, video, data. These services can be offered to fixed or mobile terminals. This raised to a first classification satellite services [1]:

- Broadcasting satellite service (BSS): point-to-multipoint unidirectional connectivity with fixed ground terminals, mainly used for video broadcasting
- Mobile satellite service (MSS): point-to-point bidirectional connectivity with mobile ground terminals, mainly used for voice
- Fixed satellite service (FSS): point-to-point bidirectional connectivity with fixed ground terminals, mainly used for data.

This classification is mainly applicable for satellite architecture design and in addition, broadband satellite service has emerged with the provision of higher data rate (more than few Mbps per user) to several users simultaneously. Broadband service was initially considered as an evolution of FSS with higher data rate for several users. This has evolved through the decades, partially due to the digitization of voice and video and to the adoption of voice and video over the internet. Today, broadband satellites can encompass FSS, BSS and MSS. Figure 1.1 represents this service categorization.

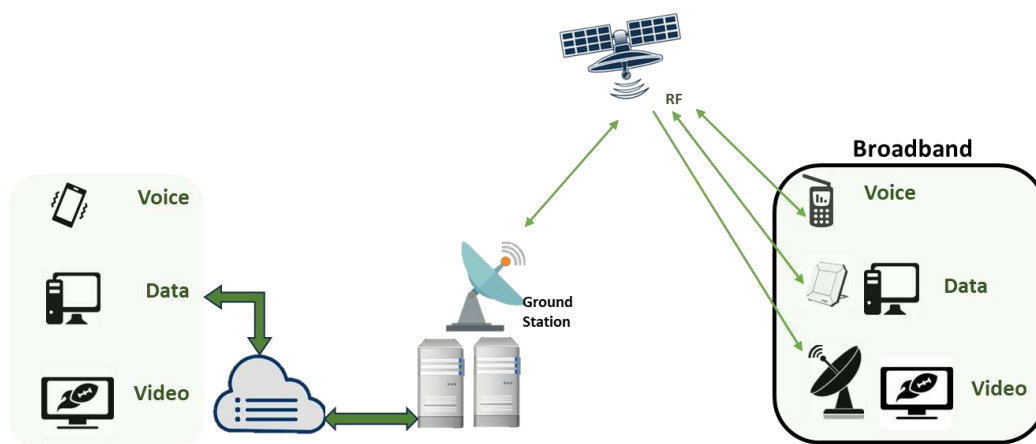


Figure 1.1: Service over a Satellite communication system

With the evolution of the demand, satellite systems delivering broadband services have progressively evolved to high throughput satellite (HTS) (up to 100 Gbps) and

very high throughput satellite (VHTS) (above 100 Gbps) systems [2] as represented in Figure 1.2 and Figure 1.3 below. The constellations in Non-geostationary earth orbit (NGSO) aim to bring complementary or competitive capacity to geostationary (GEO) VHTS systems with the advantage of low latency but the challenge of increased complexity, especially on the ground segment [3].

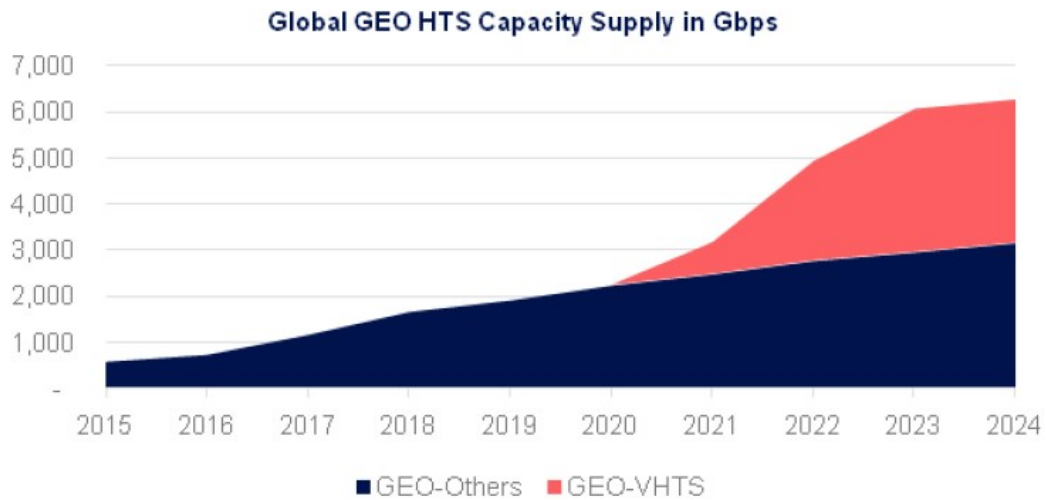


Figure 1.2: Global Satellite communication system capacity supply in Gbps
 (Source: Euroconsult research "Satellite Connectivity and Video Market", 2020)

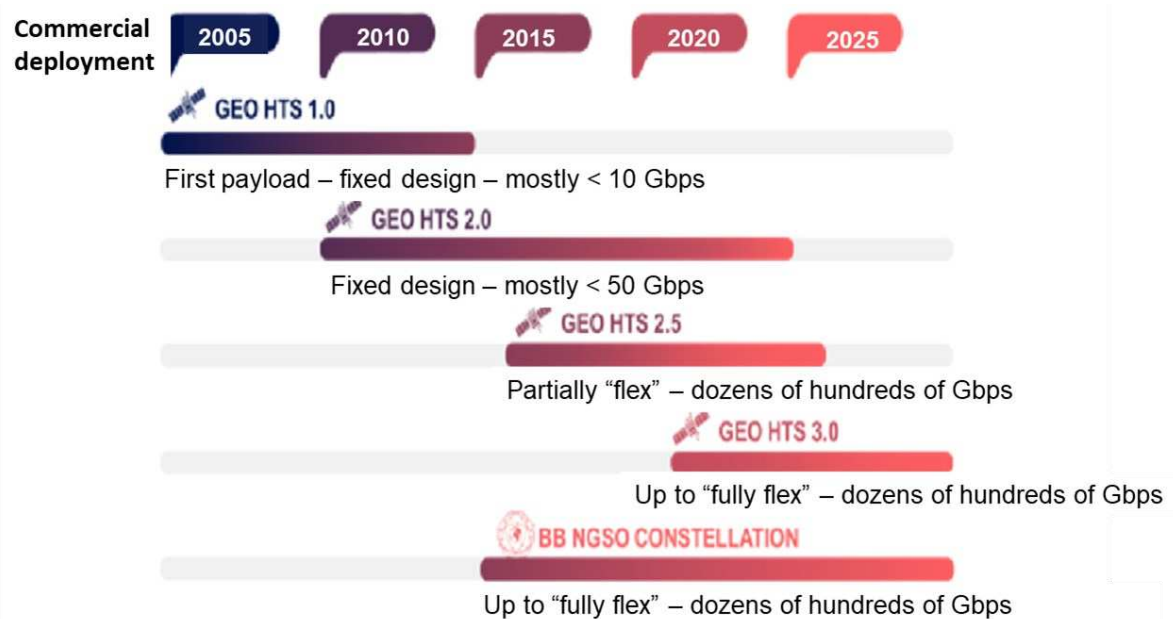


Figure 1.3: Evolution of (Very) High throughput satellite systems
 (Source: Euroconsult research "Satellite Connectivity and Video Market", 2020)

1.2 CONTEXT AND OBJECTIVES OF THE MANUSCRIPT

Satellite communications networks (SatCom) are evolving and embracing techniques and technologies from the most advanced digital evolution driven by several trends such as virtualisation, cloud computing, network slicing paradigms. As for the final objective of seamless integration with other networks, SatCom systems need to improve their capacity, flexibility, connectivity capabilities and cost effectiveness.

Historical satellite communication systems performance criteria of coverage, achievable capacity, target availability and signal latency remain key aspects to improve through the adoption of new techniques and concepts.

Coverage can now be extended on GEO satellites without significant signal level decrease on key areas thanks to new antenna shaping, improved amplification techniques and novel system resources allocation techniques. Therefore, the most capacity demanding area can be kept at an increased level. Full Earth coverage will also be achievable with satellites on non-geostationary orbits through Medium Earth Orbits (MEO) satellites (e.g., O3B MEO) and with the arrival of mega-constellations projects with Low Earth Orbits (LEO) satellites (OneWeb, Starlink, Kuiper Systems, Telesat Lightspeed).

Achievable satellite system capacity has certainly been the most important research topic of interest in order to face the always growing capacity demand. Hence, this topic certainly counts the highest innovations to achieve the evolution of average satellite capacity from 100 Gbps in the mid-2000s to terabit satellites in the mid-2010s. Combination of satellite systems allow to target almost 8 Tbps in the 2020s. VHTS growth pushes the VSAT (very small aperture terminal) based system and Broadband satellite market to require up to 15 Tbps by 2030 [4]. The principal innovation is the adoption of multibeam techniques and several impairments mitigation techniques (interference mitigation techniques mostly), which allows aggressive frequency reuse schemes. The higher frequency bands (Ka, Q and V Band) also allow more bandwidth in addition to traditional C band or Ku band. Other techniques such as optical feeder link and beam hopping are also being adopted for further capacity increase.

Satellite link availability (the normalised duration a link can support a given service) has been one of the most challenging topics in the past decades. The adoption of multibeam satellites increases the interference and may reduce availability. Most importantly, the adoption of higher frequency bands implies signals susceptible to signal degradation. But rain fade mitigation techniques such as uplink power control (UPC) and adaptive coding and modulation (ACM) and gateway (GW) diversity allow signal resiliency to such impairments [5].

System latency has essentially been improved by the adoption of non-GEO satellites which have reduced distance (and then signal latency) between the satellite and the earth. In addition, some techniques allow to keep this latency at the minimum. Thus, mesh network topology limits "on-system" latency [6]. The effect of signal latency on network protocols and services at application level can also be limited with improved techniques such as TCP Performance Enhancing Proxy (PEP) [7].

Besides the mentioned “legacy” satellite characteristics, two latest trends and associated requirements have emerged in the 2010s: the flexibility and the connectivity readiness.

In SatCom systems, the flexibility is ability to change over the lifetime of the system, some characteristics which used to be fixed or overly complex to modify (e.g., satellite coverage area, beam layout, beam allocated bandwidth, beam allocated power). The flexibility requirements mostly come from the inadequate even capacity distribution in the first HTS systems without possibility to move available capacity from one area to another, which has high demands. In general, implementing in-orbit satellite flexibility enables better usage of satellite resources during satellite lifetime. The flexibility contributes to increase system capability and effectiveness, reduce long term cost, encourage innovation, and protect against uncertainty [8]. In orbit satellite flexibility mechanisms include beam resizing, coverage modification, power redistribution. This is enabled by innovative designs based on active antennas, on-board digital processors, powerful Beam Forming Network (BFN) and techniques such as beam hopping [9].

Connectivity readiness can be summarised as the ability of SatCom network to interconnect to any third-party network (essentially Cloud and terrestrial 5G network) and support associated requirements (service requirements, time-out, support of network slicing, etc.). The connectivity readiness of SatCom and its integration with terrestrial networks is an interesting trend which has been investigated for years and has been subject of various proposals [10]. But recently, with the advent of the 5G system, there is an opportunity to specify and standardise such integration from day one. Satellite and terrestrial integration in the 5G context is seen as a complementary system to address coverage extension and various other use cases and the associated requirements and solutions are still under identification and specification [11].

This manuscript presents some of my research activities during the past decade, contributing to the evolution of satellite communication systems with focus on system performance enhancement and satellite-terrestrial connectivity in the 5G context. The first objective is to review the improvement of satellite communication systems with respect to legacy SatCom characteristics (coverage, availability, latency and capacity) and to propose some frameworks for performance assessment of the proposed techniques. Addressed topics include continuous phase modulation (CPM) evaluation for SatCom; and global optimization of satellite high power amplifier operation point in a context of the performance evaluation of a selected predistortion technique. The second objective is to address satellite and terrestrial integration in the 5G context. Thus, the use cases, the role models, the key issues, architecture options and the solutions for the seamless integration satellite and terrestrial integration in the 5G context are investigated. Finally, a concept of operation for capacity management in live satellite communication systems is also proposed and discussed.

1.3 ORGANIZATION OF THE MANUSCRIPT

The PhD thesis is divided into six chapters and organised as follow:

Chapter 1 introduces the context and the objectives of the dissertation.

Chapter 2 gives an overview of the state of the art of high throughput broadband satellite communication systems with their key characteristics and challenges which have pushed my research activities. It is concluded with a problem statement which clarifies the aspects which have motivated my research activities and the selected topics further investigated in this manuscript.

In Chapter 3, I focus on the SatCom based technologies on which I have performed research work in the recent years. It addresses performance improvement through adoption of some techniques at signal or system level: continuous phase modulation, optimization of satellite high power amplifier operation point for predistortion and associated performance evaluation.

Chapter 4 introduces the contemporary topic of 5G satellite-terrestrial integration and presents my research work on uses cases, role models, architecture specification and evaluation of key enablers (e.g., QoS mapping, edge delivery management, support of end-to-end network).

Chapter 5 discusses a performance assessment framework in live satellite systems and associated concepts of operations.

Finally, Chapter 6 summarises the thesis and sets some perspectives for the future work. It introduces a discussion on latest trends, including a recent proposal of a common end-to-end satellite performance evaluation framework and an ensuing concept of operations.

Appendices provide supplementary materials, including the summary of published/submitted contributions.

Chapter 2. STATE OF THE ART OF SATELLITE COMMUNICATION SYSTEMS EVOLUTION AND REQUIREMENTS FOR INTEGRATION WITH TERRESTRIAL SYSTEMS

2.1 SEGMENTS OF SATELLITE COMMUNICATIONS SYSTEMS

The SatCom systems are usually split into two segments: the space segment and the ground segment.

The space segment includes the satellite (or satellites) in orbit and its control system located at the satellite control centre and ensuring the satellite Tracking, Monitoring, Telemetry, Command (TMTC) [1]. It can also be referred to as control segment [12].

The term ground segment usually refers to gateways which transmit/receive radio wave signals to/from the satellite and support traffic from the remotes or satellite terminals for the spot beams they serve, usually to ensure the connection to the Internet backbone. TMTC systems are not included in the ground segment. Flexible and reconfigurable satellites require pre-computation of the satellite configuration on the ground, and thus it is sometimes referred to as mission ground segment and located in the mission control centre. Terminals or remotes (fixed or mobile) which are used to provide diverse types of services and traffic (e.g., voice, data) are identified as the user segment. Figure 2.1 below represents the SatCom segments.

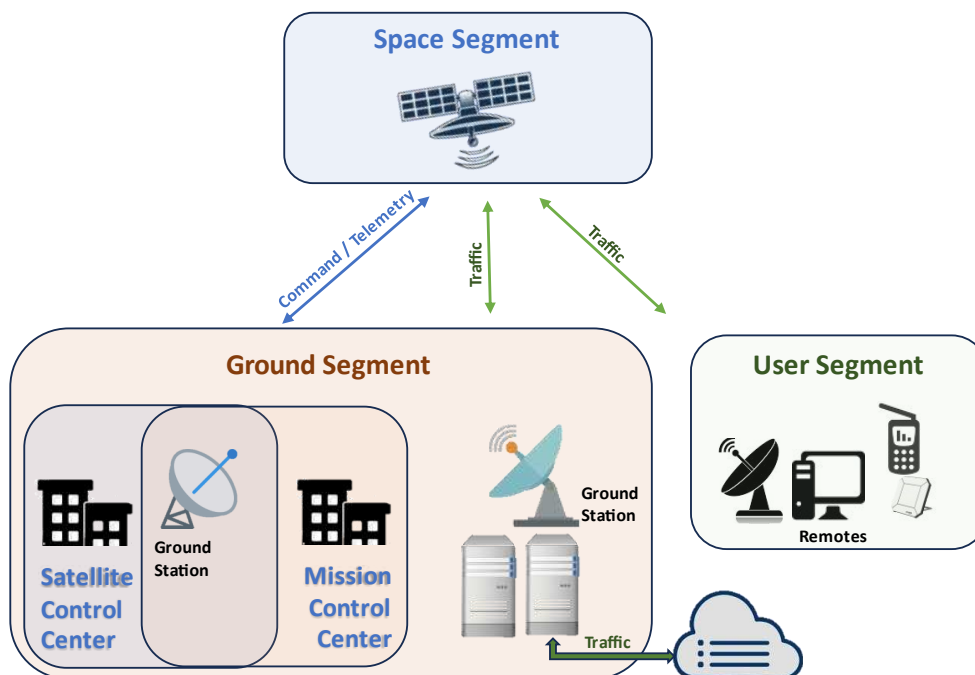


Figure 2.1: Segments of Satellite communication system

2.2 SATELLITE LINKS AND NETWORK ARCHITECTURES

2.2.1 Satellite links

Satellite links, as in any communication system, use the traditional communication link characteristics: simplex, half-duplex, and full duplex.

In addition, some terms and link characteristics are specific to SatCom systems. Hence, an uplink is a link from the earth station to the satellite. A downlink is a link from the satellite to the earth station. The forward link is the link from the gateway to the terminal and is a combination of uplink from the gateway and downlink to the terminal. The return link is the link from the terminal to the gateway and is a combination of uplink from the terminal and downlink to the gateway.

Figure 2.2 provides an overview of the different links in SatCom systems with the earth stations A and B representing the gateway and the remotes respectively.

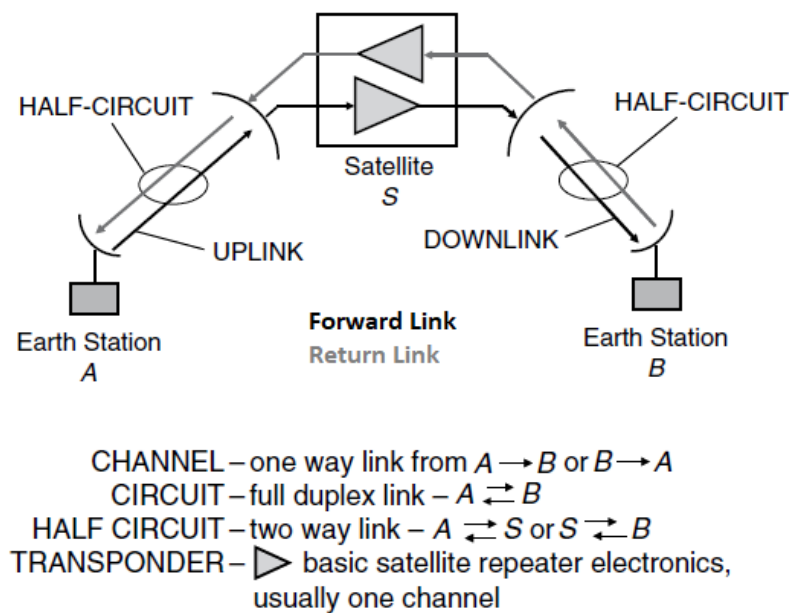


Figure 2.2: Overview of SatCom links and associated parameters [1]

2.2.2 Network architectures

SatCom systems operate in two main architecture configurations: mesh and star.

As shown in Figure 2.3, In the mesh configuration, two satellite terminals communicate directly with each other (point-to-point) which lower delay than in the star configuration. In the star configuration, there will be a central station (called a hub), and remote stations communicate via the hub, which implies a higher latency. The star architecture is the simplest one to connect several remote sites to a central facility. It can be seen as several point-to-point links. The star configuration is the most widely used configuration because it is easier to implement, more flexible and more cost-effective as resource access techniques can be used to share the resources with many more users than in the mesh architecture. Star and mesh architectures can also be combined in a dual architecture where, for instance, several remotes' sites are grouped in a cluster. The clusters use mesh architecture internally but communicate with other clusters via a single gateway (star architecture).

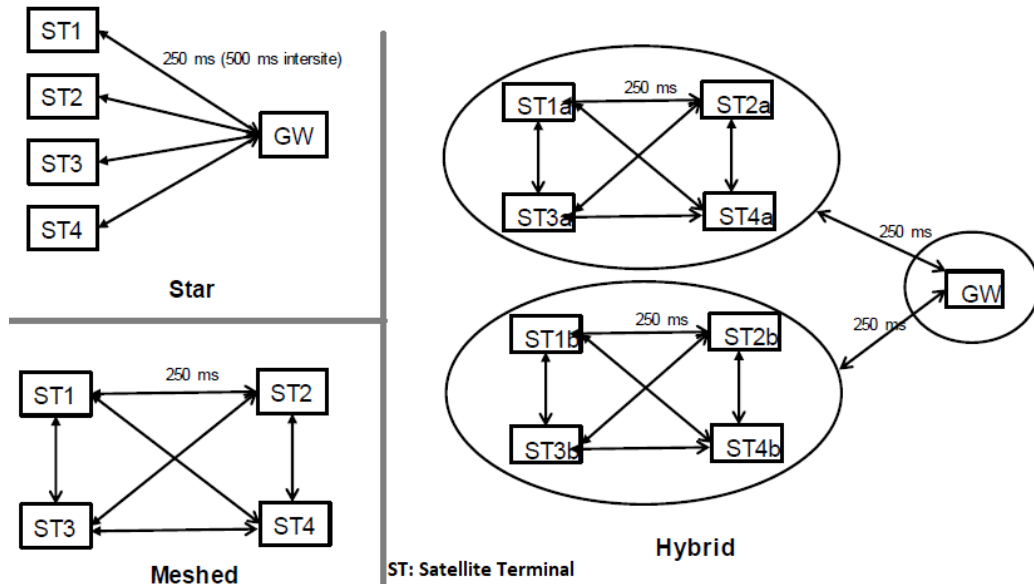


Figure 2.3: Star, Meshed and dual architecture [1]

2.2.3 Interconnection with terrestrial networks

The connectivity anywhere, anytime in the earth planet has been a growing objective for decades.

The SatCom system has always been a natural complementary to terrestrial connectivity solutions given its coverage capabilities, rapid deployment potential, and immediate high availability [13].

The initial SatCom systems were delivering FSS, BSS and MSS independently, with limited interaction with terrestrial systems (e.g., interconnection with public switched telephone network (PSTN) for voice circuits [14]). Only few protocol adaptations were implemented to cope with terrestrial systems and limit the potential negative impact of SatCom systems on some services (higher latency, higher bit error rate (BER) than terrestrial systems).

However, the requirement for further interconnection and management with terrestrial networks has arisen with recent use cases such as using satellite link in complement of a fixed terrestrial link [15].

With massive digitalization of networks and services, including voice over IP, and adoption of some protocols initially developed for terrestrial networks, the interconnection has evolved into advanced interconnection at several layers.

Several studies have investigated satellite and terrestrial integration options, and various solutions were proposed. This includes Satellite-WiMAX initiatives, proposing combination of satellite and WiMAX for remote connectivity [16], spectrum sharing studies [17], [18], satellite and LTE (Long Term Evolution) interconnection [19] and most recently satellite and terrestrial integration in 5G context.

The main architecture principle of satellite and terrestrial interconnection solutions is provided in *Figure 2.4*.

Recent use cases identified in the frame of the 5G integration and capabilities of new broadband satellite systems have led to new satellite and terrestrial network integration requirements and challenges. An overview of the main requirements and challenges are provided in section §2.4.5 and some of them are further investigated in Chapter 4, including the 5G integrated satellite and terrestrial network architecture.

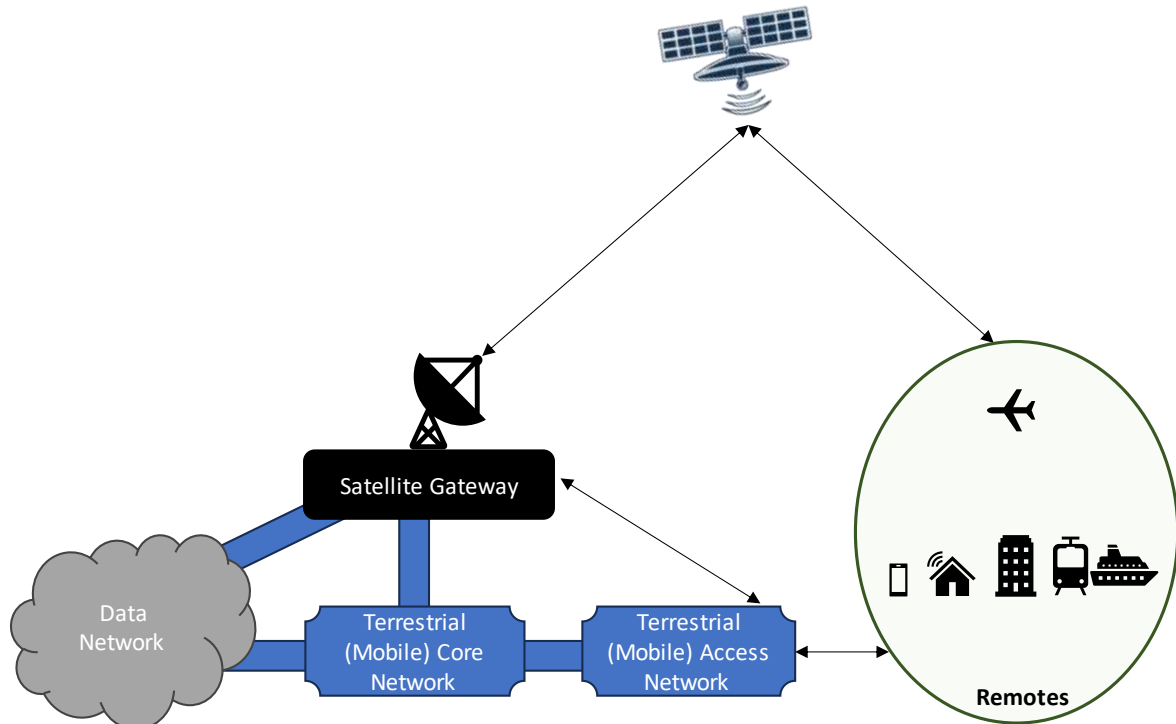


Figure 2.4: Overview of satellite and terrestrial interconnection architecture

2.3 CHARACTERISTICS AND PERFORMANCE ASSESSMENT

2.3.1 Coverage

Coverage has always been a key argument for SatCom systems compared to terrestrial systems. Near global coverage of the Earth can be reached with three equally spaced wide coverage GEO satellites. Full constellation in non-GEO (i.e., MEO or LEO) can also provide entire world coverage. The footprint of the satellite on a region on the earth, sharing the same resources (frequency, polarization and power) is called beam.

In complement of GEO satellites providing global coverage though global beams (up to 1/3 of the world), there are several satellites focused on a specific area, with smaller beams. HTS and VHTS typically use several smaller beams to offer regional coverage, which imply higher signal performance compared to the global (larger) beams.

Figure 2.5 represents an example of HTS regional coverage (SES-14).

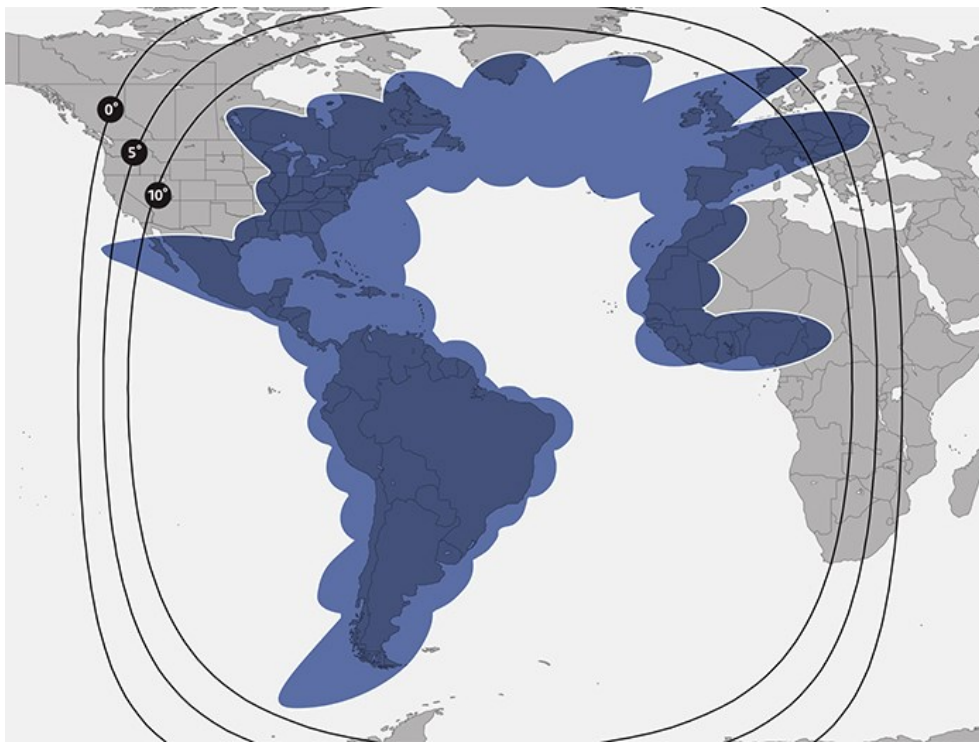


Figure 2.5: SES-14 regional coverage with spot beams (Source SES)

2.3.2 Latency

The latency encompasses the propagation delay and the processing delay. In SatCom systems, the propagation delay is the main contributor to the latency, in particular with the GEO satellite, the propagation delay between the earth and the satellite being around 240 ms. The satellite links have an average round-trip time (RTT) of around 480 ms in this case (excluding the processing delay) and it can affect several types of service (typically voice) and network protocols.

SatCom systems with satellites on lower orbit will have reduced propagation delay compared to GEO: the one-way latency reduces to around 4 ms for a LEO orbit at 600 km of altitude and a little over 60 ms for a MEO orbits at 10000 km of altitude.

Congestion can also increase due to the effect of the latency at network/transport protocol layers as packets of data can be delayed due to queuing or retransmission when using acknowledgement-based protocol like Transport Control Protocol (TCP). Solutions exist (e.g., header compression, acceleration or “spoofing”, http2) to accelerate the downloading of Web pages and modern browsers include features that help such as pipelining requests, pre-fetching content and data compression. Content caching, consisting of sending the “popular” contents before the user requests it, may also conceal the delay issues [20].

2.3.3 Link budget and spectral efficiency

The link budget is the basis of several performance assessment and analysis of SatCom systems as with any telecommunication system.

A link budget is based on the transmit location characteristics, the receive location characteristics, and the satellite characteristics.

The equations (eq. 1), **Error! Reference source not found.**, **Error! Reference source not found.** and (eq. 5)**Error! Reference source not found.** represent the well-known satellite link budgets models [12] used to compute the carrier to noise and interference ratio, noted CNIR or $C/(N + I)$.

$$CNIR^{-1} = CNR^{-1} + CIR^{-1} \quad (eq. 1)$$

Where CNR is the carrier to noise ratio in natural units and CIR the carrier to interference ratio in natural units, further detailed in section §2.3.6.

The CNR in dB is calculated as specified in **Error! Reference source not found.****Error! Reference source not found.:**

$$CNR = EIRP + G/T - FSL - k - A_T - 10\log_{10}(BW_b) \quad (eq. 2)$$

EIRP is the effective isotropic radiated power of the transmitter in dBW, G/T is the figure of merit of the receiver in dB/K, FSL is the Free Space Loss in dB, k is the Boltzmann constant (-228.6 dBW/K/Hz), A_T is the atmospheric attenuation in dB, and BW_b is the allocated bandwidth in Hz.

Once the CNIR is calculated, the energy per symbol to noise density ratio (E_s/N_0) can be derived and be compared to the E_s/N_0 threshold to identify the achievable modcod of the used waveform. The achievable spectral efficiency¹, noted SE, is then provided according to the waveform. In the case of DVB-S2X, expected efficiency per modcod and related energy per symbol to noise density ratio E_s/N_0 threshold are provided in the Table 2-1.

The Table 2-1 shows the spectral efficiency for a Newtec modem [21].

The spectral efficiency, noted SE in this thesis, is the bit rate (in Mbps, bps, etc..) per unit of bandwidth or symbol rate (in MHz, kHz, Hz, etc.) of a communication channel or data link. According to Shannon theory, the maximum spectral efficiency can be defined by $SE = \log_2(1 + E_s/N_0)$

Table 2-1: Some DVB-S2X modcods and associated required EsNo and spectral efficiency [21]

Modcod	Es/No threshold (dB)	Efficiency per symbol (bps/ baud)
QPSK1/4	-2.62	0.36
QPSK1/3	-1.28	0.62
QPSK2/5	-0.25	0.74
QPSK1/2	1.14	0.83
QPSK3/5	2.37	1.13
QPSK2/3	3.22	1.26
QPSK3/4	4.18	1.39
QPSK4/5	4.81	1.48
QPSK5/6	5.32	1.56
8PSK3/5	5.66	1.69
QPSK8/9	6.45	1.69
8PSK2/3	6.7	1.88
8PSK3/4	8.12	2.08
16APSK2/3	9.12	2.51
8PSK5/6	9.54	2.34
16APSK3/4	10.39	2.76
16APSK4/5	11.19	2.93
16APSK5/6	11.77	3.1
16APSK8/9	13.16	3.36
32APSK3/4	13.64	3.42
32APSK4/5	14.56	3.63
32APSK5/6	15.12	3.84
32APSK8/9	16.64	4.16

2.3.4 Capacity / Throughput

The capacity in SatCom systems is the main key performance indicator and the main point of improvement since decades.

In modern SatCom systems, it is usually an estimation of the data rate (in Mega, Giga or Tera bit per second - Mbps, Gbps or Tbps) that the satellite can deliver (see 2.3.4.1) and/or the data rate that a user can achieve in both forward and return direction (usually in Mbps, see §2.3.4.1)¹.

The computation of capacity is based on link budgets which will provide the links (forward and return) performances in terms of carrier to noise and interference ratio (CNIR) or signal to noise ratios (SNR) (eq. 3).

$$C = BW * SE \quad (eq. 3)$$

Where C is the capacity, BW is the channel bandwidth in Hz, and SE is the spectrum efficiency in bit/s/Hz as defined in section §2.3.3.

¹ Satellite system capacity can also refer to the total available bandwidth or the maximum number of simultaneous users that the satellite can support. In this latest case, it is mostly driven by the access layer design and the scheduling capabilities of the user ground segment.

2.3.4.1 User capacity or user data rate

The user capacity is the data rate that a single user can reach. It is the visible parameter and a key technical performance indicator from the end user perspective. The user data rate is often provided in both forward and return links in terms of committed information rate (CIR) and maximum (or peak) information rate (MIR or PIR). It depends on resources allocated by the SatCom network (essentially bandwidth, time slot) and on end user characteristics such as location with respect to the SatCom beam, user equipment (UE) capabilities, mainly the antenna size and figure of merit and the maximum transmit power.

Based on the mentioned parameters, user data rate is assessed by establishing link budgets and assessing link performances as described in section §2.3.3.

The forward link user data rate is established based on the link budget of the forward link (based on teleport GW transmitter, UE receiver and allocated system resources for the given user) which will provide a signal noise ratio and a derived EsNo. Based on the waveform performance table (an example is the Table 2-1 provided above), for a given user, the achievable EsNo allows to identify the achievable modcod and the associated efficiency. Then, the value of the forward bandwidth allocated to the user is multiplied by the modcod efficiency to obtain the forward user data rate.

The same process is done for the return link to obtain the return link user data rate.

2.3.4.2 Overall system capacity assessment

Overall forward and return system capacity is assessed based on the total forward and return bandwidth that the system can achieve and considering average spectral efficiencies which are themselves based on the average forward and return links performances. Only clear sky attenuation is usually considered and precision of the capacity assessment is related to the precision of the contributors such as interference assessment, waveform and margins, spectral efficiency, etc.

$$\Gamma_{sat}(d) = \sum_{b=1}^N (BW_b^d * SE_b^d) \quad (eq. 4)$$

Hence, in (eq. 4), d is the direction, forward or return, $\Gamma_{sat}(d)$ is the estimated satellite capacity on direction d , N is the number of beams in the system, BW_b^d is the total bandwidth of the beam b and direction d , SE_b^d is the average spectral efficiency of the beam b on direction d .

2.3.5 Link availability

The link availability is the percentage of time over a year during a communication can be established with a predefined minimum quality of service. The link availability is specified on a statistical basis, since it is mainly affected by propagation conditions which is a non-deterministic event [22].

The Table 2-2 shows an estimation of the outage time corresponding to some common availability targets in SatCom systems.

Table 2-2: Annual and monthly outage duration for given link availability

Target availability A (%)	Estimated outage 100-A (%)	Outage duration on annual basis (hr/min per year)	Outage duration on monthly annual basis (hr/min per month)
100	0	0 hr	0 hr
99.999	0.001	5 min	0.4 min
99.995	0.005	26 min	2 min
99.99	0.01	53 min	4 min
99.9	0.1	8.76 hr	44 min
99.95	0.05	4.38 hr	22 min
99	1	87.6 hr	7.3 hr
90	10	876 hr	73 hr

As identified in section §2.3.6, the effect of the propagation conditions varies according to the location, the frequency band, carrier capabilities, etc. Thus, satellite network performances will be better under clear sky conditions than perturbed conditions, and less affected in lower bands (L band, C band) than higher bands (Ka, Q, V) and optical link.

The CNR would thus be dependent on the propagation condition.

To reach higher availability values (higher than 95%) the considered modcod is often lower (i.e., more robust, and less spectral efficient) than the one used to compute or assess capacity. It means that announced estimated availability of a SatCom system is often the target availability with a capacity lower than the announced estimated capacity (which is usually computed considering clear sky conditions as stated above).

The link availability is a key requirement when designing SatCom systems and is taken into account to select the GW locations and to implement various technologies and functions to reach the target availability. These technologies are addressed in section §2.4.2.

2.3.6 Transmission losses and impairments

The characteristics and performance of a satellite system can be affected by losses and impairments on the transmission link. These can happen at different points of the RF transmission chain, from the transmitter to the receiver. Losses and attenuation are characterised by a decrease of the signal power while impairments are usually characterised as noise or interferences.

The main transmission losses and impairments are:

- Free-Space Losses (FSL): attenuation of signal due to the distance between the transmitter and the receiver. It is expressed as $FSL = (4\pi d/\lambda)^2$, where d is the distance in m and λ is the wavelength of the signal carrier in m.
- Propagation attenuation: atmospheric perturbation including rain, gaseous, cloud and fog attenuation. The ITU-R recommendations P.676, P.840, and P.618 provide statistical models and databases to compute propagation attenuations.
- Ground segment equipment impairments: this includes antenna cross-polarisation isolation, potential intermodulation distortions (IMD) when the amplifier is operated close to saturation, and other equipment losses and interference from terrestrial systems.
- Satellite equipment impairments: this includes antenna cross-polarisation isolation, and transponder impairments including IMD resulting from operation of the HPA close to saturation (Figure 2.6).
- System impairments: these are the main origin of most known interferences characterised by CIR (dB) calculated following (eq. 5) **Error! Reference source not found.** where:
 - CCI is the co-channel interference in dB: interferences due to the frequency reuse, especially considerable in HTS and VHTS systems based on multi-beams.
 - ACI is the adjacent channel Interference in dB: interferences due to the utilisation of adjacent frequency.
 - ASI is the adjacent system interference in dB: interferences due to adjacent satellites covering the same area and transmitting with overlapping frequency ranges. It can also include interference due to terrestrial systems transmitting and the same or overlapping frequency range.

$$CIR^{-1} = CCI^{-1} + ACI^{-1} + IMD^{-1} + ASI^{-1} \quad (eq. 5)$$

Some impairment effects are limited thanks to agreed or normalised techniques (e.g., regulatory limit of power flux density limits inter-satellite or inter-system interference). But others need the development and adoption of efficient mitigation techniques.

The IMD for instance can be addressed by predistortion techniques which consist of applying an estimation of the inversed function characterising the IMD. This is further detailed and investigated in section §3.2. of this thesis.

The total degradation (TD, in dB) (eq. 6) is used to characterise the impacts of output backoff (OBO in dB) on the overall link performance. Increased OBO leads to lower output power and reduced CNR, but also induces reduced IMD [23].

$$TD = (E_s N_0)_{req}^{NL} - (E_s N_0)_{req}^{AWGN} + OBO \quad (eq. 6)$$

Where TD is the total degradation in dB, $(E_s N_0)_{req}^{NL}$ is the required EsNo on a nonlinear channel in dB and $(E_s N_0)_{req}^{AWGN}$ the required EsNo on linear channel or AWGN in dB. OBO is the output backoff¹ in dB.

The illustration of a power amplifier main characteristics is provided in Figure 2.6.

The saturation point is the point at which an amplifier can no longer increase the output signal level, resulting in a distorted output signal.

The operation point of a power amplifier is defined the point in the power transfer curve which match with the level of the power of the carrier at the input of the amplifier and the level of amplified signal at the output of the power amplifier. It is characterized by the input backoff (IBO), the OBO, the maximum power of the power amplifier or its saturation point and its power transfer curve.

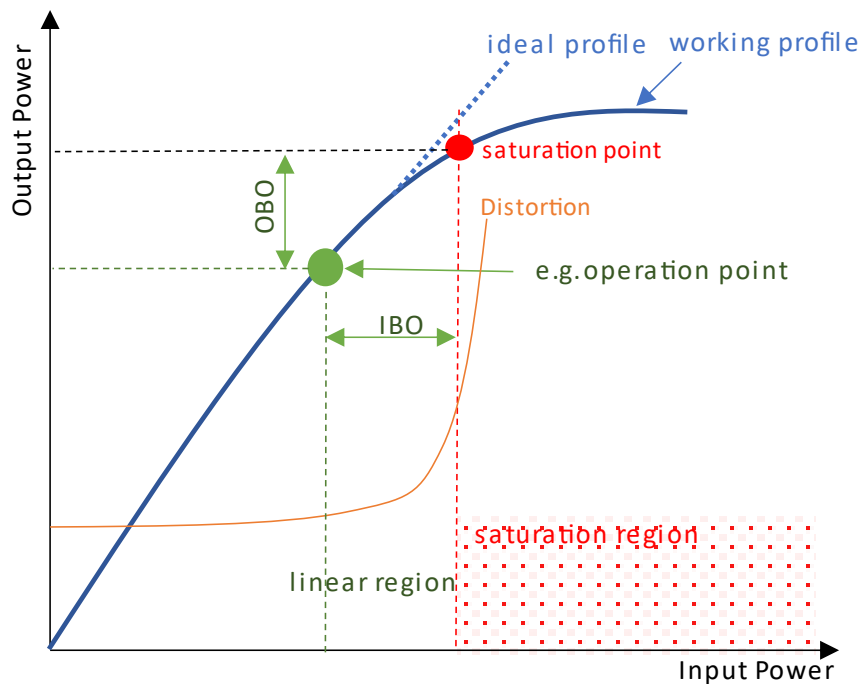


Figure 2.6: Illustration of amplifier operation profiles, regions and resulting distortion

¹ The input backoff (IBO) [and the output backoff (OBO)] is the difference between the input [output] saturation power and the input [output] power of the actual operation point of an amplifier.

2.4 TECHNOLOGY EVOLUTION AND CHALLENGES OF SATELLITE COMMUNICATION SYSTEMS

2.4.1 Capacity enhancement

Capacity is one of the main important characteristics of SatCom systems and the main focus for optimization and enhancement since the first day of communication satellites. It is probably linked to the fact that capacity does not necessarily increase linearly with investment whereas it is the main source of revenue. Thus capacity optimization would lead to an increase of profitability.

2.4.1.1 Bandwidth increase

Among all the parameters impacting the achievable capacity, it can be deduced from (eq. 3) that increasing the total available bandwidth is the most efficient way to increase the achievable capacity.

Higher frequency bands:

Upper frequency bands (Ka, Q, V) provide additional spectrum [24]. As shown in Table 2-3, the available spectrum can therefore vary from 5.5 GHz in Ku band to 8.5 GHz in Ka band, and >5 GHz in Q/V/W bands (for feeder link) [25]. But higher frequency bands also imply systems facing as important impairments as the frequency bands increase (cf. §2.3.6), resulting in system availability issues which can be addressed by techniques described in section §2.4.3.

Table 2-3: SatCom spectrum in different frequency bands

SatCom Frequency Band	SatCom Frequency Range	Main usage
L band	1 - 2 GHz	Used for Mobile SatCom and IoT over satellite
S band	2 - 4 GHz	
C band	5.850 - 6.425 GHz	Primarily used SatCom for satellite TV and wide beams
X band	7.9 - 8.4 GHz	Used for SatCom uplink, military SatCom
Ku band	10.5 - 14.5 GHz	Used for SatCom uplink and downlink, FSS and maritime services
Ka band	17.3 - 21.2 GHz 27.5 - 31 GHz	Used for SatCom downlink, uplink FSS and VHTS
Q/V Bands	37.5 - 42.5 GHz 42.5 - 43.5 GHz 47.2 - 50.2 GHz 50.4 - 51.4 GHz	Used for SatCom feeder link and VHTS

Multibeam and frequency reuse:

The total bandwidth of a satellite system is also commonly increased in modern communication satellites by adopting today's well known multibeam or multispot techniques associated with frequency reutilisation techniques. It is the main basis of the design of Terabit/s satellite [26].

Initial communication satellites typically had a wide and single beam coverage. Multibeam techniques allow to cover a given area with several smaller beams (or spot beams) instead of a single wide beam (Figure 2.7).

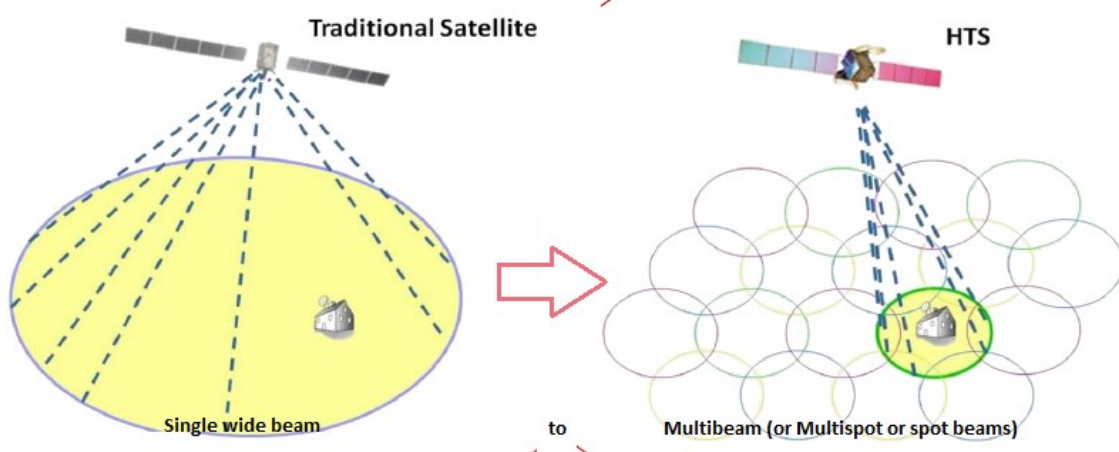


Figure 2.7: Wide beam vs Multibeam coverage

The multibeam coverage is not necessarily uniform in terms of beam size and resources allocation (e.g., frequency and power). In addition to frequency reuse in different spot beams, multibeam with smaller beam and similar power would also lead to the increase of power spectrum density, which can also improve the spectral efficiency and thus the capacity as explained in section §2.3.3. A "beam colouring" is then performed to assign colour (combination of frequency + polarisation) to the beam and minimise Co-Channel Interferences (CCI) by a certain spatial isolation (minimum distance) of 2 beams using the same colour. The resulting total bandwidth of the system is increased. So is the total throughput and the capacity density.

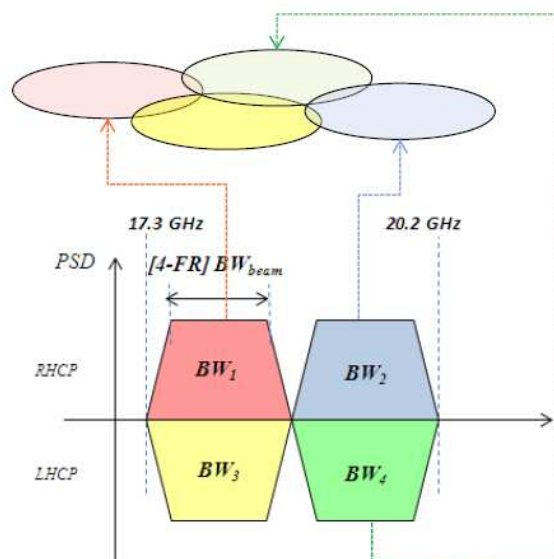


Figure 2.8: Homogenous bandwidth allocation with a 4-colour pattern

The common frequency reuse scheme is the 4-colours pattern which has a good combination of limited complexity in implementation and very good robustness against CCI. As represented in Figure 2.8, the 4-colours pattern combines isolation by a mix of opposite polarisations and sub-bands. Then for available bandwidth BW_{av} , half of the bandwidth (and a polarisation) is allocated to a beam. The resulting total bandwidth of the system is then provided in (eq. 7).

$$BW_{total} = N_{beam} BW_{av} * \frac{N_{polar}}{N_{colour}} = FRF * BW_{av} \quad (eq. 7)$$

Where N_{beam} is the number of beams in the system, BW_{av} is the available spectrum for the considered link (FWD or RTN) and N_{polar} refers to the two possible polarisations (usually 2), and N_{colour} is the number of colours. FRF is the frequency reuse factor. There is no common definition of the frontier between HTS and VHTS and the level of FRF can be one of the relevant metrics for the distinguishment. Thus, HTS would have FRF up to 4 and VHTS FRF greater than 4.

2.4.1.2 Improve spectral efficiency

Improved spectral efficiency is another approach to improve the capacity of a communication satellite and can be achieved by improving the link budget (CNR, CIR, CNIR, SNR) or with improved modem performance with lower modcod threshold.

Improve the link budget: higher power and interference mitigation techniques

To improve the link budget and target a higher (thus more efficient) modcod, it is important to identify the limiting factors or the global link budget. The link can be power, and/or interference limited (cf. §2.3.6). A cumulative distribution function (CDF) of the main link budget contributors is commonly used to identify the limiting factor. Figure 2.9 shows an example of thermal or power limited link budget as the CNR is the limiting contributor to the global link budget (CNIR). In such cases, the priority will be to improve the thermal link budget by increasing the transmitting power, under the limits of the regulatory allowed power density in the area and pending ability to improve power, especially on the downlink as power is a limited resource on-board the satellite. Some techniques can however allow the reduction of the OBO and operate the satellite transponder closer to the saturation points with limited additional impairments. It is the case of predistortion which is one of the topics developed in this manuscript (cf. §3.3.4).

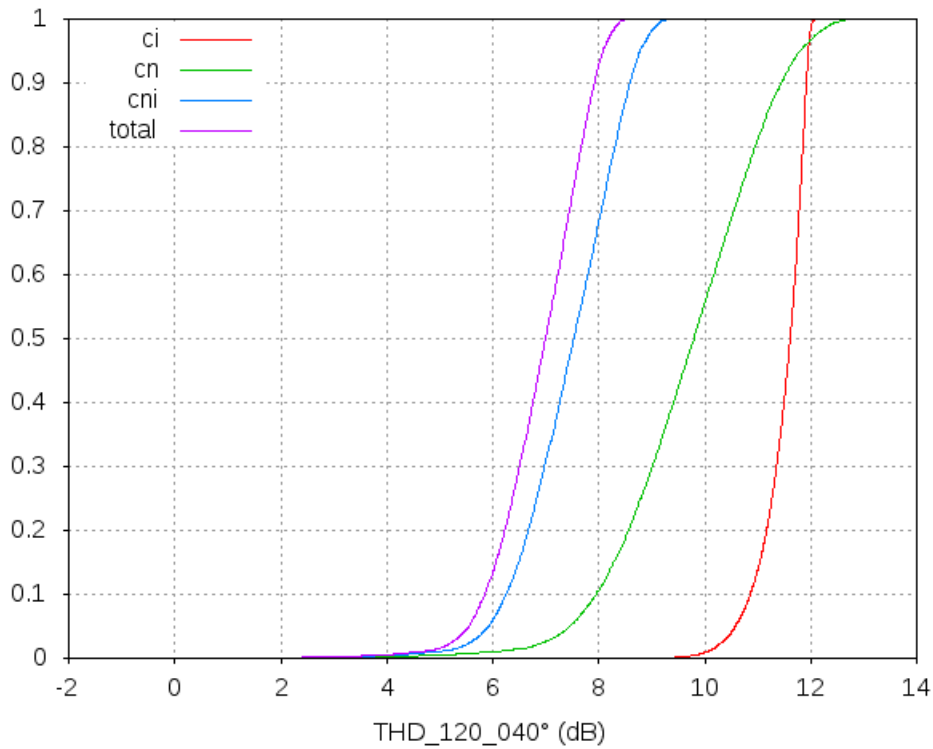


Figure 2.9: Thermal limited link budget

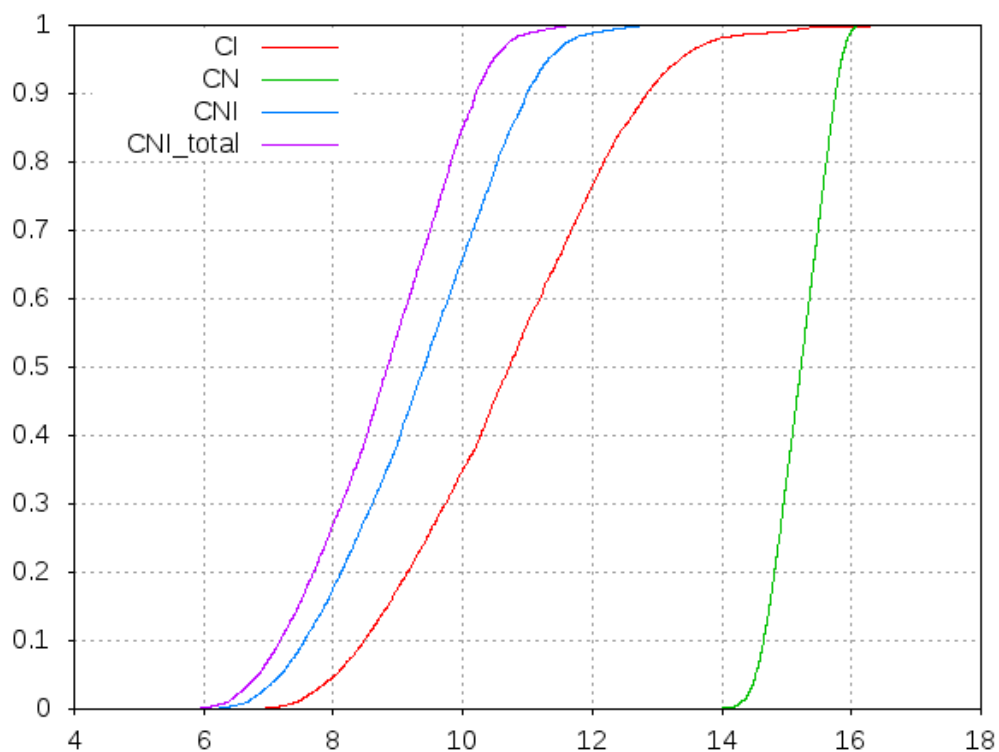


Figure 2.10: Interference limited link budget

In the same manner, Figure 2.10 shows an example of interference limited link budget as the CIR is the limiting contributor to the global link budget (CNIR). In such cases, the priority will be to improve the interference link budget. As interferences represented here are the combination of various interference contributors, it is important to identify which is the main interference contribution to mitigate.

In VHTS systems, implementation of a large number of beams with frequency reuse to increase the total system bandwidth leads to significant co-channel interferences (CCI). If some fading mitigation techniques, such as Adaptive Coding and Modulation (ACM), emerged with the aim of providing a higher flexibility and increased system availability (cf. §2.4.3), other techniques, known as pre-coding, are proposed to mitigate the resulting CCI [27]. Such techniques would improve the interference link budget and then the system capacity in an interference limited system [28].

In addition, increased available bandwidth per beam in VHTS systems leads to the introduction of several carriers per channel resulting in intermodulation products or distortion [29], which is a significant interference contributor in multi-carriers' systems. Various interference mitigation techniques (IMT) based on data predistortion [30] and signal predistortion [31] aim to mitigate the so-called nonlinear predistortion.

An innovative digital predistortion (DPD) technique and associated throughput gain has been investigated and evaluated during the research activities described in this manuscript and is further detailed in §3.3.4.

2.4.1.3 Improve waveform and enable connectivity at low SNR

Apart from the adoption of higher order (and more efficient) modulation schemes, another approach to increase the HTS system capacity is to reduce the gap between thresholds of the modcod with an improved and more efficient modem. This can be achieved by adopting a finest granularity of SNR vs modcod as proposed by DVB-RCS2 standard [32].

On the other hand, the transmission at "very low" SNR allows additional capacity by enabling connectivity in difficult situations. For instance, terminals at the edge of coverage or with very limited equipment (antenna size and block up converter (BUC) power) are then able to use the satellite and increase the overall system capacity. Such an approach is introduced by the DVB-S2x standard for the forward link with $\pi/2$ modulation scheme [32] and in DVB-RCS2 standard [33] with continuous phase modulation scheme. This latest approach is evaluated in this manuscript as part of my research work in §3.1.

To further increase system capacity, other techniques are foreseen, in particular the beam hopping for GEO systems. It consists of successive allocation of the maximum bandwidth to a selection of active beams on a time basis. It allows to target a frequency reutilization close to full frequency reuse (i.e., each beam can use the entire available bandwidth) and to provide the capacity where it is needed [34]. The beam hopping technique has been one of my research topics, but was not selected to be further addressed in the frame of this manuscript, which could not address all the topics as discussed in the problem statement (section §2.5).

2.4.2 Latency enhancement

Propagation delays, as the most contributor to the system latency cannot be reduced. Unless a deep review of system conception is adopted (e.g. by using lower orbits (non-geostationary orbits)).

Processing latency is improved by faster processing capabilities and innovative design of computation in the communication chain, in particular the time and frequency synchronisation mechanisms and FEC (Forward Error Correction).

At network level, techniques such as TCP acceleration allow not to increase the latency due to congestion control and packet retransmission scheme in standard TCP [35].

Finally, indirect improvement can be achieved through caching techniques which allow contents preloading before actual request or consumption. Such concepts are particularly investigated in the frame of satellite and terrestrial integration in the 5G context and technical implementation are proposed in section §4.4.5.

2.4.3 Availability enhancement

As a key requirement for communication systems, the availability is always monitored when improving other SatCom system parameters. For instance, capacity enhancement through adoption of higher frequency bands and even optical link leads to lower link availability as extremely high frequency (EHF: 30 to 300 GHz) are very sensitive to rain and other atmospheric impairments (cf. 2.3.6).

Therefore, various techniques are implemented to maintain the target availability. The most notable techniques are:

- Uplink Power Control (ULPC): Transmit power is increased to mitigate potential signal attenuation by atmospheric impairment to meet required SNR; ULPC is commonly implemented at gateway site by adjustment of the operating point of a High-Power Amplifier (HPA) based on calculation of the attenuation by a correction algorithm [36] with respect to the clear sky transmission conditions.
- Adaptive coding and modulation ACM and Low SNR waveform: ACM is a technique widely applied in wireless communication. Following a link degradation, a more robust (and least efficient) modcod is selected based on the evaluation performed by an ACM algorithm. DVBS S2X and DVB RCS2 standards both include and clearly describe the ACM mechanism in their perimeters i.e., for forward link [32] [37] and return link [33]. Low SNR waveforms permit the ACM to use very robust modcod (e.g., $\pi/2$ BPSK) at the expense of lower spectral efficiency.
- Gateway diversity: sometimes UPLC might not be sufficient to mitigate attenuation either due to the power limitation of the HPA; or generation of undesirable intermodulation products; or to the power density regulatory limits. The gateway diversity consists of the ability to divert the traffic of an unavailable gateway, due to temporary exposure to bad propagation conditions (e.g., rain fade), to another (or other) gateway(s) under better conditions. Several approaches are proposed in the literature [38].

2.4.4 Coverage enhancement

The main challenge about coverage is flexibility. For years, the coverage of a satellite was predefined in terms of location and shape and fixed once the satellite was in

orbit. Potential modification implies reorientation of the satellite or repositioning at a different orbit position with an increased cost of time and fuel consumption.

Satellite systems are featuring embedded phase array antennas with on-board or on-ground numerical beamforming [39] and coverage can thus be modified digitally by configuration of the feeds with given weights computed on the ground or in the space [40], [41].

Limiting the coverage is sometimes also motivated by the desired level of performance in the coverage (downlink Equivalent Isotropic Radiated Power-EIRP). With the beam hopping technique, a wider coverage can still be selected since the technology allows to focus the power on different areas on the time basis [34].

2.4.5 Enhancement of satellite and terrestrial interconnection

As depicted in *Figure 2.4*, satellite and terrestrial network interconnection can be achieved at different points: between satellite gateway and a data network; between satellite gateway and a terrestrial core network and access network.

The interconnection is made both at physical and logical levels or at different layers of the communication protocol stack. Among the topics to address, use cases definition, protocol optimisation, multi-connectivity and handover management, resource management, security, and quality of service are the main interconnection constraints in “before the 5G era” as identified in [10].

More specifically, the following topics have been widely studied and in this context of satellite and terrestrial interconnection initiatives:

- Co-development of new use cases and related integrated architectures (e.g. Edge delivery further addressed in section §4.4.5.3).
- Co-development of multi-connectivity management and handover between the two systems.
- Adoption and enhancement of terrestrial technologies and protocols (including enhanced TCP).
- Joint mitigation of the constraints and impairments by satellite and terrestrial actors (including spectrum sharing), under the control of frequency regulation organisms.

Satellite and terrestrial interconnection in 5G context inherits some outcomes of these studies but it also has its specific constraints and requirements which requires the improvement of some solutions and the developments of others. This includes architecture studies, adopting terrestrial waveforms on satellite systems, service continuity, edge delivery, etc. The aspects are further investigated in Chapter 4.

2.5 PROBLEM STATEMENT AND NEW SYSTEM REQUIREMENTS

Like every system, satellite communication systems aim to evolve, with improved services and performances. Some topics related to the main characteristics of SatCom systems have been introduced in section §2.3; there are: coverage, latency, spectral efficiency, capacity, and transmission impairments in general.

The technology evolution and main challenges related to these characteristics are discussed in section §2.4. The main topics are then: the capacity enhancement, the latency enhancement, the availability enhancement, the coverage enhancement, the flexibility enhancement, and the seamless satellite-terrestrial network interconnection.

My overall research activities have dealt with the mentioned topics as summarized in Table 2-4.

Though each of these topics is very relevant for SatCom and has a non-negligible interest, I have not contributed at the same level to their study, and I could not tackle each of them in the frame of the present manuscript. I had to select a few but most important topics, with considerable and essential contributions from myself, for further analysis.

After analysis of the topics and my contributions with my supervisors, two main topics have been selected: capacity enhancement and the satellite-terrestrial interconnection framework.

The capacity enhancement is addressed in Chapter 3 and is divided in two main sections. The first section specifies the problem of distortions in satellite high power amplifiers, provides an overview of distortion mitigation techniques and a specific one selected for the implementation. It finally discusses my proposal for global optimization of the operation point of the power amplifier for a complete advantage of predistortion and it is concluded with a proposed model for performance evaluation of any predistortion technique. The second section tackles the modelling approach for the implementation of the new modulation scheme in SatCom (CPM) and its performance evaluation and potential evolution.

The satellite-terrestrial interconnection framework is addressed in Chapter 4. Main topics are the new use cases enabled by potential 5G satellite-terrestrial integration, a new proposed role model and the proposed backhaul architecture and associated key enablers features.

Finally, with the (V)HTS systems and various satellite technologies and architectures arising to the market or announced in the future, there is a need for a common performance evaluation framework of such systems for proper comparison and exploitation by the satellite network operator or service provider. This is a novel research topic I have recently started to work on, and some early findings and materials are provided in Chapter 5.

Table 2-4: Overview of the past, present and future SatCom functionalities, performances, and technologies addressed in my research activities and in this document

Functionalities or Performances enhancement	Addressed topics in my research activities	Section of the document if detailed in this manuscript
Capacity enhancement at low SNR	Continuous Phase Modulation design	§663.3 Continuous phase modulation channel modelling and hardware implementation
Capacity enhancement	Predistortion: optimization of the point of operation of the satellite amplifier	3.2.5 Proposed algorithm for the determination of the optimal operation point
Capacity enhancement	Predistortion: Introduction of the throughput gain and a gain metric	§3.2.6 Proposed framework for performance evaluation
Capacity and flexibility enhancement in general	Beam hopping; Software Defined Network and Network Function Virtualization (SDN/NFV) applied to SatCom	N/A
Interconnection of satellite and terrestrial network	Use cases, Role model, Architecture options	§4.2 Use cases specification §4.3 Integrated network role-model
Interconnection of satellite and terrestrial network	Service continuity, QoS and Management and orchestration	§4.4 Specification of key enablers
Interconnection of satellite and terrestrial network	Support of network slicing in integration satellite-terrestrial network	N/A
Capacity evaluation	SatCom capacity evaluation framework	Chapter 5 Actual and future work

Chapter 3. SATELLITE COMMUNICATION SYSTEM TECHNOLOGIES FOR PERFORMANCE ENHANCEMENT

3.1 INTRODUCTION AND OVERVIEW OF THE CHALLENGES

The main point of improvement addressed during my research activities in recent years is capacity enhancement, with investigation of more efficient waveforms during my early career and optimization and evaluation of predistortion techniques. Section §3.2 specifies the problem of distortions in satellite high power amplifiers, provides an overview of distortion mitigation techniques and a specific technique selected for the implementation. It finally discusses my proposal for global optimization of the operation point of the power amplifier for a complete advantage of predistortion and it is concluded with a proposed model for performance evaluation of any predistortion technique.

Section §3.3 presents the principles of continuous phase modulation (CPM) and the selected modelling approach for the implementation of the CPM based satellite communication chain. The hardware implementation of an expected cheap user terminal based on CPM is also discussed.

3.2 PRE-COMPENSATION AND GLOBAL OPTIMIZATION OF THE POWER AMPLIFIER OPERATION POINT

3.2.1 Overview of the impairment mitigation techniques: pre-compensation and post-compensation

In general, the term pre-compensation refers to the techniques implemented at the transmitter side (i.e., GW for a forward link) to mitigate specific impairments (typically distinct types of interferences), at various levels in the communication chain, that the signal will encounter. Similar techniques implemented at the receiver side are named post-compensation.

The generic assumption for pre-compensation (and post compensation) is that the function representing the impairment to mitigate is known or can be estimated. It is also assumed that this function can be inverted and multiplied by the signal to transmit. Thus, the logic of pre-compensation will consist of applying the inverse function of the impairment to the signal at the transmitter side; post-compensation consists of applying the inverse function at the receiver side.

Figure 3.1 provides an overview of pre-compensation and post-compensation concepts.



Figure 3.1: Forward link pre-compensation and post-compensation in satellite systems

In section §2.4.1 we explored the evolution of satellite systems, in particular to provide improved system capacity. The main techniques for such capacity enhancement include the system bandwidth increase, e.g., through multibeam system and frequency reuse (section §2.4.1.1) which leads to interferences. Pre-coding is a pre-compensation technique to mitigate interferences [27], [28] [42].

As introduced in section §2.3.6, intermodulation distortions (IMD) are due to nonlinearities of the amplifiers or operating close to saturation. IMD are considered as an important contributor to the total carrier over interference ratio especially in case of multi-carrier amplification. Pre-compensation techniques called predistortion are then designed to mitigate such impairments.

This technique has been one of my research works. Related activities, constraints, developments, and results are further presented in the next sections.

3.2.2 Specification of the distortion in multi-carrier amplification

A satellite communication system capacity can be increased by improving the SNR and adopting higher order modulation schemes, thus increasing spectral efficiency

(cf. section §2.4.1). Forward link standard DVB-S2X introduces sharper roll-off and higher order modulation schemes, up to 256-APSK [33] and equivalent spectral efficiency of 5,9 bps/Hz for the modcod 256-APSK 3/4, requiring SNR of approximately 20dB [43].

As introduced in section §2.3.6, the satellite channel has several nonlinear components, especially the on-board satellite amplifier which can generate important distortion identified as Nonlinear Inter-Symbol Interference (NISI), when it is operated close to its saturation point [30].

The NISI is increased with sharper roll-off and higher modulation order since the Peak to Average Power Ratio (PAPR) is increased with such configuration, in particular in multi-carrier systems [44].

In fact, the PAPR is the figure of merit of a signal amplification and is defined as below (eq. 8).

$$\text{PAPR} = 10 \text{ Log} \frac{P_{peak}}{P_{avg}} \quad (\text{eq. 8})$$

Where P_{peak} and P_{avg} are the peak power and the average power of a signal.

In multi-carrier systems, the intermodulation products between the different modulated carriers, combined with higher order modulation, will increase the PAPR and the resulting signal will have high dynamics at the input of the power amplifier leading to distortions. The distortion will increase as the power amplifier is operated closer to saturation as represented in Figure 2.6.

3.2.3 Candidate solutions and challenges

To overcome distortions, one approach is to add linearization features to the power amplifier [45], [46], [47], to extend its linear zone. But such an approach is generic and cannot be adapted to the characteristics of each signal to be amplified. This linearisation approach can contribute to the mitigation of the intermodulation distortion [48] and to improve the efficiency of the amplifier. But it still requires considerable back-off. For instance, 3dB is a typical output back-off for a 4-carriers amplification using a 4-ary modulation order (16-APSK) [49]. Note that with a non-linearized amplifier, the output back-off will be higher for similar multi-carrier amplification leading to operation points that are not economically viable. The efficiency of the power amplifier can be improved with another technique: the predistortion.

Predistortion has then been proposed in [50], [51], [52], [53] as a solution to mitigate intermodulation products for multi-carriers amplification and improve the efficiency of the power amplifier.

Linearization mentioned above can also be referred to as analog predistortion.

Compared to analog predistortion techniques, digital predistortion (DPD) techniques are suited for satellite communication thanks to their configurability and improved performances [54].

DPD techniques can be implemented at two different levels of the transmission chain: symbol level, before the pulse shaping filter (PSF) or signal level, after the

pulse shaping filter (PSF). These techniques are identified in the literature respectively as data predistortion and signal predistortion [55]. The predistortion function is applied with selected coefficients which can be adjusted with iterations. This technique is known as iterative or successive predistortion.

In addition, with larger transponders, it is more and more common to amplify several carriers in the same transponder [56], thus requiring a joint multicarrier predistortion which can be based on any of the mentioned categories.

Figure 3.2 provides an overview of a multicarrier predistortion architectures, with u_i and x_i referring to the symbol of a carrier i before and after the PSF (P_i), f_i the frequency conversion and MASK the low pass filter to limit the uplink out-of-band emissions, as detailed in [57].

For all these approaches, the determination of the optimal operation point of the satellite high power amplifier is a key performance factor.

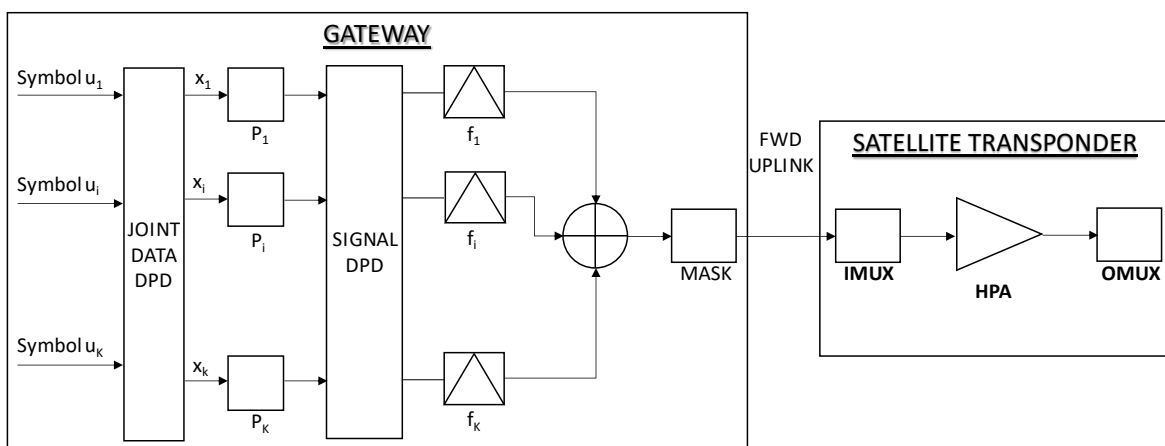


Figure 3.2: Multicarrier data and signal predistortion block diagram

3.2.3.1 Signal level implementation

Sample or signal DPD techniques are applied at the sample or signal domain, after the PSF of the transmitter. It is less complex than data DPD and mostly addresses in-band distortions but is quite inefficient to address out of band distortions due to, e.g., carriers overlapping. It also has difficulties to tackle distortions from linearized transponders due to the HPA characteristics on and beyond saturation. Therefore, it is quite inadequate as it is (when used solely) for satellite communications.

3.2.3.2 Data or symbol level implementation

Data predistortion techniques operate at symbol level before the PSF. The first approach of DPD technique is the static symbol-level predistortion or static distortion compensation which statically changes the transmit constellation to mitigate the constellation warping [58], [59]. Dynamic data predistortion is an advanced DPD technique initially proposed by [52]. It consists of selecting the symbol to be transmitted based on the neighbouring symbol of the initial symbol. It is commonly implemented based on a look-up table (LUT) and requires considerable off-line computation capability and memory to compute and store the multidimensional constellation. As analysed in [57], the memory requirement is

taken to the power of the number of carriers in a multi-carrier system. Such computation and memory requirements are the main disadvantages of data DPD. Data DPD can however be implemented on polynomial-based symbol-level. This technique can also be referred to as non-parametric DPD. The coefficients in this case can be based on direct or indirect learning. In indirect learning, the considered predistortion coefficients are copied from the computed coefficients of a Volterra base equaliser [60]. Due to inaccurate noise measurement and difficulties to correctly model the inverse function of the power amplifier in satellite systems, the indirect learning has an inherent performance loss and is very sensitive to the quality of the system identification [30]. In direct learning, the coefficients are directly estimated which increases accuracy but at the cost of higher complexity and slow convergence [61].

3.2.3.3 Iterative or successive predistortion

Iterative or successive DPD techniques aim to address the difficulty to model the channel with data DPD and to improve the performance of signal-level DPD. It consists of iterations and adjustments of the inputs and outputs of the predistortion function. This technique is also called Successive Interference Cancellation (SIC). Iterative DPD can be performed based on signal DPD as proposed in [62] or data DPD as proposed in [30], [57] or combination of both signal and data DPD. The latest approach is the one implemented in our context and is further detailed hereafter in section §3.2.4.

3.2.3.4 Optimal operation point

The determination of the optimal operation point is a key requirement for efficient implementation of predistortion, in particular in case of adaptive predistortion techniques. It is demonstrated in [63] that operating the satellite HPA close to saturation with predistortion can lead to worse results than without predistortion. Also note that the satellite operators under the recommendation of amplifier manufacturers, often specify two modes of the operation of the transponder: single carrier and multi-carrier and both with fixed predefined Input Back-Off (IBO¹). The optimal operation point is however important to determine to take advantage of a DPD technique. The proposed joint optimization algorithm is described in section §3.2.5 and in the evaluation of the iterative DPD technique, it is demonstrated that optimal operation point is another optimization aspect of the mitigation of distortions.

¹ GIBO: The terminology Global IBO or GIBO is also often used in case of multi-carrier systems to specify that the considered "IBO" is applicable to the sum of the power of the carriers. In the frame of this manuscript, GIBO and IBO have the same meaning.

3.2.4 Considered predistortion technique and testbed

3.2.4.1 Considered predistortion technique

The considered DPD associates data and signal DPD and aims at reducing the required number of iterations for the convergence of the algorithm. A transmission link model (i.e., transmit filter, HPA, and receive filter) is applied to the symbol to send and the resulting symbols are compared to the initial symbol. The difference is applied as an input and another iteration is taken until a defined minimum difference is reached following the concept provided in *Figure 3.3*.

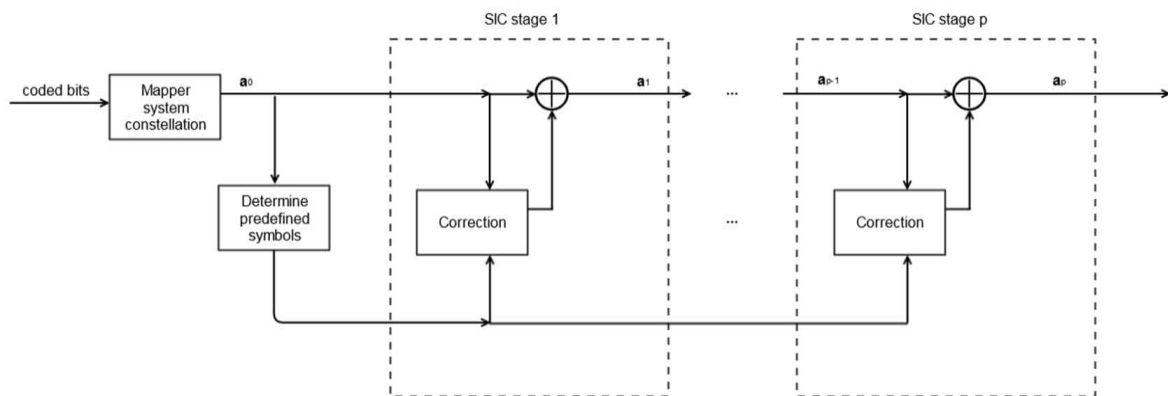


Figure 3.3: Block diagram of successive interference cancellation for multicarrier predistortion

Note that the DPD with iteration approach is quite efficient for out of band interference and it can also mitigate the interferences due to carrier overlapping. Thus, association of iterative DPD techniques with advised carrier overlapping can lead to some throughput gain [57] in multi-carrier systems. This property was the inspiration to aspire a throughput gain even with small DPD performance and for the definition of a new framework for such performance evaluation. These aspects are discussed in section §3.2.6.

The co-signed article [57] and the ST Engineering Newtec patent [64] provide the details of the implemented DPD technique considered for my contributions which are the framework for performance evaluation (§3.2.6), the proposal of an algorithm for optimal operation point determination (§3.2.5) and the algorithm for the optimisation of the carrier overlapping (§3.2.6.2).

3.2.4.2 Considered testbed

A proper testbed is necessary to address the two other challenges identified after the selection of the DPD techniques (i.e., the determination of the optimal operation point addressed in section §3.2.5 and the performance evaluation framework in section §3.2.6).

Figure 3.4 depicts the laboratory validation testbed architecture employed for the experimentation of the proposed algorithms and frameworks. It comprises the following subsystems:

- A Gateway Emulator (GWe): it performs the multi-carrier (four) transmission and multi-carrier predistortion
- A User Terminal (UT): it is able to receive and demodulate one of the four transmitted carriers
- A Satellite Channel Emulator (here referred to as CSIM): it emulates the behaviour of a satellite channel and it is configured with a given Input Multiplexer (IMUX), Output Multiplexer (OMUX) and amplifier AM/AM, AM/PM transfer function;
- A Monitoring & Control (M&C) Unit: it is used to configure the different equipment of the testbed and to monitor and store the values of interest
- A Noise Generator : it is used to introduce a controlled amount of noise into the system. It is configured through an attenuation system (in dB). The higher the attenuation is, the lower the noise level is
- A Spectrum Analyser: it is used to monitor the shape of the signal at different points in the transmission chain and to measure the level of various parameters such as the carrier, the noise and the distortion.

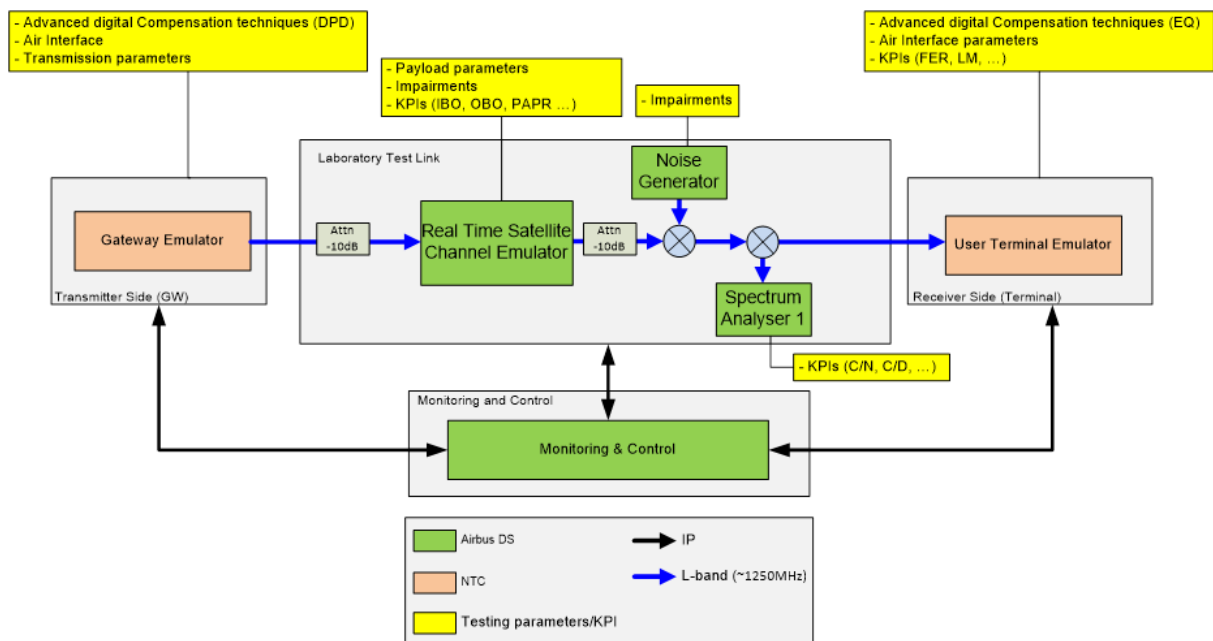


Figure 3.4: Testbed for optimization of the operation point and predistortion performance evaluation [57]

3.2.5 Proposed algorithm for the determination of the optimal operation point

3.2.5.1 Motivation

In general, the optimal operation point (OOP) of a power amplifier on a system needs to be determined as operating the power amplifier too close to saturation may lead to high intermodulation products that the predistortion algorithm will not be able to cancel; whereas operating too far from saturation would not involve or benefit from the predistortion and would degrade the carrier to noise ratio.

The determination of the OOP becomes very crucial when implementing a predistortion technique as it is observed that their performance depends on the

operation point [63] and that operating the satellite HPA close to saturation with predistortion can lead to worse results than without predistortion.

The selected DPD technique has a considerable challenge as it requires quite precise configuration (offset, number of iterations, convergence criteria, etc.) for optimal results. Nevertheless, the determination of the OOP of the satellite power amplifier has been identified as a major performance driver and will also provide a more precise framework for comparison of predistortion techniques.

It is necessary to define the OOP for every system (with and without predistortion) to accurately assess the intrinsic benefits of a predistortion technique.

Most analysis regarding the operation point aim to calculate the optimal input power back-off (IBO) to resist to HPA nonlinearity, as well as guarantee an appropriate signal-to-noise ratio (SNR), by minimising the mean square error (MSE) between the received symbols and the original constellation points [65]. Such an approach is complex to implement on a live system since it requires complex installations and dedicated equipment.

Moreover, no framework, procedure, or algorithm available in the literature includes the monitoring of the actual system performance, and the proposal is to use the link margin (LM)¹ and the frame error rate (FER)² provided by the system, considering a defined maximum noise level N_{\max} .

3.2.5.2 Modelling and classification of the proposed solution

The problem of defining the OOP can be classified as a nonlinear bi-criteria joint optimization, on two dimensions, based on continuous variables. The problem is therefore specified following the model below:

Let Y be the GIBO, and φ the noise level. Let f be a continuous function which generates the LM noted α , in the closed interval $L=[Y_{\min}, Y_{\max}]$ which represents the interval between the minimum GIBO and the maximum GIBO which is 0 dB.

Let g be a dual-parametric continuous function which generates the real values of the FER noted β , in the closed intervals $L=[Y_{\min}, Y_{\max}]$ and $K=[\varphi_{\min}, \varphi_{\max}]$. K represents the interval between the Noise_{\min} (or noise floor) and Noise_{\max} .

We define the series of values x_i in L , and x_{i+1} is derived from the values of $f(x_i) = \alpha_i$, i being the iteration index following the iteration logic.

We define the series of values x_j in L and y_j in K and (x_{j+1}, y_{j+1}) is derived from the values of $g(x_j, y_j) = \beta_j$

It is assumed that f is concave, and g is convex, and the a priori probability density of the location of the OOP is not uniform. The OOP can be characterised by the set of values $\{Y_o; \varphi_o; \alpha_o; \beta_o\}$ or just Y_{opt} for simplification and can be determined with (eq. 9), (eq. 10) and (eq. 11).

¹ The link margin (LM), measured in dB, is the difference between the estimated or measured $E_s N_o$ and the $E_s N_o$ of the selected modcod. High LM (>2dB) implies a robust (but less efficient) link.

² The frame error rate (FER) is the ratio of errored frames to transmitted frames.

$$\gamma_{opt} = \underset{x \in L}{\operatorname{argmax}}(f) \cap \underset{(x \in L, y \in K)}{\operatorname{argmin}}(g) \quad (\text{eq. 9})$$

The objective of the joint optimization is to resolve the equation above.

With an iterative approach, x_{i+1} and (x_{j+1}, y_{j+1}) are derived from the values of $f(x_i)$ and $g(x_j, y_j)$ respectively.

Thus, it can be concluded that:

$$\underset{x \in L}{\operatorname{argmax}} = \lim_{i \rightarrow \infty} f(x_i) \quad (\text{eq. 10})$$

And,

$$\underset{(x \in L, y \in K)}{\operatorname{argmax}} = \lim_{j \rightarrow \infty} g(x_j, y_j) \quad (\text{eq. 11})$$

In theory, the number of steps could be exponential (or infinite as announced in the equation above) depending on the granularity of L and K. Under some realistic granularity assumption, a root-finding algorithm could be used. But the fact of having a joint optimization is still a major concern.

As candidate solutions, we can consider the common root-finding algorithms: the bisection method and Newton's method.

Newton's method requires that the derivative can be calculated directly. And in this case, analytical expression for the derivative is not easily obtainable.

Given that the approach is to base the proposed algorithm on actual system performances with actual KPI (Key Performance Indicator), the proposed solution is based on empirical KPIs (LM, FER) and the bisection method is quite appropriate in such a situation.

However, to have a quick convergence and to overcome the inconvenience of the bisection method, which is its potential slowness, in particular in a multiparametric and multicriteria system, the proposed approach is to divide the algorithm in three steps. The first step focuses on the function f with quite high granularity to have a quick convergence. The second step focuses on the function g with a fixed x (found in the previous step) and then the noise y can be assessed. The last step is a joint optimization algorithm with a finest granularity on x and y for a more precise search, but on a limited range of L and K, thanks to the first two steps.

The objectives and classification of the three steps of the proposed joint optimization algorithm are provided below:

(1) Classic root-finding algorithm – bisection method

For a problem simplification, it is proposed to start with a mono-criterion (here the LM) optimization in one dimension based on variable IBO. Thus, for this step, the noise N_{\max} is assumed to be low to avoid the C/N limitation and it is thus assumed that the distortion is the only LM limiting parameter. The FER is not considered at this stage. The problem is then simplified to maximisation of a concave function (the LM) and the bisection algorithm [66] which is a classic approach of unidimensional convex optimization is proposed. This step is based on the classic dichotomous search [67]. At the

end of this step, the system is then more limited by the distortions. This step is identified as the GIBO optimization coarse search.

(2) Classic root-finding algorithm – bisection method

The objective of the second step is to determine the maximum noise applicable to the system for a FER of $1e-3$. Another research algorithm based on the FER criterion and the noise variable is proposed. It is assumed that the FER increases with the noise, thus the proposed algorithm is another classic root-finding algorithm, also based on the bisection method as in step (1) and as described in [66], with the criterion being the FER target of $1e-3$. At the end of this step, the system is close to the region it is limited both by the noise and the distortions. This step is identified as the quasi error free (QEF) search.

(3) Custom ad-hoc heuristic

The third and last step proposed aims at refining the OOP search by adjusting the IBO with smaller granularity while adjusting the noise level and monitoring the FER target. This step implements a joint optimization based on the findings of step (1) and (2). It can be classified as a custom ad-hoc heuristic for precise local search. This step is identified as the GIBO optimization fine search.

The principles and state machine of the proposed 3-steps algorithm is provided in the next section §3.2.5.3, the results and conclusion in section §3.2.5.4.

3.2.5.3 Detailed description and state machines - confidential

The proposed 3-steps algorithm for the determination of the optimal operation point of the power amplifier considering the performances at system level is applicable to SatCom systems with and without the multi-carrier predistortion technique. The principles and state machines of the proposed 3-septs algorithm are provided in Figure 3.5.

(1) GIBO optimization coarse search

The goal of this algorithm step is to find the GIBO which maximises the link margin for a given noise level. Figure 3.5 presents an illustration of the objective (Figure 3.5a) and the description via a state machine (Figure 3.5b) of the coarse search: Firstly, a calibration of the noise level is done in order to have a link margin around 2 dB at UT side. The operation point is changed by variation of GIBO by steps of 3 dB to quickly detect the tendency or steps of 0.5 dB to confirm the tendency since changing the GIBO directly impacts the link margin. In the example of Figure 3.5 below, the optimum coarse GIBO is 6 dB (LM = 3.5 dB). Figure 3.10 shows the different parameters used for the GIBO optimization Coarse Sequence in three different panel sections.

The first and second panel sections show respectively the noise level injected by the noise generator and the couple E_s/N_o - Link margin record from the User Terminal. The third panel section shows the behaviour of the GIBO optimization showing how modulator power varies to obtain the maximum link margin.

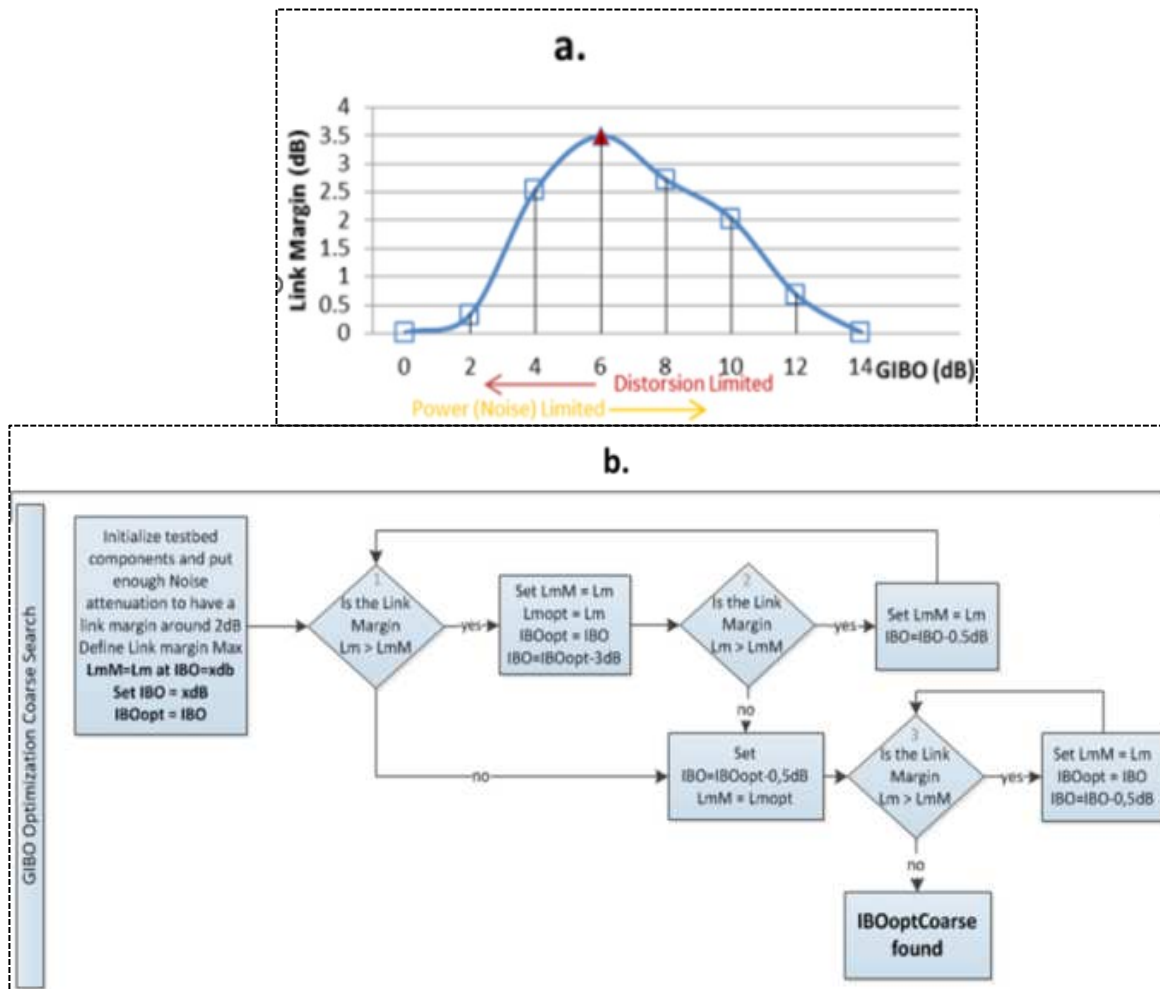


Figure 3.5: Illustration (a) and State machine (b) of the GIBO Optimization – Coarse Search [57]

(2) QEF search

The objective of this algorithm step is to find and apply the maximum noise level without any errored frame within 20s (this duration is enough to target an FER of 1e-3).

Figure 3.6 gives an illustration of the objective (Figure 3.6a) and the state machine (Figure 3.6b) of the QEF algorithm.

The algorithm starts with the whole parameters found at the end of the GIBO Optimization – Coarse Search described above. Then the noise level is increased firstly by steps proportional to the link margin, then by steps of 1 dB and when we obtain some errors, the noise level is slowly decreased (i.e., step of 0.1 dB) until no frame with errors is detected. For realistic time evaluation purposes, 20 seconds of observation for error detection is assumed to be enough in a stable system.

In the illustration below, the QEF point is found at the final noise level of attenuation of 11.3 dB.

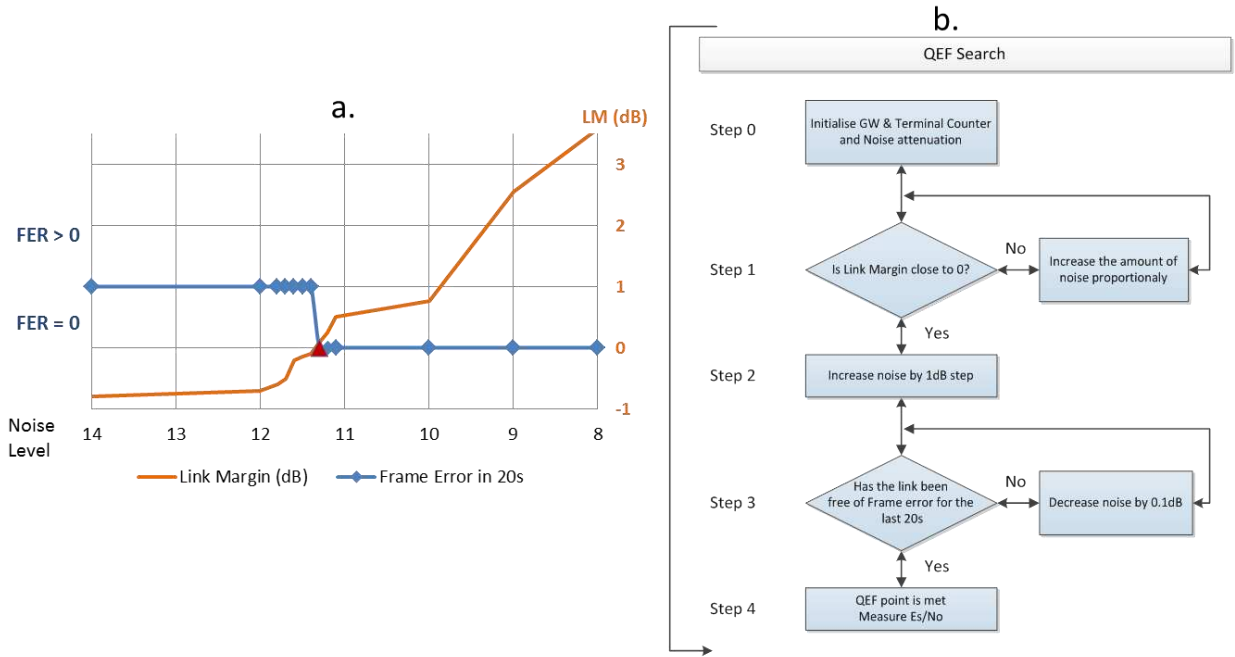


Figure 3.6: Illustration (a) and State machine (b) of the QEF search

(3) GIBO optimization fine search

The objective of the fine search is to adjust the GIBO (starting at the coarse GIBO) and the noise level (starting at the QEF noise level) to target a precise FER around $1e-3$. The state machine of the algorithm is given in Figure 3.7

At the GIBO coarse search, only the GIBO is changed and at the QEF search only the Noise Level is changed; here, both the GIBO and the noise level need to be managed. The algorithm starts at the final state of the QEF search (GIBO = GIBOoptCoarse; Noise Level = QEF Noise Level).

While the measured FER in 30 seconds is lower than $1e-3$, the noise level is decreased by a step of 0.1 dB. If a FER greater than $1e-2$ is found, the GIBO is changed by a step of 0.5 dB and the noise level is adjusted again to target a FER around $1e-3$. The algorithm stops when no more noise can be added without a FER getting greater than $1e-2$.

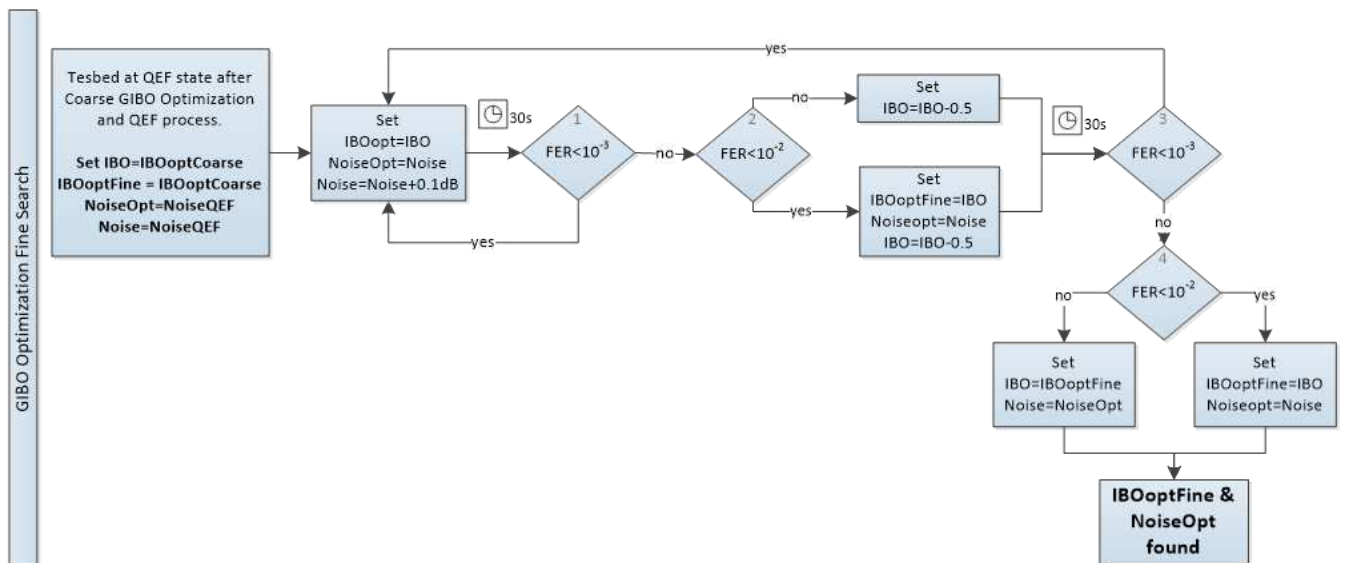


Figure 3.7: State machine of the GIBO Optimization – Fine Search

3.2.5.4 Results and analysis

The proposed 3-steps algorithm for the determination of the OOP has been evaluated under the testbed specified in Figure 3.4.

The HPA model used in the channel emulator for the evaluation is a linear power amplifier with AM/AM and AM/PM transfer function provided in Figure 3.8. Note that it is a transfer function of an actual satellite in space.

The evaluation is made based on the following setup:

- Multi-carrier transmission (4 carriers) on a 36 MHz transponder (Figure 3.9)
- The four carriers are using the same modcod and roll-off
- The considered predistortion algorithm is the MCPRED algorithm described in §3.2.3 and in [57]
- For the calibration of the testbed and the initial setting of the algorithm, the $GIBO_{\min}$ is set to -10 dB and $Noise_{\min}$ is set to -62.8 dBm which is the noise floor of the system (noise without any transmission measured by the spectrum analyser)
- The selected KPI are the applicable noise level and SNR.

The Table 3-1 provides the results for an 8-PSK, 16-APSK and 32-APSK with 10% roll-off.

In all the cases, the operation point (IBO and OBO) is different, with the amplifier operating closer to saturation with DPD on.

In all the cases, the level of noise applied with DPD on is higher than with DPD off while the carrier to distortion ratio may decrease (C/D) as well as the SNR (C/ND).

We can conclude that the proposed approach based on actual system performance and KPI (LM and FER) allows to increase the benefits of any DPD technique as the operation point would be adapted to the performances of the DPD technique and it is preferable than an only fixed operation point approach.

In general, the approach can be applied without any DPD as it optimises the operation point based on the system metric.

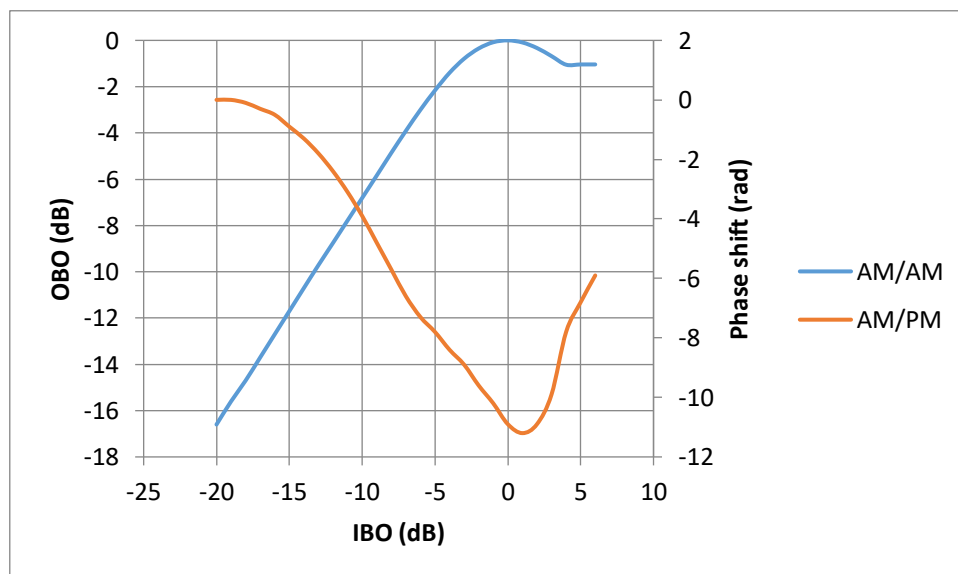


Figure 3.8: Transfer curves of the considered satellite HPA

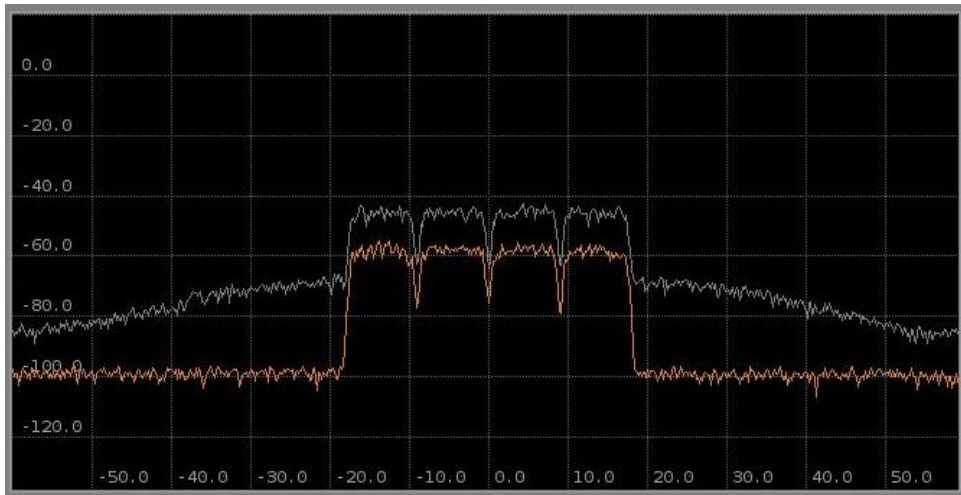


Figure 3.9: Overview of the multi-carrier transmission before amplification (orange) and after amplification (white)

Table 3-1: Results of determination of optimal operation point for 4-carriers amplification

Test case	C/N	C/D	C/ND	Csat/N	IBO	OBO	PAPR	Noise Att
8-PSK DPD OFF	7.32	14.47	6.55	9.40	2.50	2.08	10.32	20.50
8-PSK DPD ON	7.25	14.35	6.48	9.05	2.02	1.79	6.06	20.10
16-APSK DPD OFF	9.96	16.34	9.06	12.45	3.40	2.49	10.69	23.40
16-APSK DPD ON	9.68	15.90	8.75	12.22	3.35	2.54	7.07	23.10
32-APSK DPD OFF	15.45	20.86	14.35	19.07	5.46	3.63	10.98	30.00
32-APSK DPD ON	15.28	18.29	13.52	18.68	4.83	3.40	8.02	29.70

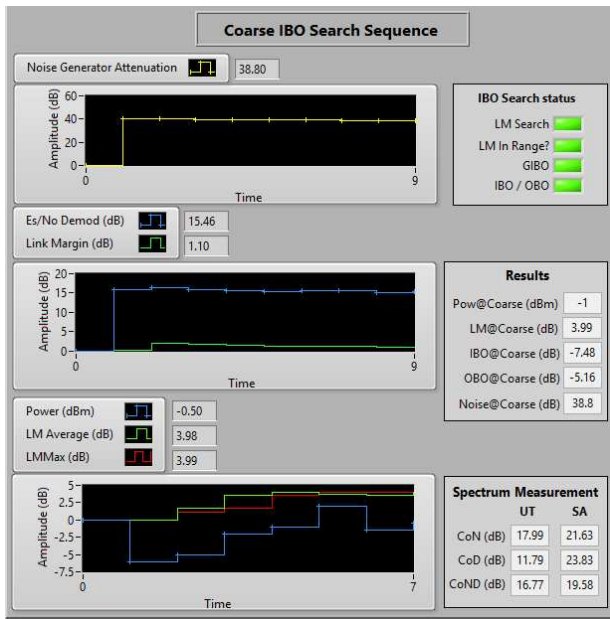
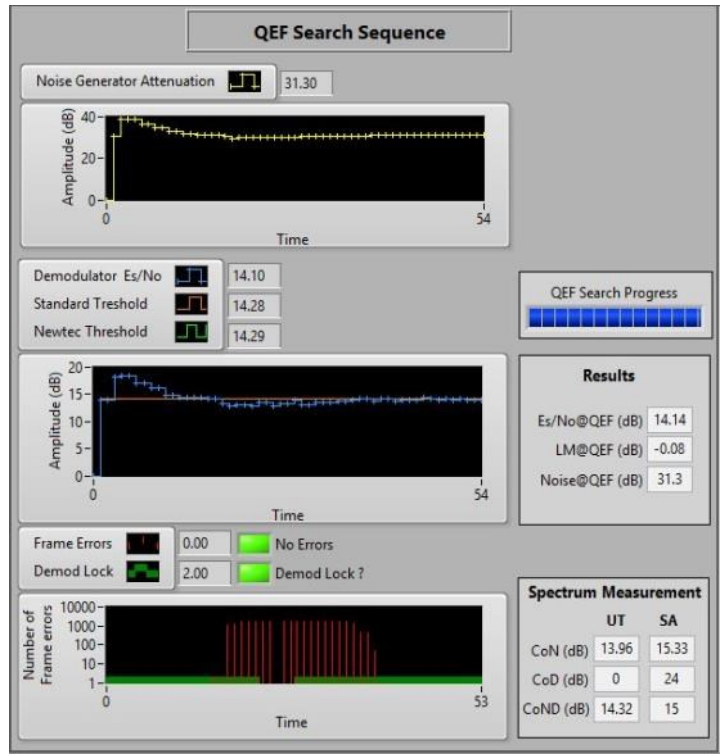
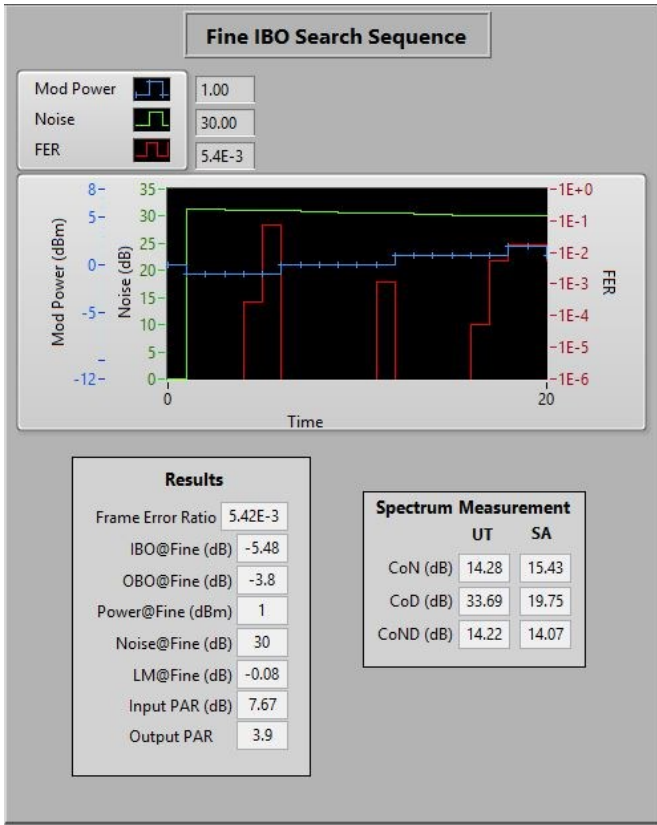


Figure 3.10: GUI of the GIBO Optimization Coarse and Fine Search and QEF search

3.2.6 Proposed framework for performance evaluation

3.2.6.1 Motivation and limitation of existing models

In the different performance evaluation of predistortion, the main figures of merit are the actual reduction of the PAPR and carrier over distortion ratio. Predistortion efficiency at system level is often evaluated based on various criteria: normalised minimum square error [55] and/or total degradation (TD) gain (or dB gain) [55], and/or the consumed vs dissipated power [68],.

But in the end, the predistortion is classified as a performance enhancement technique to improve the throughput and it is necessary to clearly evaluate how much it could contribute to increase the throughput in SatCom systems.

In theory, the dB gain can be considered to reduce the link budget margin [23] leading to a potential more efficient modcod.

In an operational system with ACM activated, a sufficient dB gain can allow the selection of a more efficient modcod. But this requires the dB gain to be higher than the gap between the modcods SNR thresholds.

Let us consider 3 modcods with close SNR thresholds from the modcod table provided in Table 2-1. Assuming that the threshold of a more efficient modcod is higher than the threshold of a less efficient modcod (which is true most of the time), we provide in Table 3-2 the required dB gain and the estimated throughput gain, for the same allocated symbol rate (SR).

Thus, it is observed that when there is a dB gain, but it is lower than the delta between the actual modcod and the next more efficient modcods, this gain will not be converted into throughput increase and then be useless in that regard.

Table 3-2: Required dB gain and expectable throughput gain based on modcod increase

Modcod	Es/No threshold (dB)	Symbol efficiency (bps/baud)	Ref.	Delta dB compared to ref. ⇔ Required dB gain	Throughput gain
QPSK5/6	5.32	1.56	-	-	-
8PSK3/5	5.66	1.69	QPSK5/6	0.34	8%
8PSK2/3	6.70	1.88	8PSK3/5	1.04	11%
8PSK3/4	8.12	2.08	8PSK2/3	1.42	10%
16APSK2/3	9.12	2.51	8PSK3/4	1	21%

For example, referring to Table 3-2, if the actual modcod is QPSK5/6 and a dB gain of 0.3 dB is obtained following the implementation of a DPD technique, the actual throughput gain will be 0% since the required dB gain to switch to the next modcod (and obtain 8% throughput gain) is 0.34 dB.

Even in a system with more modcods and then small granularity of required SNR margin, to switch from one modcod to another (e.g., 0.3 dB), there is a system delta

margin implemented in life systems (typically >1 dB) to avoid recurrent and useless changes for non-significant gain.

As presented in Annex A.2, the common dB gain of the implemented DPD techniques on linearized HPA is around 0.5 dB which is considerable, but still not enough on a live system to allow the modification of the modcod and then an improved throughput.

The proposed approaches to face these limitations are (1) to combine an intentional carrier overlapping with DPD techniques to convert any gain into throughput gain and (2) to introduce the throughput gain as a direct metric for predistortion techniques.

3.2.6.2 Principle of the proposed model: carrier overlapping and throughput gain

Introducing carrier overlapping

The proposal is to exploit the ability of predistortion to mitigate intermodulation interference due to carrier overlapping. Then, a more direct throughput gain of a DPD can be obtained by increasing the symbol rate of the carriers.

Overlapping the carriers consists of reducing the carrier spacing (CS) and increasing the symbol rate (SR) by an equivalent amount.

The relation between the SR, the CS, and the allocated bandwidth (BH) is given in (eq. 12):

$$SR = \frac{BW}{1+CS} \quad (\text{eq. 12})$$

$$SR' = \frac{BW}{(1+CS-\Delta_{CS})} \quad (\text{eq. 13})$$

$$\Lambda = \frac{SR'-SR}{SR} = \frac{\Delta_{CS}}{(1+CS-\Delta_{CS})} \quad (\text{eq. 14})$$

$$\Delta_{CS} = \frac{\Lambda}{(1+\Lambda)} + \frac{CS}{(1+\Lambda)} \quad (\text{eq. 15})$$

In (eq. 13), SR' represents the increased symbol rate when the carrier spacing CS is reduced by Δ_{CS} which can be linked to the throughput gain as shown in figure (eq. 14) and (eq. 15).

The objective of the optimization problem is to find the adequate CS, or Δ_{CS} (and associated SR) which maximises the throughput gain (Λ). An iterative approach based on a classic root-finding algorithm is also proposed, with a monitoring of the FER. A bisection approach is selected since the domain of research can be easily limited. Assuming that the achievable gain is less than 20%, and that a precision of 0.5 % is acceptable and with common values of carrier spacing (5% to 20 %).

Typically, granularity of 0.01 for Δ_{CS} is acceptable. The state machine and result of experimentation of the proposed approach are provided in §3.2.6.3 and §3.2.6.4.

Throughput gain as a metric

The proposal to introduce the throughput as a predistortion gain metric needs to come with a clear framework for throughput gain evaluation, in particular if the predistortion technique is associated with other indirect techniques and features optimising the performances.

For instance, the two optimization objectives presented in the previous sections (determination of OOP in §3.2.5 and carrier overlapping in §3.2.6.2) need to be implemented with and without predistortion. But the noise level applied without predistortion should be the same level applied when the predistortion is enabled. The ACM dB margin (required to switch to the next modcod) should be the same with and without predistortion. For simplicity in our analysis, we propose to set this margin to zero.

The proposal is therefore to compare the predistortion techniques based on the computed achieved throughput with and without predistortion within a given occupied bandwidth and exposed to the same impairments and optimization algorithm. This approach also allows to compare the performances with theoretical Shannon capacity within the same occupied bandwidth.

3.2.6.3 Detailed description and state machines - confidential

A single implementation is proposed for the implementation of the carrier overlapping and for the evaluation of the throughput gain in Figure 3.11

The FER is monitored to stop at maximum symbol rate increase (minimum CS).

For the sake of completeness, the process is to be combined with the proposed 3-steps algorithm for the determination of the OOP as described in §3.2.5.

The complete procedure of evaluation is provided in Figure 3.12.

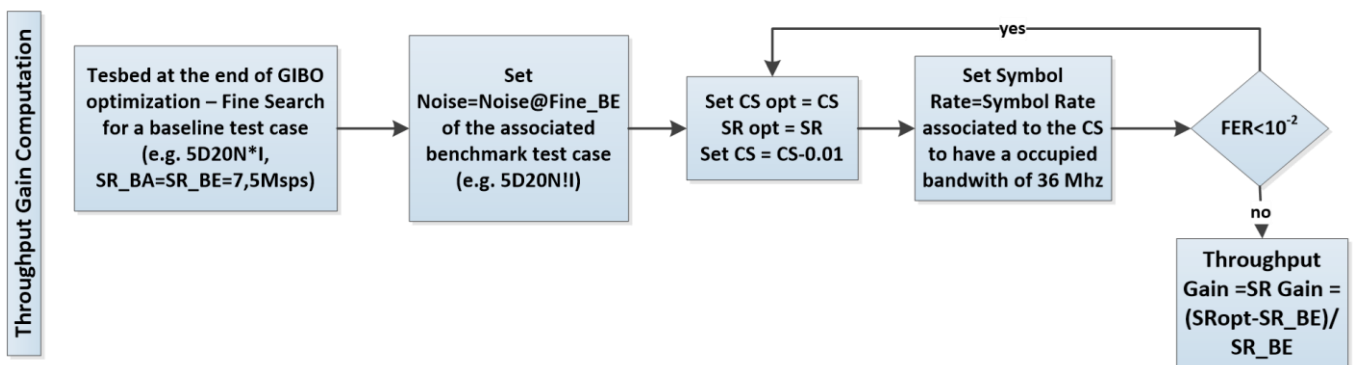


Figure 3.11: State machine of the throughput gain computation

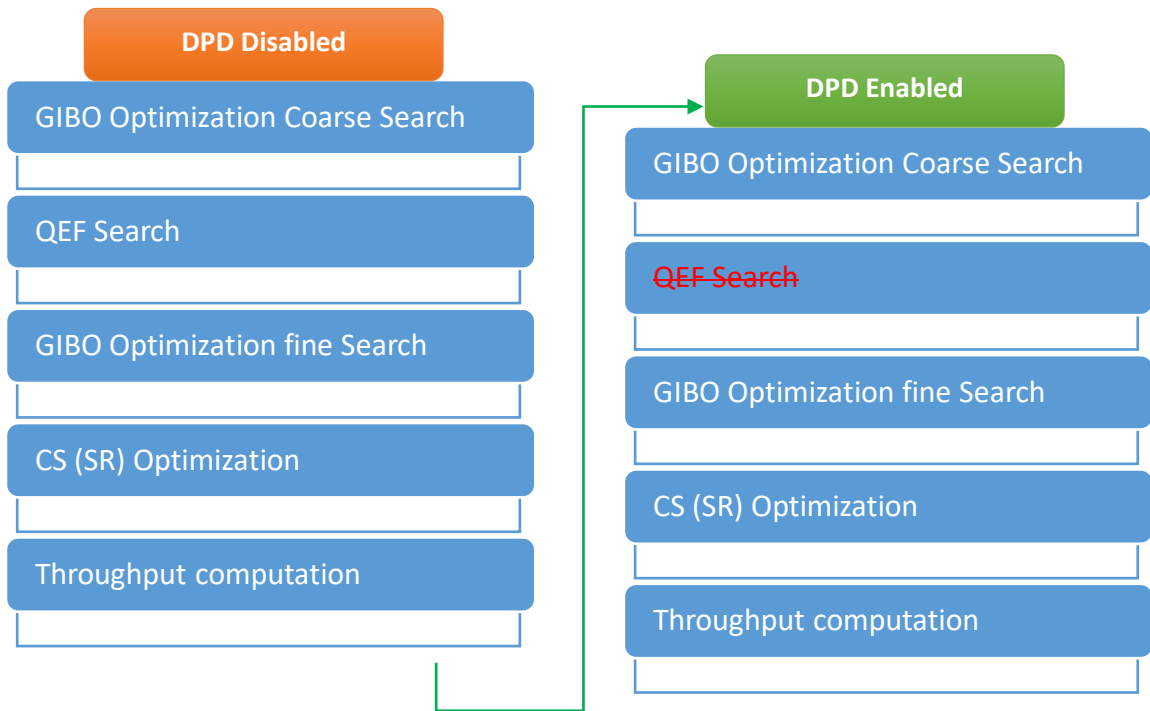


Figure 3.12: DPD throughput gain evaluation procedure

3.2.6.4 Results and analyses

The proposed carrier overlapping process and the proposed process for the evaluation of associated throughput have been evaluated under the testbed specified in Figure 3.4.

The HPA model used in the channel emulator for the evaluation is a linear power amplifier with AM/AM and AM/PM transfer function provided in Figure 3.8. Note that it is a transfer function of an actual satellite in space.

The evaluation is made based on the following setup:

- Multi-carrier transmission (4 carriers) on a 36 MHz transponder
- The four carriers are using the same modcod and roll-off
- The considered predistortion algorithm is the MCPRED algorithm described in §3.2.3 and in [57]
- The GIBO coarse and fine search are executed following the process described in Figure 3.12
- For the calibration of the testbed and the initial setting of the algorithm, the $GIBO_{min}$ is set to -10 dB and $Noise_{min}$ is set to -62.8 dBm which is the noise floor of the system (noise without any transmission measured by the spectrum analyser)
- The selected KPI are the carrier spacing and the associated SR
- The throughput gain is computed based on the potential SR increase and eventually a modcod modification thanks to ACM
- The ACM link margin is set to 0 to maximise the chance to benefit from any potential dB gain higher than the gap between.

These steps are further detailed in Figure 3.13.

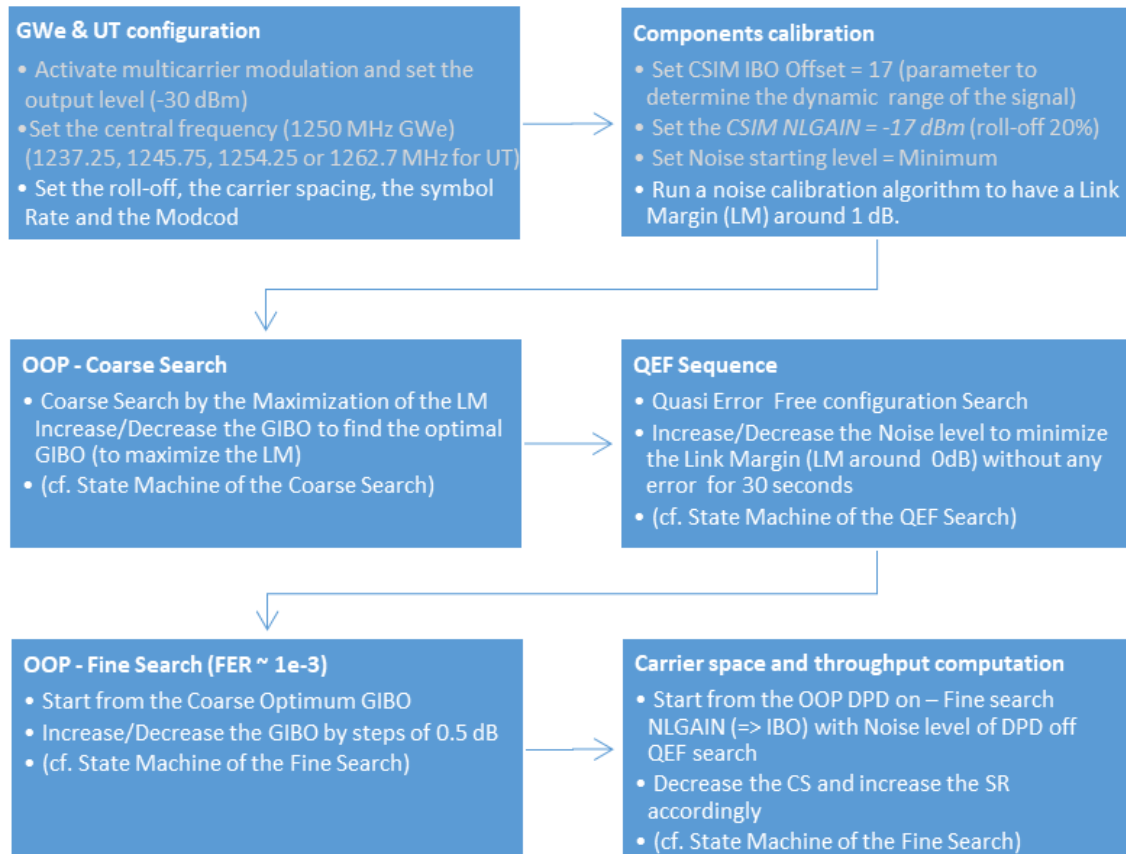


Figure 3.13: Overall DPD, OOP and throughput estimation procedure

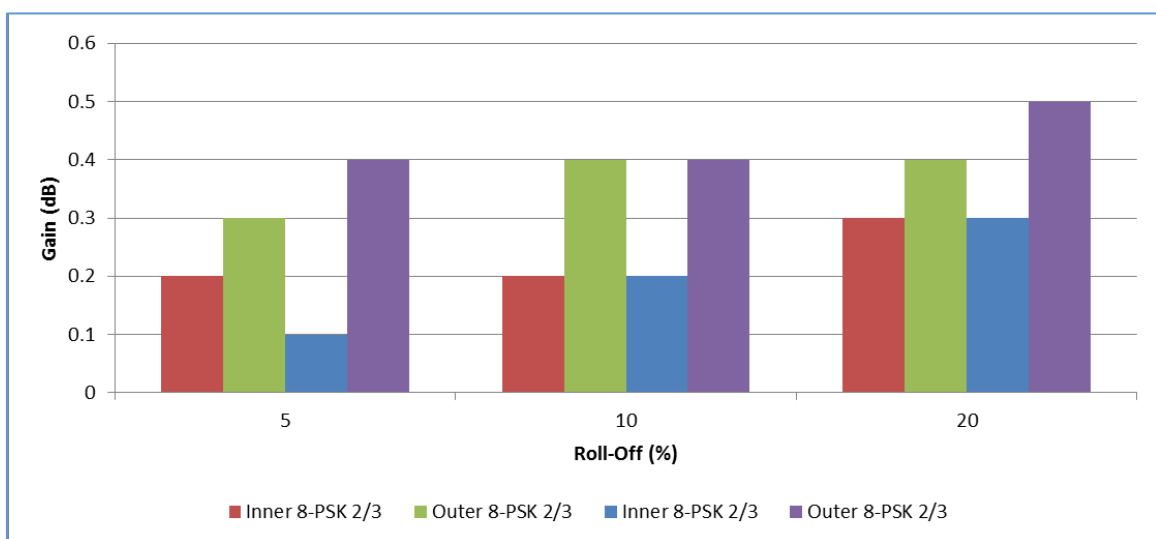


Figure 3.14: DPD dB gain estimation for 8-PSK 2/3

Based on the described setup, some dB gain values have been estimated as provided in Figure 3.14 for the modcod 8-PSK 2/3 and in [69] and Annex A.2 for other modcods.

The main conclusion is that evaluated DPD technique leads to dB gain up to 0.8 dB. However, when referring to, e.g., the results of the modcod 8-PSK 2/3 provided in Figure 3.14, it can be deduced that the obtained dB gain, up to 0.5 dB for the outer left carrier at 20% roll-off, cannot be converted into throughput gain if the considered modcods in the system are the ones provided in Table 2-1.

Actually, based on the analysis done in Table 3-2, the required dB gain to upgrade to the next modcod and gain 10% additional throughput is 1.4 dB.

With only 0.5 dB gain, the evaluated DPD technique can only help the system by providing more robustness to noise but will not help to increase the throughput.

Table 3-3: Capture of the step to obtain a throughput gain with carrier overlapping

Carrier spacing Roll-off 20%	Symbol Rate (MBaud)	IBO/OBO (dB)	FER	Rs Gain (compared to DPD off)	Occupied Bandwidth
1.13	7.5	4.5/3.3	0	0.00%	34.425
1.13	7.9	4.5/3.3	0	5.33%	36.261
1.13	8	4.6/3.3	0	6.67%	36.72
1.1	8	4.6/3.3	4.00E-03	6.67%	36
1.1	8.1	4.6/3.4	7.00E-03	8.00%	36.45
1.09	8.05	4.6/3.3	1.50E+02	7.38%	36

The Table 3-3 provides the results of the CS optimization and demonstrates that in the same context, a throughput gain of 6.7% can be observed.

Based on the different modcod tested, we found that the proposed framework can lead to throughput up to 10% as evocated in the co-signed article [57].

3.3 CONTINUOUS PHASE MODULATION CHANNEL MODELLING AND HARDWARE IMPLEMENTATION

3.3.1 Overview of the DVB-RCS2 Continuous Phase Modulation and motivation

The DVB RCS2 standard [33] was first edited in June 2011 as the evolution of the standard DVB RCS. DVB RCS2 defines two transmitter configurations: one using Turbo coding and linear modulation (TC-LM) and one using convolutional coding and continuous phase modulation (CC-CPM).

The TC-LM configuration introduces shaper roll-off and new modulation schemes with higher orders than the previous DVB RCS. Higher bit rates can be achieved with this combination.

The linear modulations have variable envelope and e.g., a delta of up to 3dB can be observed in the power dynamic of the QPSK modulation as shown in [70], leading to the requirements of a linearized and then costly amplifier for the user terminal to avoid or reduce interferences and distortions.

The second configuration introduces the Continuous Phase Modulation, a premiere in space systems, which is robust to amplifier nonlinearities. Thus, lower cost terminals as they (with a cheaper amplifier) can be used.. This modulation is also less complex to implement and the overall cost of a terminal based on this configuration is expected to be cheaper than the TC-LM configuration.

The standard definition focuses on the description of the transmitted waveform described in §3.3.2. Though such implementation shall strictly be aligned with the specification to ensure system interoperability, it is important to optimise the implementation cost.

On the other hand, there was no definition of the receiver, thus leaving the receiver specification and design open. The challenge was to propose different approaches and evaluate their performances. An overview of the different approaches and a focus on the recommended approach, based on iterative decoding, are provided in section §3.3.3.

Finally, in the context of the conception of a cheap user terminal, a design of an actual CPM based terminal for hardware implementation is proposed as described in §3.3.4.

3.3.2 DVB-RCS2 CPM transmitter definition

The following definition is provided DVB RCS2 standard [33].

The complex baseband DVB RCS2 CPM signal is given by:

$$s(t) = \sqrt{\frac{2*E_s}{T_s}} * \exp(j(\phi(t))) \quad (eq. 16)$$

where T_s is the symbol duration and E_s the energy contained in one symbol.

The information is defined by phase $\phi(t)$, which is given by:

$$\phi(t) = 2\pi h * \sum_{i=0}^{\infty} a_i q(t - iT_s), t \geq 0 \quad (eq. 17)$$

where:

- a_i is the input symbol to the modulator, such that $a_i \in \{-3, -1, 1, 3\}$
- h is the modulation index and is a rational number of the form $h = m_h/p_h$;
- $q(t)$ is the CPM phase response and is a continuous function, such that:

$$q(t) = \begin{cases} 0 & t < 0 \\ \int_0^t g(\tau) d\tau & 0 \leq t \leq 2T_s \\ 0.5 & t > LT_s \end{cases} \quad (\text{eq. 18})$$

where L is the memory length of the modulator and is set to $L=2$.

The pulse shape filter, known as *weighted average (AV) CPM pulse shape*, is a linear combination of the raised-cosine (RC) and rectangular (REC) pulse shapes, following (eq. 19) and (eq. 20).

$$g_{AV}(t) = \alpha_{RC} g_{RC}(t) + (1 - \alpha_{RC}) g_{REC}(t), \quad \text{where } 0 \leq \alpha_{RC} \leq 1 \quad (\text{eq. 19})$$

$$g_{RC} = \begin{cases} \frac{1}{4T_s} (1 - \cos \frac{\pi t}{T_s}), & 0 \leq t \leq 2T_s \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad g_{REC} = \begin{cases} \frac{1}{4T_s}, & 0 \leq t \leq 2T_s \\ 0, & \text{otherwise} \end{cases} \quad (\text{eq. 20})$$

For the implementation of this signal modulation, let us propose the following linearization of the signal definition.

Let us assume the following decomposition of a CPM signal transmitted at time t , $nT_s \leq t \leq (n+1)T_s$ as described in (eq. 21)

$$\phi(a, t) = 2\pi h \sum_{i=0}^N a_i q(t - iT) \quad (\text{eq. 21})$$

$$\phi(a, t) = 2\pi h a_n q(t - nT) + 2\pi h \sum_{k=n-L+1}^{n-1} a_k q(t - kT) + \pi h \sum_{k=0}^{N-L} a_k$$

$$\phi(a, t) = 2\pi h a_n q(t_n T) + \phi_n(t) + \theta_n$$

Where:

- $\phi_n(t) = 2\pi h a_n \sum_{k=n-L+1}^{n-1} a_k q(t - kT)$ and $\theta_n = \pi h \sum_{k=0}^{N-L} a_k$
- θ_n is the **phase state** of the modulator. It takes its values in a set of 2π -modulo phases defined by:

$$\left\{ 0, \pi \frac{m_h}{p_h}, \pi \frac{2m_h}{p_h}, \dots, \pi \frac{m_h(p_h-2)}{p_h}, \pi \frac{m_h(p_h-1)}{p_h} \right\} \quad \text{when } m_h \text{ is even;}$$

$$\left\{ 0, \pi \frac{m_h}{p_h}, \pi \frac{2m_h}{p_h}, \dots, \pi \frac{m_h(2p_h-2)}{p_h}, \pi \frac{m_h(2p_h-1)}{p_h} \right\} \quad \text{when } m_h \text{ is odd.}$$

- Φ_n is the contribution of the L symbols in memory ($a_{n-L+1}, a_{n-L+2}, \dots, a_{n-1}$)
- $2\pi h a_n \cdot q(t - nT)$ represents the contribution of the current symbol, occurring at time nT_s .

Therefore, the transmitted signal in the interval $[nT, (n+1)T]$ depends on the phase state of the modulator θ_n , the last L symbol $(a_{n-L+1}, a_{n-L+2}, \dots, a_{n-1})$ and the current symbol a_n .

At nT_s , the modulator is at a state defined by:

$$\sigma_n = (\theta_n, a_{n-L+1}, a_{n-L+2}, \dots, a_{n-1})$$

The arrival of the symbol a_n at that time triggers the output of the phase $\varphi(a_n, t)$ and a transition from the modulator state σ_n to σ_{n+1} given by:

$$\sigma_{n+1} = (\theta_{n+1}, a_{n-L+2}, a_{n-L+3}, \dots, a_n)$$

where $\theta_{n+1} = (\theta_n + \pi h a_{n-L+1}) \bmod [2\pi]$ is the new **phase state** of the modulator.

This decomposition allows a trellis representation of CPM with $p_h M^{L-1}$ or $2p_h M^{L-1}$ states and $p_h M^L$ or $2p_h M^L$ transitions according to m_h being even or odd.

Therefore, the architecture proposed by Rimoldi [71] and shown in Figure 6.2 is adopted to implement a CPM modulator.

It introduces the continuous phase encoder which computes the signal phase based on L previous symbols, and a memoryless modulator.

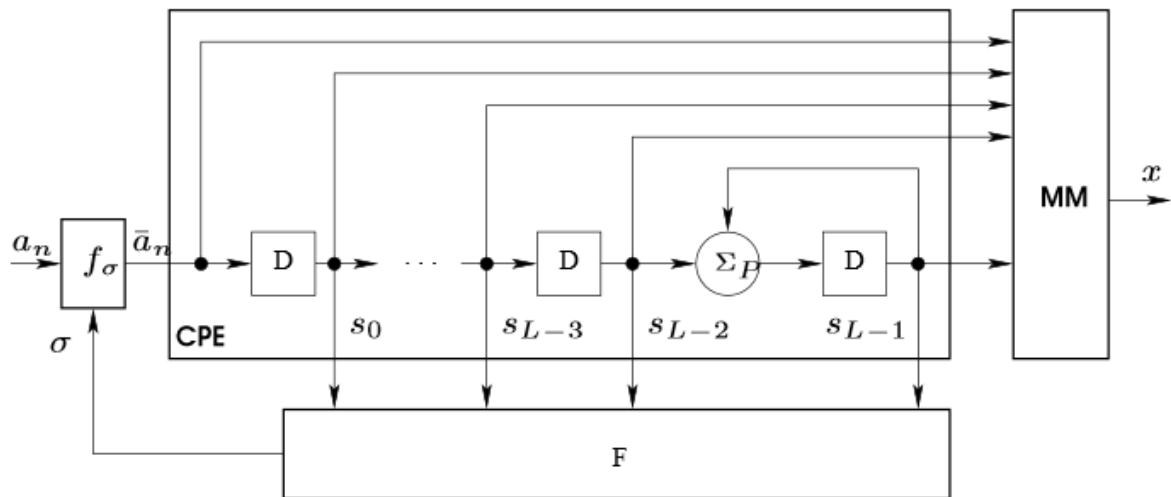


Figure 3.15: CPM encoder with feedback

At the beginning of the process, the modulator phase state is set at 0 as well as the L memories containing antecedent symbols.

Then, when a symbol a_n occurs, the modulator combines the three contributions (θ_n , Φ_n and $2\pi h a_{n,q}(t - nT)$) to output the constellation points (I,Q) respectively being the cosines and the sinus of the output phase $\varphi(a_n, t)$. A state transition is also done after the transmission of the symbol a_n (which last T_s) from σ_n to σ_{n+1} .

This decomposition allows a simple and smooth implementation of the waveform and thus potentially important cost efficiency. It is the basis of the proposed CPM hardware implementation as presented in section §3.3.4.

3.3.3 DVB-RCS2 CPM receiver options

The DVB-RCS2 standard does not specify the receiver since the system compatibility is ensured by the specified transmitted signal. The conception of the receiver is thus

under the responsibility of different manufacturers and can be a performance and cost differentiator.

Based on the nature of the defined DVB-RCS2 CPM signal which can be represented as a trellis, one solution is to decode the CPM signal using a Viterbi decoding as in [72].

The concatenation of a convolutional encoder and a CPM separated by an interleaver as proposed in the DVB-RCS2 standard has been identified as a turbo codes like configuration. Thus, the concept of turbo decoding can be applied at the receiver. It has been investigated in several researches [73], [74], [75] and though its complexity can considerably increase with the memory length and the modulation index, it remains the most efficient approach for CPM decoding.

The following architecture based on [73] was therefore proposed for the iterative decoding of the combination of a convolutional encoder and CPM.

The idea was to benefit from the soft decoding of the CPM to combine the decoding of the CPM and the FEC and then have an architecture similar to the decoding of a turbo code.

The main development in the proposed iterative decoding model is the metric calculation in the SISO CPM and SISO CC blocks.

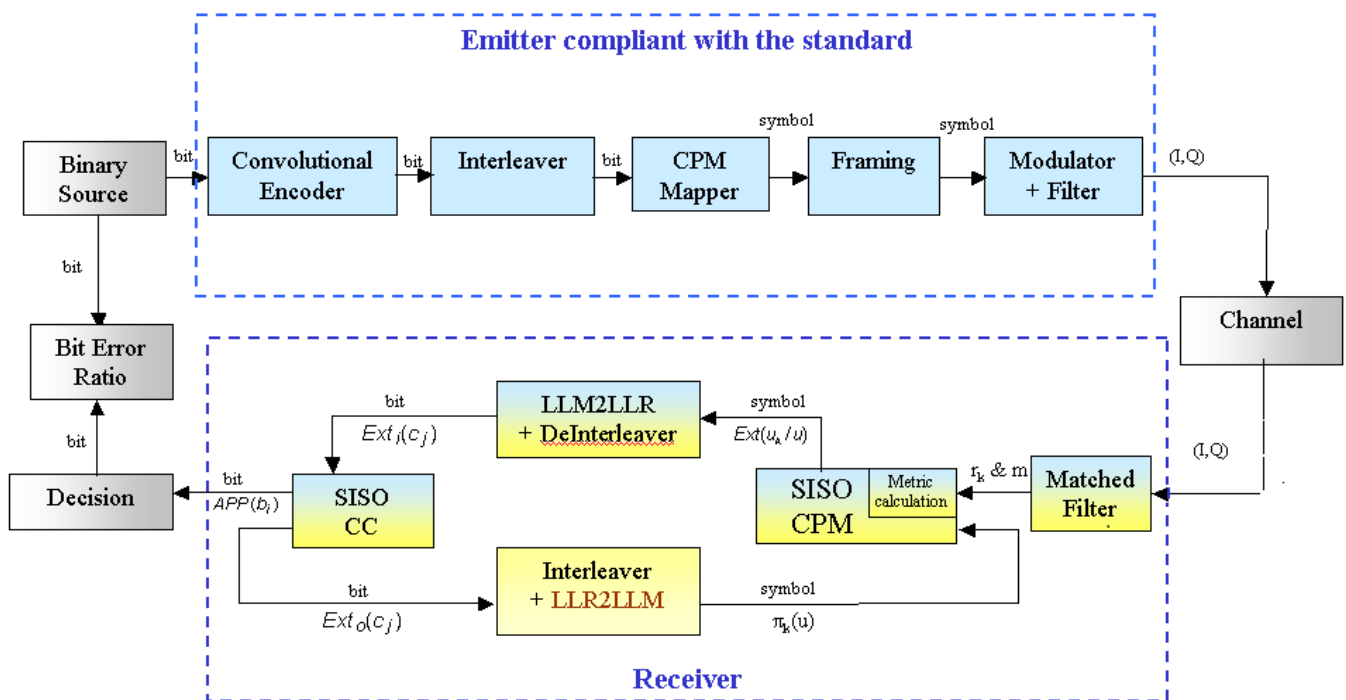


Figure 3.16: Simulator architecture with iterative decoder

SISO CPM block:

The module has two inputs:

- Channel observation \mathbf{r}_k (and set of $p_h M^{L-1}$ possible optimum signals).
- An input giving A Priori Probabilities on symbols $\pi_k(u)$. $\pi_k(u)$ is a M-size symbol: $\pi_k(u) = \Pr(u_k=u)$, where $u=0,1, \dots, M-1$

The SISO CPM must use these two inputs and trellis description of the CPM to compute two outputs:

- A Posteriori Probability $APP(u_k/u)$ on transmitted symbols, which gives the probability of transmission on each symbol channel symbol.
- Extrinsic probability $Ext\left(\frac{u_k}{u}\right) = APP\left(\frac{u_k}{u}\right) / (\pi_k(u))$, which represents A Priori Information on coded symbols.

LLM2LLR + DeInterleaver:

This next module uses the LLM2LLR function to compute $Ext_i(c_j)$, which is A Priori Information on coded bits. The function takes $Ext\left(\frac{u_k}{u}\right)$ as input and computes $\pi_k(c_j) = Ext_i(c_j)$,

The result is deinterleaved using the same permutation table as the interleaver on the emitter side, in order to reorganise the probabilities into the correct order.

The computed A priori information, $Ext_i(c_j)$, is then fed to the SISO CC.

SISO CC:

SISO CC works like the previous block, the SISO CPM. The only difference is that the SISO CC has only one input port and it does not work on symbol probabilities but on bit probabilities.

The unique input of the SISO-CC is the deinterleaved $Ext_i(c_j)$. This input is used to compute:

- $APP(b_i)$, which is A Posteriori Probability on information bit. The result is then sent to the decision block that will perform Hard Decision.
- $Ext_o(c_j)$, which is an update of probabilities on coded bits $Ext_i(c_j)$, is sent as output and will be sent back to the SISO CPM after further treatment.

Interleaver + LLM2LLR:

This treatment consists in re-interleaving $Ext_i(c_j)$ and uses the function LLR2LLM to compute symbol probabilities. Afterwards, these probabilities are fed back to the SISO CPM as A Priori Probabilities on symbols $\pi_k(u)$. A new iteration can start.

The process is executed for a defined number of iterations to improve the decoding performances at the cost of complexity.

3.3.4 Proposed transmitter architecture for CPM hardware implementation

Based on the benefits of CPM based waveform evocated in previous sections, the design of an actual hardware implementing such a waveform was identified as the next step in the analysis.

The UT aims to be a cheap device based on the characteristics of the CPM and on the fact that implementing a standardised waveform (the DVB-RCS CC-CPM for instance) allows interoperability and potential economies of scale for chipset manufacturers.

3.3.4.1 Terminal architecture and selected hardware for the CPM based waveform:

The overall architecture of a CPM based user terminal is provided in Figure 3.18. This architecture includes the DVB-S2x receiver which is not discussed in this thesis. The

return link is based on the DVB-RCS2 standard and implements both TC-LM and CC-CPM modulation. The idea is that the configuration is selectable and depending on the usage, the target cost of the terminal, in line with the other selected key components, especially the power amplifier. I was responsible for the design of the whole transmission chain (Figure 3.18) in both configurations. In the frame of this thesis, I focus on the continuous phase modulator of the CC-CPM configuration.

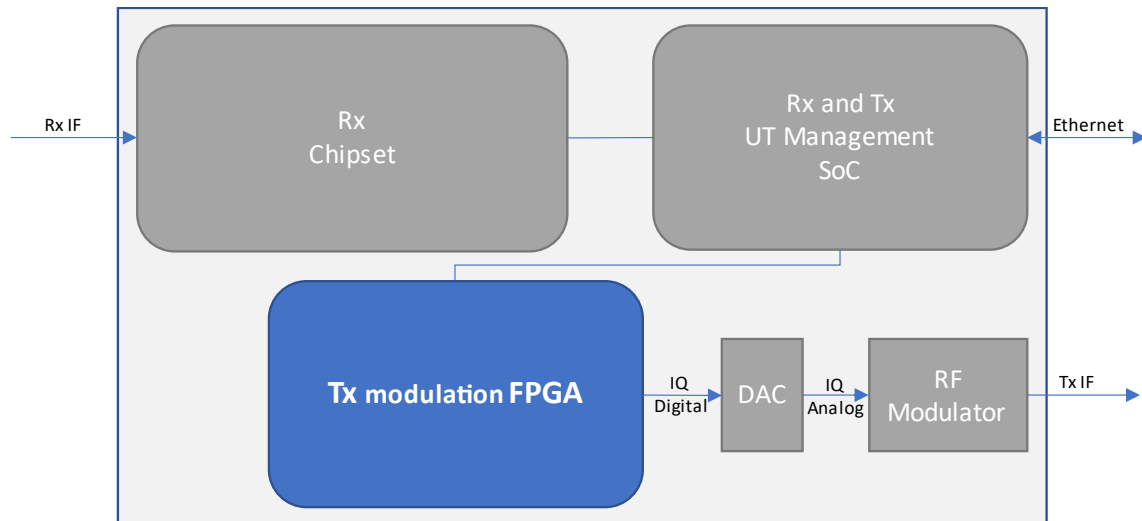


Figure 3.17: Overall DVB-RCS2 UT architecture

The baseband implementation of the return link is based on a FPGA, the Xilinx 7 series which provides a good trade-off of performances vs cost for the foreseen features. It could be interconnected with existing DVB-S2x-receivers chipset such as EZiD211 - Oxford 2 [76] for a complete DVB S2x/DVBRCS2 terminal. A system on chip (SoC) can perform upper layer functionalities such as encapsulation, framing, both for the receiver chipset and the transmitter chipset. A digital to analog converter and an RF modulator are connected successively at the output of the Tx modulation FPGA and the resulting signal is sent to the Block up converted (BUC) and the antenna.

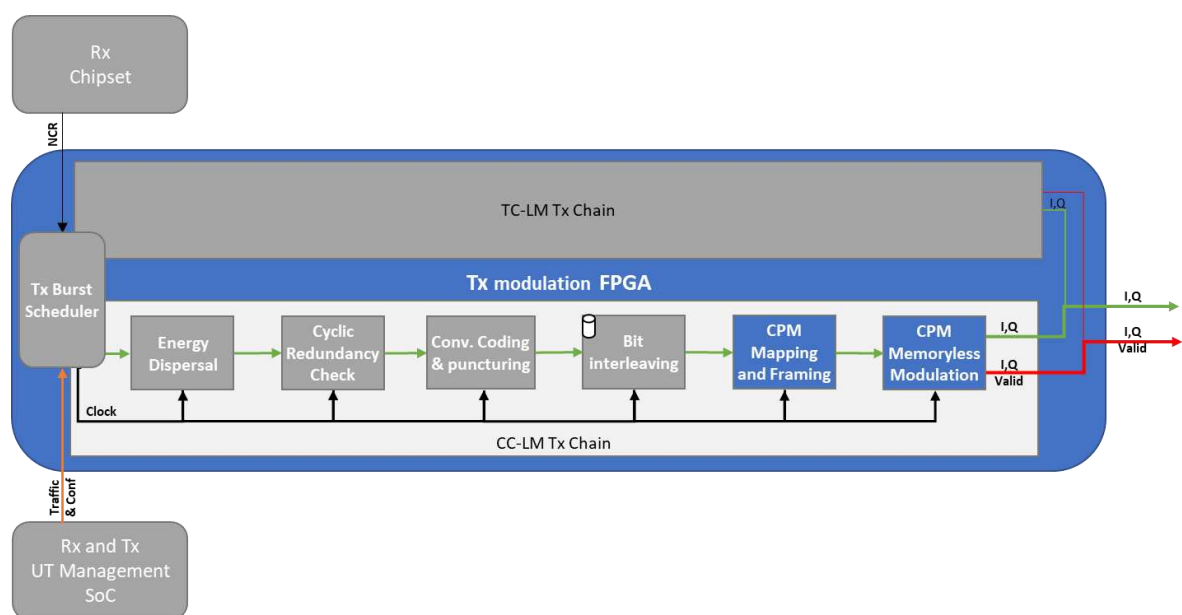


Figure 3.18 RCS2 waveform modulation chain

The TX burst scheduler receives transmission chain configuration and traffic from the SoC. The traffic is processed through different modules (energy dispersal, cyclic redundancy check (CRC), convolutional encoding, bit interleaving and finally the CPM modules which are the “CPM Mapping and Framing” and “CPM Memoryless Modulation”. The proposed architecture of the CPM modules is provided in Figure 3.19.

3.3.4.2 CPM Mapping and Framing

The CPM mapping and framing are the module performs:

- Bit to symbol mapping of the permuted encoded bits as defined in [33]
- Insertion of known symbols or unique word (UW) which are the preamble and the postamble, also defined in [33].

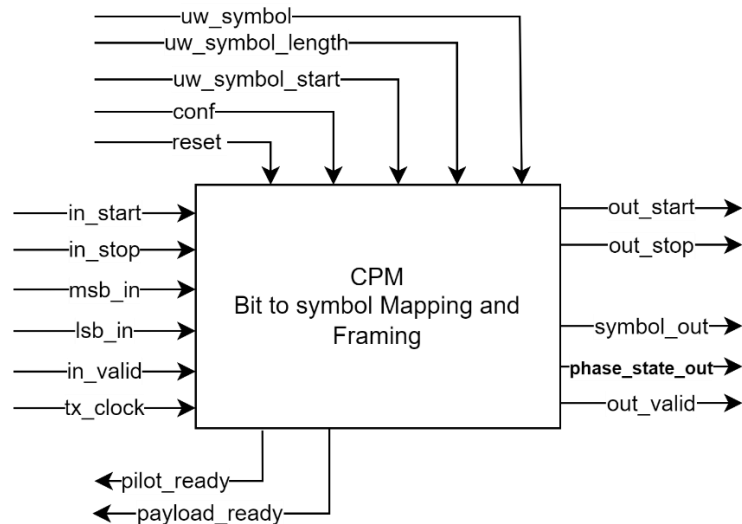


Figure 3.19: CPM bit to symbol mapping and Framing

When the start signal occurs, the module loads the burst configuration. The configuration includes the mapping scheme according to the burst configuration (linear or Gray mapping), the modulation index and the number of Unique Word segments.

For each valid input of encoded bits (msb and lsb input ports), the module maps the pair of bits to a symbol as specified in Table 3-4.

The symbols are then translated from the range $\{-3,-1,1,3\}$ to range $\{0,1,2,3\}$ as the CPM modulator is designed following the Rimoldi description of Continue Phase Modulation [71].

Table 3-4: Bit to symbol mapping for DVB-RCS2 CC-CPM

MSB	LSB	Symbol Value $h=1/3$	Symbol Value $h \neq 1/3$	Symbol value following Rimoldi $h=1/3$	Symbol value following Rimoldi $h \neq 1/3$
0	0	-3	-3	0	0
0	1	-1	-1	1	1
1	0	1	3	2	3
1	1	3	1	3	1

When it is time to send a UW segment, the module interrupts the reception of MSB and LSB payload bit from the CPM Bit Interleaver Module and instructs the TX-Burst scheduler to provide the UW symbols. The UW symbols are then read at the uw_symbol port, translated following the Rimoldi decomposition and sent at the output port.

While running, the module also sends alongside any valid symbol, a computed phase state of the memoryless modulator as described in §3.3.2.

When the stop signal occurs, the module immediately forwards it to the stop output port, unless the signal is received while sending UW symbols of a UW Segment: in this case, the stop signal is sent at the end of the UW segment.

3.3.4.3 CPM Memoryless Modulation

The CPM Memoryless Modulation module is in charge of baseband IQ continuous phase modulation, filtering, and oversampling.

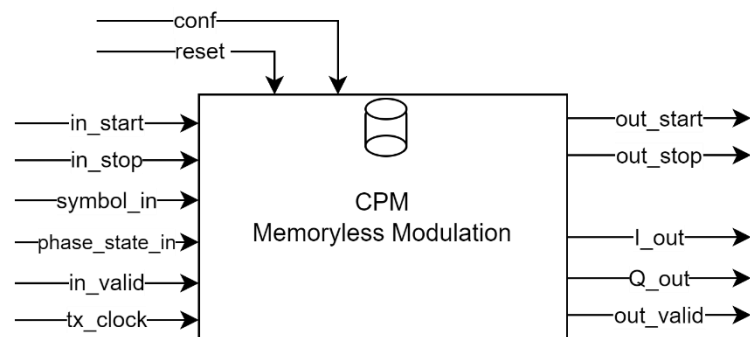


Figure 3.20: CPM memoryless modulation

The module carries out the Memoryless Modulation function as described in the Rimoldi decomposition of CPM signal [71].

When the start signal occurs, the module loads the applicable burst configuration (i.e., the modulation index, the roll-off factor, the oversampling factor).

The module computes a Look-up-table of the filter phase response coefficients. These coefficients are used with the pair of input data (modified symbol and modulator phase state) to compute the modules outputs, I and Q following the decomposition provided in (eq. 16), (eq. 17), and (eq. 18) (section §3.3.2).

3.3.5 Results and analysis

The results of the proposed chain are provided as a BER vs Eb/No plots in Figure 3.21 and were demonstrated to match early feasibility analysis, considering perfect time and frequency synchronisation. The simulations are performed for a 4-ary CPM (M=4) and a modulation index $h=2/5$ and code rate of 5/7. The soft input decoding demonstrated an improvement of the required Eb/No by 2 dB for BER < 1.00 E-04.

Hence, according to the simulation and with the observed performance, a system requiring a BER not higher than 1.00E-04 would need an Eb/No of 5 dB to then ensure a spectral efficiency of $2 \cdot 5/7 = 1,42$ bps/Hz.

The hardware receiver implementation was not addressed during the activities and the performance of the implemented CPM transmitter was evaluated using the (I,Q) output as input of the receiver simulator and similar results were confirmed.

However, the proposed implementation approach did not improve the performance as evaluated in the literature, but it allowed us to achieve expected performances at lower cost and with reconfigurable hardware. It opens the door to future implementation of potential improved waveforms.

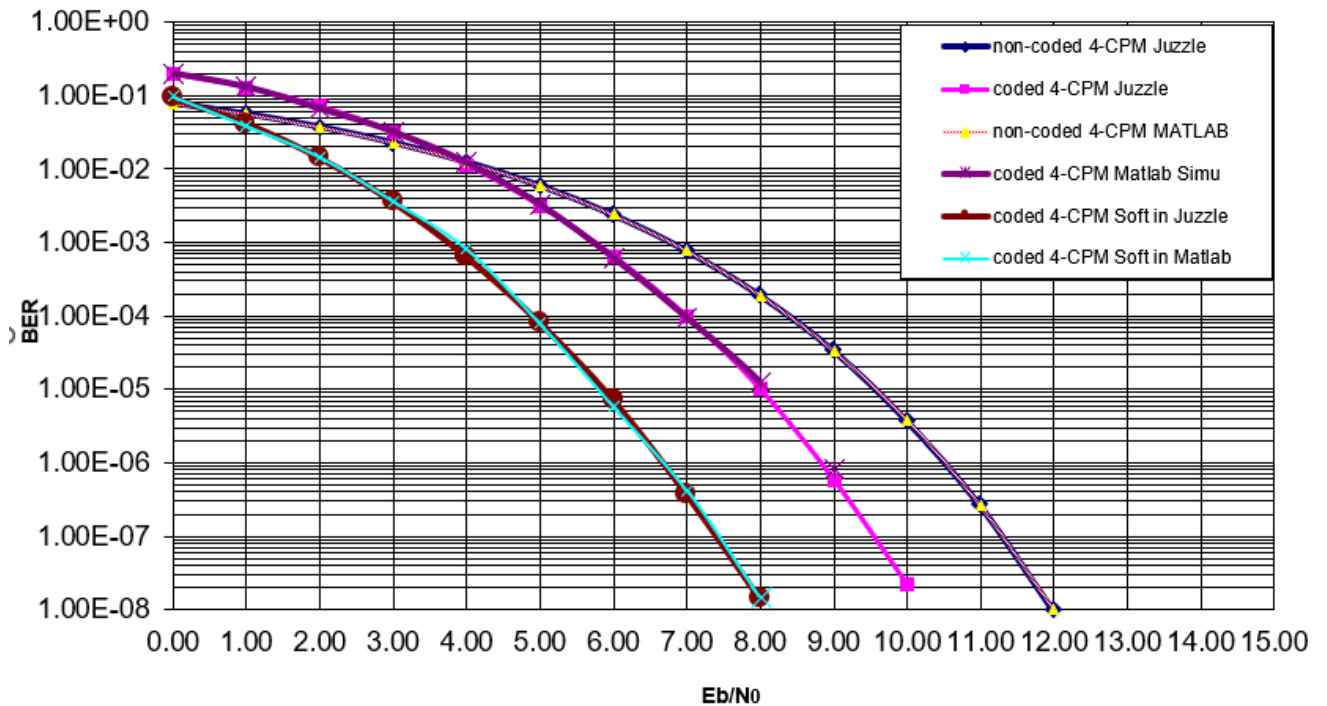


Figure 3.21: DVB-RCS2 CC-CPM BER performance based on hard and soft decoding

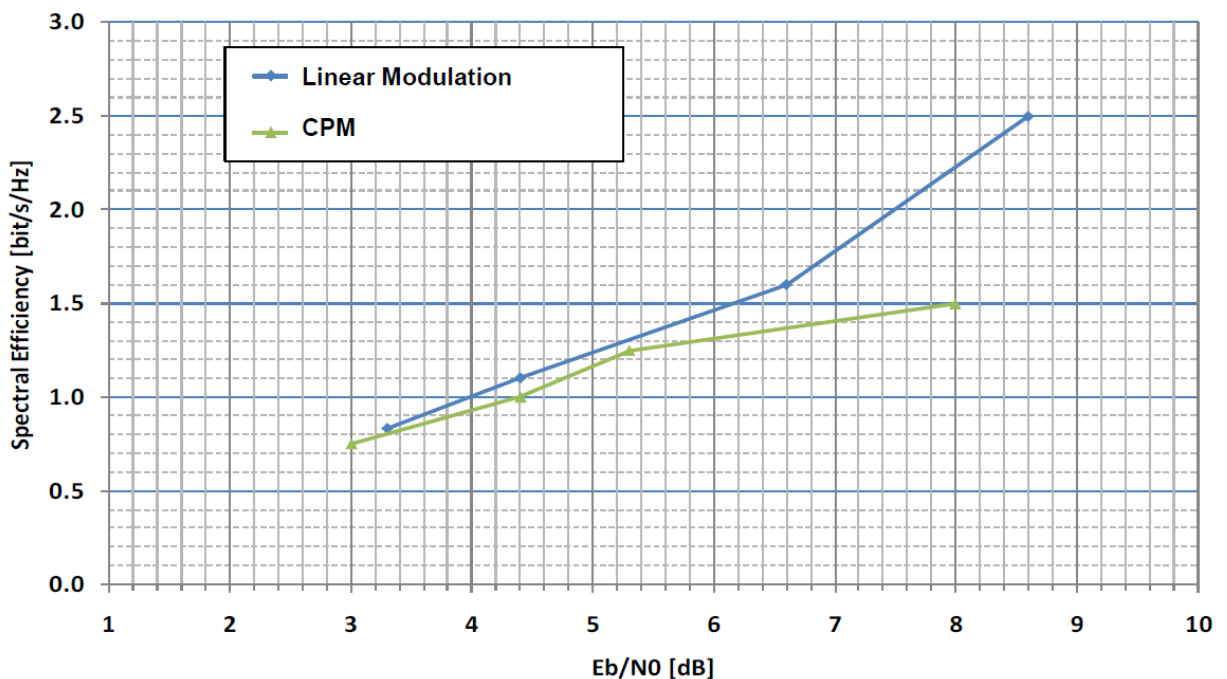


Figure 3.22: CPM vs LM spectral efficiency

Finally, the CC-CPM can be simple and cheap, but the demodulator is quite complex and compared to low SNR waveforms, the performances are limited for a cost gain which is difficult to demonstrate. For instance, Figure 3.22 built in provides an overview of CPM versus LM performance and shows that LM always performs better than CPM. Thus, the question is to assess if the potential reduced cost of a CPM terminal may justify such performance inferiority compared to LM.

3.4 CONCLUSION

In this chapter, we have investigated two topics related to the enhancement of the capacity of a SatCom system and presented our proposal on some identified key issues: (1) the multi-carrier predistortion and associated optimizations and (2) Continuous phase modulation and DVB-RCS2 performance. The current conclusion firstly addresses this latest topic, before addressing the first topic which has more materials presented in this thesis.

Continuous phase modulation and DVB-RCS2 performance:

We have investigated techniques to decode the CPM and evaluated the performances on various contexts, and especially the announced robustness of the CPM with regard to nonlinearities.

The results of the proposed approach show that it was a good starting point but some topics such as multi-user management needed to be further investigated in order to conclude on the benefits of the CPM in mass-market SatCom.

The proposed UT architecture based on reconfigurable hardware to implement the flexible return channel waveform has the benefits to remain generic and to combine the upper layer features for TC-LM and CC-CP in a single module. However, such an approach remains more expensive than a dedicated CC-CPM hardware/chipset and it reduces the potential cost benefits of the configuration to the selected BUC (potentially cheaper BUC for CC-CPM configuration).

Although it was clear that linear modulation is more efficient than CPM to achieve higher throughput, the latest development of very low SNR (VL-SNR) waveform based on linear modulation and efficient FEC has decreased the interest in CPM at VL-SNR [77].

CPM has not really been adopted and implemented in SatCom until nowadays, even though some ground segment products such as the Dialog platform include a CPM waveform [78].

Nevertheless, the characteristics of CPM remain of interest given the low complexity and power saving terminal and can be an option for massive communication type (of IoT) over satellite.

Multi-carrier predistortion and associated optimizations:

While the throughput gain is obviously a tangible and concrete gain for operators, the dB gain is also important for satellite manufacturers that can target aggressive (reduced) OBO and reduce some link budget margin.

We have identified the issue of the determination of the optimal operation point of the satellite high power amplifier based on actual system key performance

indicators. We have highlighted the requirement of a framework for proper determination of the OOP based on system KPI rather than classic RF evaluation.

The proposed framework for optimal definition of the operation point has the advantage to focus on the effective throughput gain, which is the final objective of implementing the predistortion as a capacity performance enhancement technique. The proposed framework is based on data from final operating setup and requires limited additional equipment. The proposed approach, based on a three-steps algorithm with iterations, can also be used to improve the setting of a system without predistortion.

However, for effective deployment on live satellites, the proposed approach requires the ability of live modification of the operation point of satellite amplifiers based on the characteristics of the carriers to be implemented and actual satellite transponder IBO settings.

As a solution to such limitation, the algorithm to determine the OOP could be executed at the GW side with an emulated transponder which has the characteristics of the actual transponder. This can be linked to my actual research on automatization and performance optimization research described in section §6.2.

Another proposed framework is related to the intentional overlapping of the carriers thanks to the ability of DPD to cancel the associated interferences.

Hence, the proposed algorithm monitors the FER to keep it below a given level (typically $1e-3$) and successively reduce the carrier spacing and increase the symbol rate accordingly resulting in carried overlapping and symbol rate gain.

The last proposed framework for performance evaluation aims to provide an accurate measurement of the throughput gain and it is an important material for the evaluation of future performance enhancement features.

Finally, all the proposed frameworks were designed in the frame of the optimization and evaluation of an iterative DPD technique.

It has been clarified that the proposed frameworks need to be applied to benchmark scenarios (in this case with DPD disabled) in order to capture any potential gain before the activation of the DPD. When the frameworks and processes are executed with DPD activated, the benchmark gain is then deducted from the observed gain to obtain the effective accurate gain related to the selected DPD technique.

The performances of the proposed algorithms combined with the efficiency of the selected DPD technique have led to the demonstration, confirmed both on lab and on several real satellites, of a throughput gain up to 10% [57], [79], [80].

Chapter 4. SATELLITE-TERRESTRIAL INTEGRATION ARCHITECTURE AND CONCEPTS IN 5G CONTEXT

4.1 INTRODUCTION AND OVERVIEW OF THE CHALLENGES

Recent evolutions in communication networks are highly expected to lead to the increase of data rate, enhanced coverage and availability and new use cases for the consumers/mass market. This is confirmed for 5G mobile networks, which was announced a few years ago [81], is under standardisation and deployed at radio access level (non-standalone) since 2019 [82].

The telecommunication and network companies in charge of 5G networks also view the future 5G as a more efficient network with reduced cost, CAPEX (capital expenditure) and OPEX (operational expenditure), per Mbit or per service [8]. For instance, CAPEX reduction can be done with less dedicated and costly hardware on the benefits of generic, powerful, and cheaper hardware. OPEX reduction would be achieved through adoption of paradigms such as virtualization, and network slicing, providing improved flexibility and efficiency and reduced operation costs.

Satellite networks aim to play a key role in all these aspects thanks to their characteristics. It can contribute to :

- The advance of 5G coverage (white zone, dense area, etc.)
- The advance of capacity where terrestrial connectivity is limited
- Enabling use cases (e.g., 5G connectivity in the air, on seas)
- Improving flexibility and rapid deployment for emergencies or in case of disaster.

These aspects are explored in this chapter.

On the other hand, to ensure proper satellite and terrestrial interconnection in the 5G context, there are several challenges to face and key enablers to develop, which can be summarised as “make the satellite 5G ready”. The first step being to identify and further specify such challenges and key issues at different layers, beyond what was introduced in section §2.4.5.

Table 4-1 provides an overview of the challenges and main topics to be addressed.

At the physical layer, challenges such as random access, timing advance and hybrid automatic repeat request (HARQ) have been identified [83]. At higher layers, the following challenges and key issues have been identified [84]: service continuity, support of QoS and network slicing, multilink management, edge delivery, integrated architecture with integrated management and orchestration systems, etc.

These aspects are investigated in this chapter, as well as the proposed solutions, and the adoption of some paradigms from terrestrial networks, in particular Software Defined Network (SDN) and Network Function Virtualization (NFV).

Table 4-1: Main requirements for 5G satellite and terrestrial integration

Layer	Challenges
Lower layers	Random access Timing advance Hybrid automatic repeat request Resources management ...
Upper layers	Service continuity Traffic management Integrated management and orchestration Multilink management Support of network slicing and Quality of Service ...

Note that several materials from this chapter are provided in my publications, [84], [85], and as contribution to 3GPP technical report TR 23.737 [86] and TR 28.808 [87].

4.2 USE CASES SPECIFICATION

4.2.1 Motivation

As stated in [88], a number of new access technologies are providing internet services, including wired and wireless accesses. Mobile networks were initially designed for voice services and connectivity in non-fixed locations and have evolved to provide advanced services and above all internet access. This led to the definition of next-generation network (NGN) in the 2000s, which some key concepts include interworking with legacy networks via open interfaces, generalised mobility, support of multiple last mile technologies, etc. [89].

In connectivity system evolution (as the current 5G era), each connectivity solution needs to address a specific and appropriate role to justify its adoption and potential costly investments. For example, optical fibre has been adopted for base station connectivity, backbone, and broadband fixed access. On the other hand, wireless access technologies can be directly integrated in the mobile user device (Wi-fi, Bluetooth, NFC, etc.).

Satellite access technologies can play a key role to meet network evolution objectives, especially providing connectivity to underserved areas, in the ground, in the air and on the sea. The usage of such connectivity solutions needs to be properly assessed through use case definitions and ensuing technical development requirements, especially when considering some 5G system requirements such as high capacity and extended coverage, integrated network system management, lower latency, reliability etc.

Moreover, at the difference of previous mobile system generation (up to 4G/LTE), analysing satellite connectivity role at the specification stage of the 5G system will ensure improved and more efficient 5G satellite-terrestrial integration.

4.2.2 State of the art and 5G usage scenarios

5G Usage scenarios

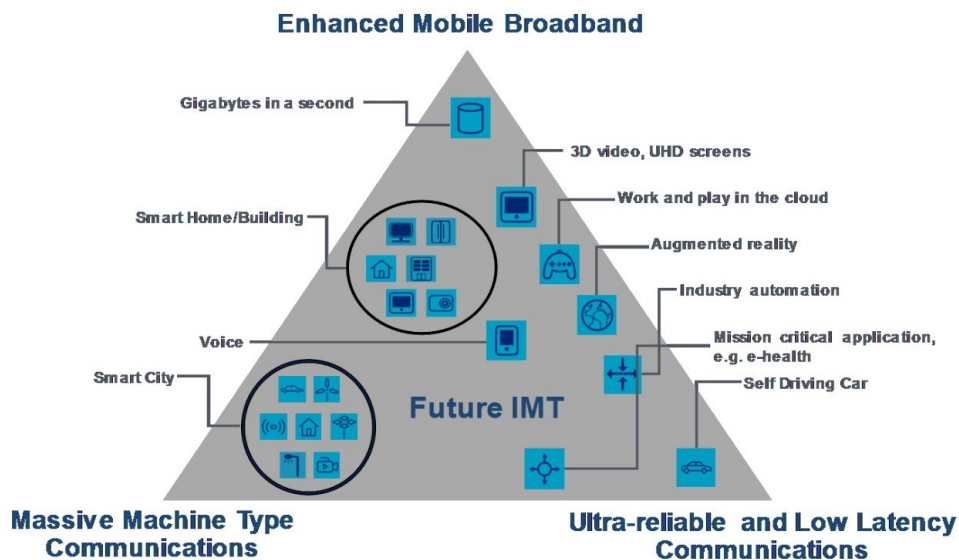


Figure 4.1: The original 5G triangle, from Recommendation ITU-R M.2083

Satellite and terrestrial hybrid network specified in [88] represents the satellite link as an access network to the terrestrial core network. It is expected that satellite connectivity can play more important roles in 5G, beyond the access network.

The ITU-R M.2083 represents the 5G usage scenarios with the well-known triangle of application families[81] (Figure 4.1):

- *eMBB - enhanced Mobile Broadband*: Somewhat the same as 4G, but with faster speed and larger capacity. eMBB supports the accelerating growth in the number of consumer devices and to mitigate the expected saturation of 4G networks
- *URLLC - Ultra Reliable, Low-Latency Communications*: URLLC fulfills requirements of vertical market segments such as industrial, health, transportation, and aviation that have high demands for low latency and high reliability. These new use cases came from stakeholders outside of the traditional telecommunications world, such as automotive and energy
- *mMTC - Massive Machine-Type Communications*: mMTC supports a massive number of connected objects. While not necessarily requiring high data rates or low latency, these connected objects have other demanding requirements such as ultra-long battery life, small footprint, and simplicity needed to enable connections for almost any kind of object.

These 5G usage scenarios are the basis for the definition of integrated satellite and terrestrial use cases, satellite link being a potential added value technology for each of the 5G usage scenarios.

4.2.3 Integrated satellite and terrestrial use cases and scenarios

In the SaT5G project [15], the first work package was dedicated to the specification of integrated satellite and terrestrial use cases to clearly identify which role the satellite would play in 5G.

The four following satellite use cases have been defined (Figure 4.2):

- **SaT5G Use Case 1: Edge delivery & offload for multimedia content and MEC VNF software** – Providing efficient multicast/broadcast delivery to network edges for content such as live broadcasts, ad-hoc broadcast/multicast streams, group communications, Multi-Access Edge Computing (MEC) and Virtual Network Function (VNF) update distribution
- **SaT5G Use Case 2: 5G Fixed backhaul** – Broadband connectivity across a wide geographic region where it is difficult or not (yet) possible to deploy terrestrial connections to towers; e.g., maritime services, coverage on lakes, islands, mountains, rural areas, isolated areas, or other areas that are best or only covered by satellites
- **SaT5G Use Case 3: 5G to premises** – Connectivity complementing terrestrial networks, such as broadband connectivity to home/office small cell in underserved areas, in combination with terrestrial wireless or wireline
- **SaT5G Use Case 4: 5G Moving platform backhaul** – Broadband connectivity to platforms on the move, such as planes, vessels, and land vehicles.

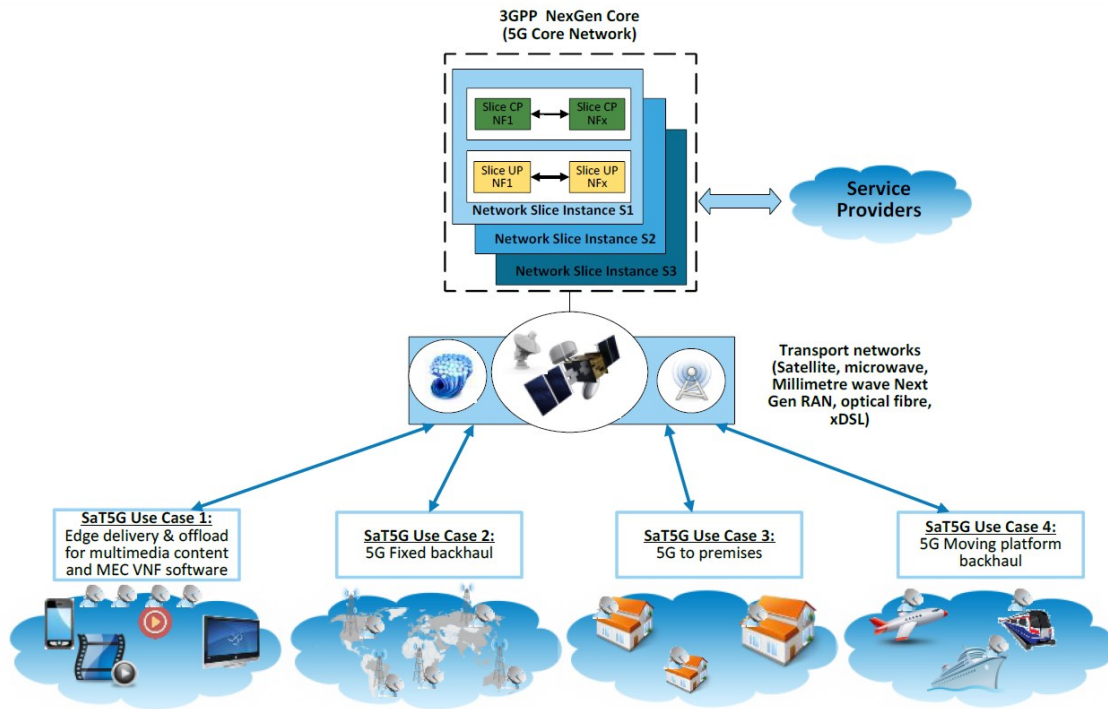


Figure 4.2: SaT5G Use Cases for Satellite in 5G [15]

In addition, for each SaT5G Use Case, a set of Scenarios, which corresponds to instantiations of the SaT5G Uses Cases for the accomplishment of a specific duty has been defined. The scenarios drive the integrated network topology and the architecture design. They are summarised in the Table 4-2.

Table 4-2: SaT5G use cases and scenarios [15]

SaT5G Use cases	Scenarios for SaT5G Use cases
SaT5G Use Case 1: Edge delivery & offload for multimedia content and MEC VNF software	Scenario 1a: Offline multicasting and caching of video contents and VNF software through satellite link
	Scenario 1b: Online prefetching of video segments through satellite links
SaT5G Use Case 2: 5G Fixed backhaul	Scenario 2a: Satellite backhaul to groups of cell towers
	Scenario 2b: Satellite backhaul to individual cell towers
	Scenario 2c: Satellite backhaul to individual small cells
SaT5G Use Case 3: 5G to premises	Scenario 3a: Hybrid Multiplay (satellite/xDSL) at home/office premises in underserved areas
	Scenario 3b: Hybrid Multiplay (satellite/cellular) at home/office premises in underserved areas
SaT5G Use Case 4: 5G Moving platform backhaul	Scenario 4a: Updating content for on-board systems and grouped media request by the moving platform company
	Scenario 4b: Broadband access for passengers and individual media requests
	Scenario 4c: Business and technical data transfer for the moving platform company

4.2.4 Moving platform backhaul (my main contribution)

The moving platform backhaul use case aims to provide connectivity to in-motion terminals on earth (e.g., train), on sea, in the air.

It targets 5G usage scenarios eMBB (for passenger communication, entertainment) and mMTC (e.g., for the monitoring of the moving platform).

The moving platform backhaul use case has three identified scenarios : scenario 4a, 4b and 4c [15].

- Scenario 4a - Updating content for on-board systems and grouped media requests by the moving platform company: this scenario aims to benefit from the broadcast capacity of SatCom systems to provide feed the media catalogue with popular contents for the passengers. This scenario implies the requirement of computing and storage capabilities within the moving platform and is linked to Sat5G use case 1 (Edge delivery & offload for multimedia content and MEC VNF software)
- Scenario 4b - Broadband access for passengers and individual media requests: this scenario is basically the individual direct access of any single passenger or user equipment to a dedicated communication session. It is mandatory to have a bi-directional communication link
- Scenario 4c - Business and technical data transfer for the moving platform company: this scenario is linked to the exploitation of the moving platform and the collecting of business and technical data for global processes. Short messages from various sensors (internet of things) could then be transmitted on live to identified servers and can be used to feed machine learning algorithms. It may be used for predictive maintenance or business modelling.

The backhaul use case, including the moving backhaul use case, will be the reference use case throughout this thesis. It is therefore the basis for the integrated network role model (section §4.3) and the specification of key enablers (section §4.4).

4.3 INTEGRATED NETWORK ROLE-MODEL

4.3.1 Overview of the value chain, the role model and associated technical challenges

4.3.1.1 Value chain and associated technical challenges

The value chain refers to the steps from the initial creation of products or services, and the successive transformations and associated value incrementation onto final products or services.

The value chain is usually analysed in organisations regarding their products for different purposes: diagnose and correction of inefficiencies, understand core competencies and areas of improvement, optimise activities to maximise revenues and/or minimise costs [90], etc.

It is important in all domains including the satellite connectivity to identify where the value is for the players, to select which role(s) they are willing to play.

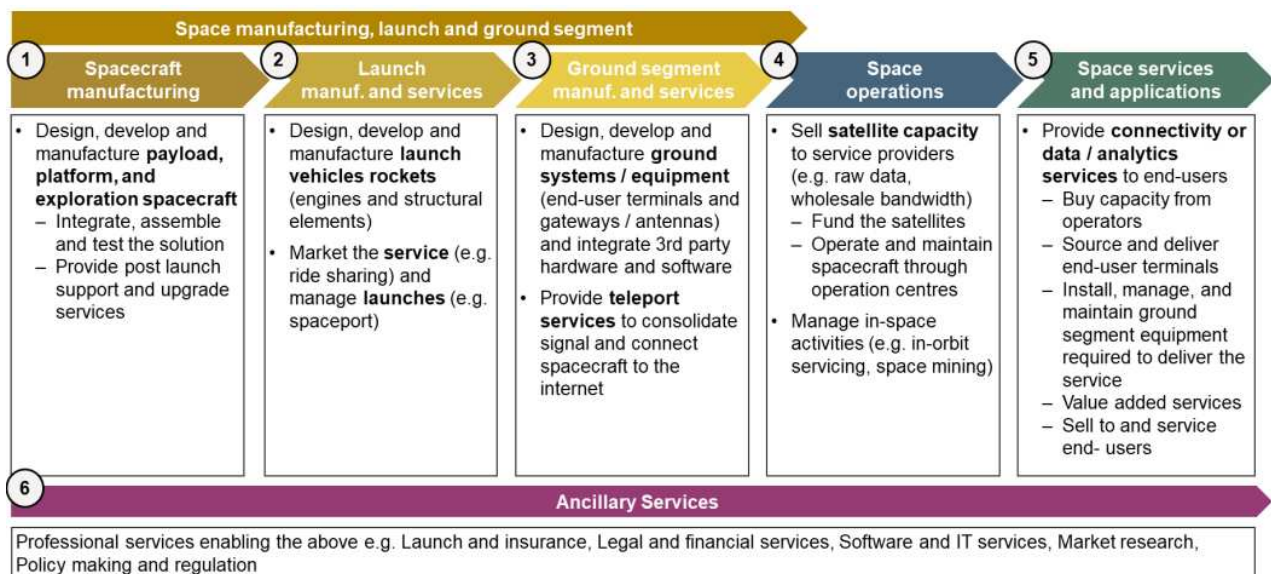


Figure 4.3: Space sector value chain: view of the UK national space strategy [91]

For satellite connectivity, the steps of the value chain may differ from country or region. However, it will often include the space manufacturing, the launch manufacturing, the ground segment and service manufacturing, space and network operation, etc. An example of the analysis of this value chain for the UK is performed in [91] and represented in Figure 4.3.

Figure 4.3 provides a view of the different steps from satellite manufacturing to final connectivity consumer. It also includes the launch services, the lease and sale of satellite capacity, which is usually the bandwidth in MHz, the connectivity service with service level agreements (SLA), and the value-added services (e.g. satellite optimised mail server, cybersecurity, etc.) for the end user.

In such a context, the value chain of a domain is very evolutive as additional steps can be included to the chain as the market and technology evolve.

Figure 4.4 represents a potential value chain for the satellite connectivity in 5G context and the interfaces to develop between domains as a new step are highlighted.

The interconnection with terrestrial networks can then lead to several technical constraints:

- The integrated network management
- The service continuity between satellite domain and terrestrial domain
- The management of the quality of service (QoS) across the two domains
- Etc.

These constraints are identified as key enablers and are further investigated in section §4.4.



Figure 4.4: Potential value chain for satellite connectivity in 5G

4.3.1.2 Role model and associated technical challenges

The role model is a set of stakeholders, connected to each other following predefined business rules and with specific roles and responsibilities.

In SatCom systems, several players can be involved, including the satellite manufacturer, the content provider, the service and connectivity provider, and the end user. Figure 4.6 provides an overview of a typical role model for satellite connectivity.

Technical requirements related to the role model may include database sharing for authentication, accounting and cybersecurity constraints as the players might have different rules. But the main requirement is resource optimization. Actually, the role model defines the business boundaries and the associated resources, services, or materials between the stakeholders. In satellite communications for instance, one stakeholder, usually identified as the satellite operator (owner of a satellite in orbit) would provide a MHz lease to a satellite network operator that would transform such MHz into a connectivity solution. A common challenge for the satellite network operator is to optimise the lease MHz to obtain the maximum Mbps but some relevant settings to achieve such goal may be under the responsibilities of another stakeholder (e.g., static IBO/OBO settings defined by the satellite operator).

Another key player in the role model for satellite communication is the ground segment provider and operator and flexibility is required to adjust the number and the size of networks on-demand.

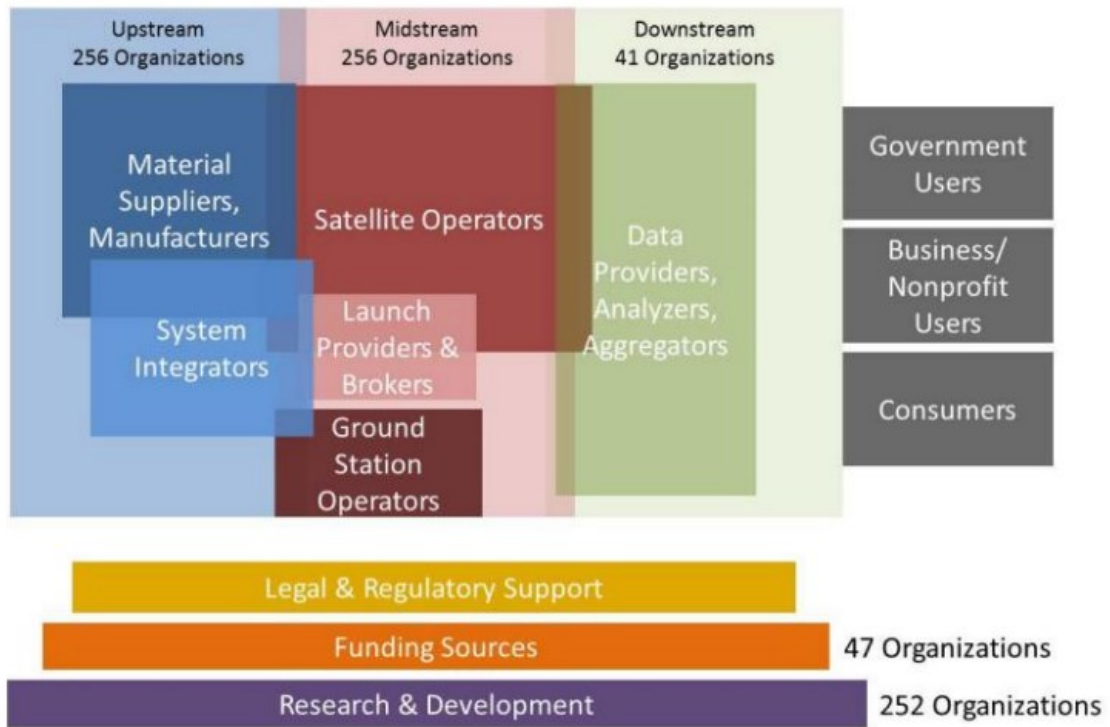


Figure 4.5: Legacy role model for satellite connectivity [92]

Such an initial rigid role model with predefined boundaries can be less effective to address certain use cases or constraints and to provide an efficient end to end satellite network management or satellite resource management.

The open/agnostic role model and the brokerage model proposed in sections §4.3.2 and §4.3.3 aim to provide different collaboration solutions to face the mentioned challenges and compete efficiently with fully vertically integrated models.

4.3.2 Proposed generic open/agnostic role model

The proposed agnostic role model is related to the value chain with interfaces with clear technical requirements, which can be simplified if done by the same organisation or be complexified based on more restrictive business rules (e.g., National GW).

An agnostic role model for integrated satellite-terrestrial network with content delivery is represented in Figure 4.6.

The advantage of such a model is that domain boundaries are defined by the type of activities and not by the players.

Thus, a stakeholder can stick to his legacy activities (e.g., SES, satellite operator) or it can also easily decide to play another role (e.g., SES, satellite network operator) in the value chain.

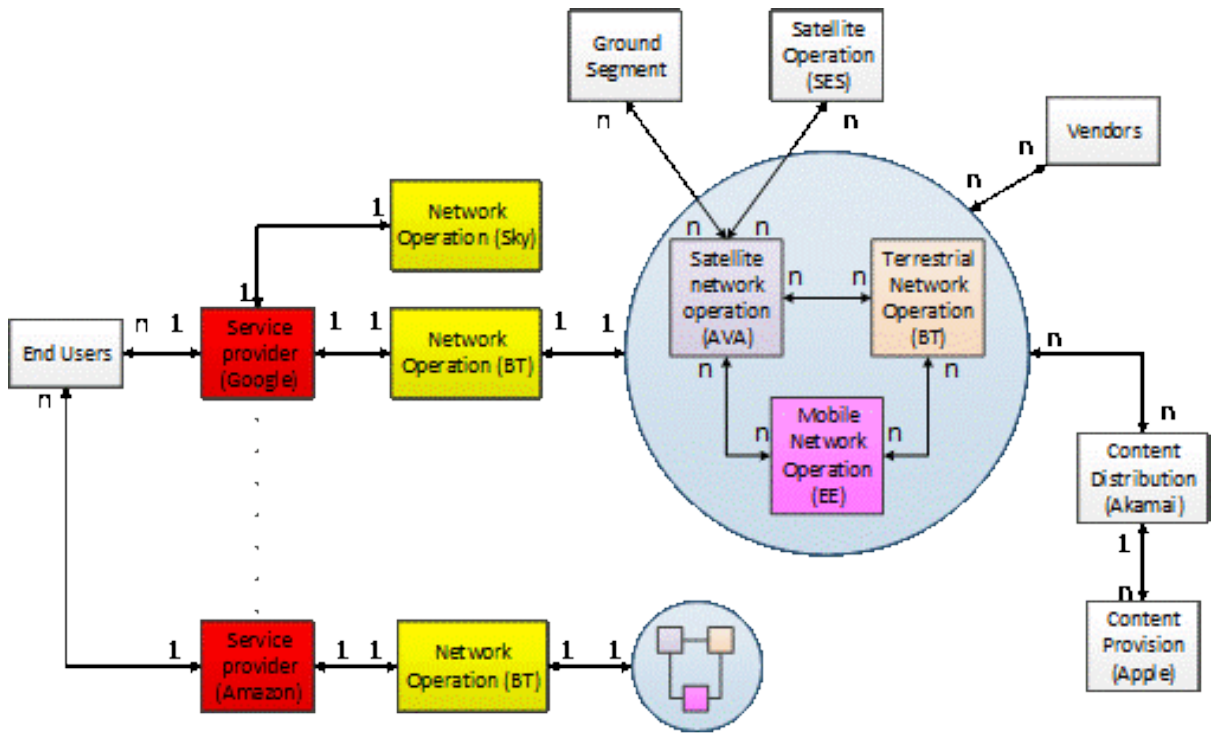


Figure 4.6: SaT5G Agnostic satellite terrestrial role model

The model is then appropriate for vertical integration of a stakeholder, but also for joint effort by different stakeholders on developing a new role (e.g., software defined ground segment in collaboration between ground segment manufacturers, satellite manufacturers, and satellite operators).

4.3.3 Proposed brokerage model and associated challenges

In the context of 5G satellite-terrestrial integration, the question of satellite resource availability is essential as several players can provide connectivity to the same area, but none can provide connectivity to all the areas.

There are therefore few questions when adding a satellite link in a 5G system: which satellite solution to take, which partners and what if the selected satellite network operator (SNO) has poor connectivity in some areas or if his system in that area is loaded?

Following the agnostic role model, it is proposed to introduce a new role to ensure satellite connectivity with adequate resource allocation when it is needed and at a fairly negotiated price: the capacity brokerage.

The brokerage role played by let us call it the "Capacity Broker" consists of negotiating the capacity with the maximum number of satellite operators in a considerable high dynamic (with few minutes) compared to how it is currently done (days, weeks).

Another advantage is that a broker would provide a single external interface to 5G system operators to deal with satellite capacity; and also for satellite operators to sell satellite capacity.

This negotiation is performed through a digital automatised interface between the players, following the logic provided in Figure 4.7 as proposed in [93].

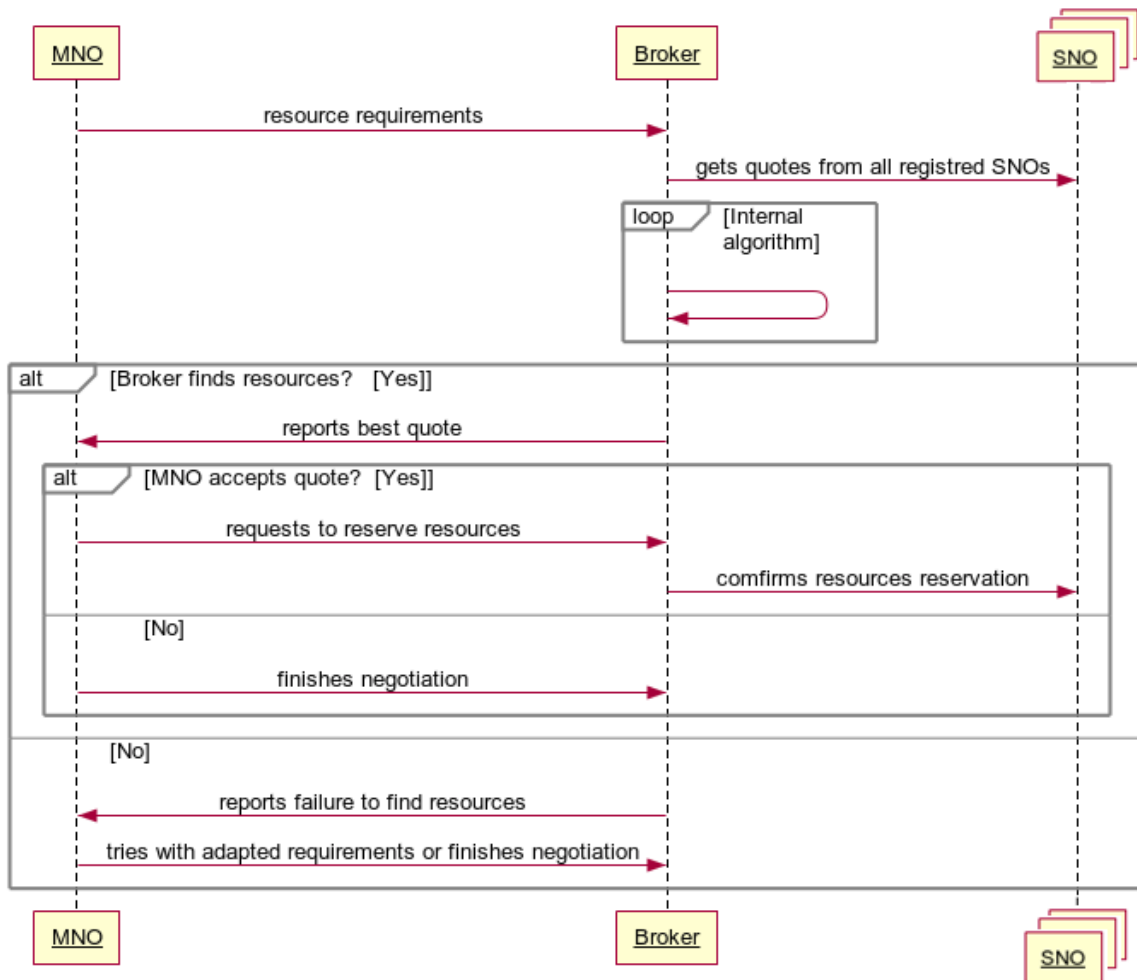


Figure 4.7: SaT5G brokerage model

In [93], I identified requirements for flexible ground infrastructure (to allow support of multiple technologies), and dynamic satellite resource allocation as key enablers for the satellite capacity brokerage model.

4.4 SPECIFICATION OF KEY ENABLERS

4.4.1 Overview of the requirements for satellite-terrestrial 5G integration

Satellite and terrestrial interconnection in the 5G context requires the identification of key issues and associated candidate solutions. The key enablers are specified based on the constraints related to the use cases, the role model, and also specific constraints inherent to the satellite system and to the 5G system.

A first mission to achieve the integration and interconnection of the systems is therefore to identify the most important constraints and key enablers applicable to most or all of the use cases.

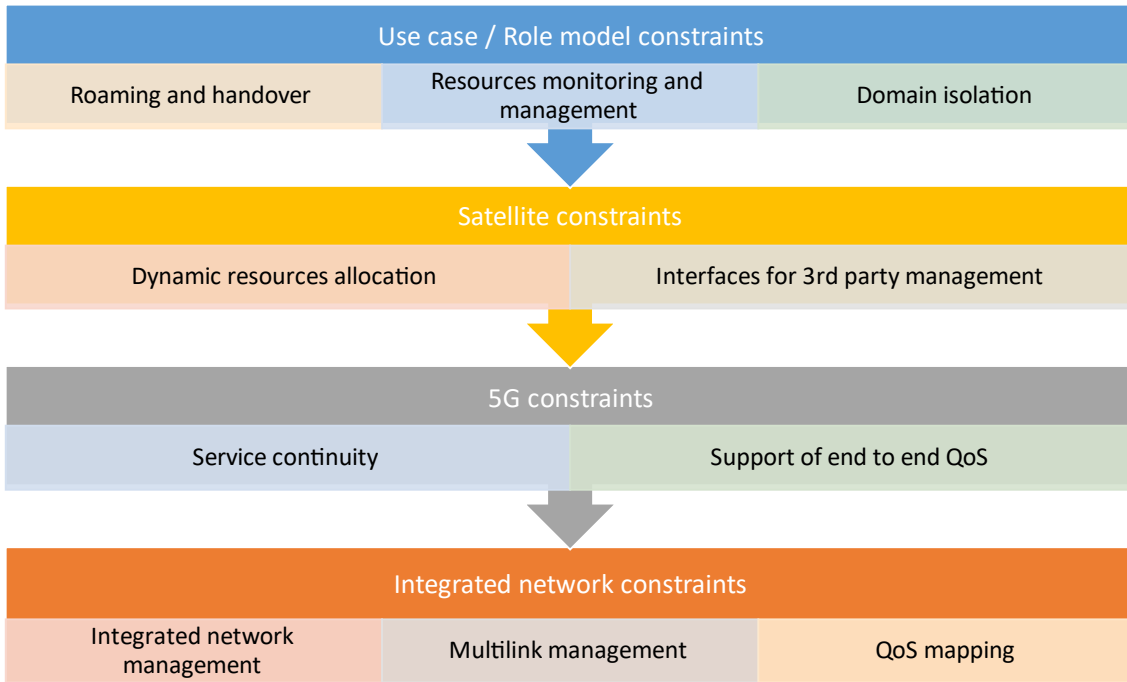


Figure 4.8: Constraints and key enablers for 5G satellite and terrestrial interconnection

Figure 4.8 provides an overview of the different types of constraints and the derived key enablers from use case and service specification to integrated network management and associated constraints.

The key enablers considered for further investigation in this thesis and in this chapter are related to the backhaul use cases. They are:

- Architecture options for satellite integration in 5G network of networks
- Service continuity and QoS mapping
- Multilink architecture and edge delivery management.

Other specific key enablers are identified as key issues in 3GPP specifications, mostly in [94], [95] for topics related to direct access (e.g., uplink timing advance, HARQ optimisation, etc.); in [86], [96], [97] for system architectures (e.g. QoS management, mobility management, etc.); and in [87] for integrated management systems (e.g., network slice management).

4.4.2 Architectures options for satellite integration in 5G network of networks

The study on architecture options is the basis to identify the building blocks of integrated or interconnected satellite and terrestrial systems. The analysis was completed in three parts: the first focuses on satellite positioning in the 5G system architecture, the second part provides a generic backhaul architecture and the last part provides some specifications for the different implementation options.

4.4.2.1 Positioning the satellite link in the 5G system architecture

Following the use cases identified for satellite integration in the 5G network, a primary question when addressing the architecture is how to represent both satellite and terrestrial systems in the same architecture.

Considering the 5G service-based architecture [98], we have identified 2 positions of the satellite link as represented in Figure 4.9. One position represents the direct UE access, and the other position represents the indirect UE access (or backhaul).

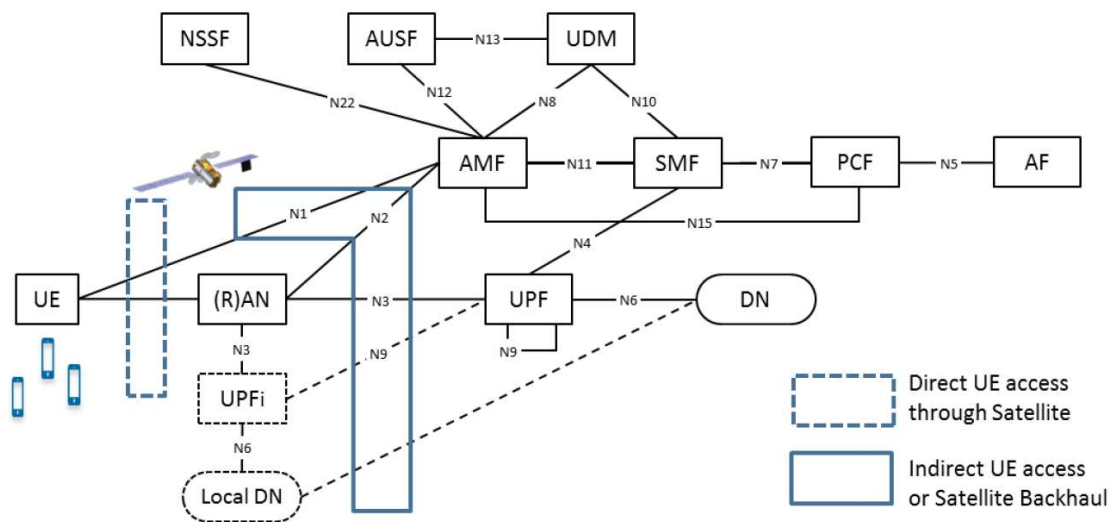


Figure 4.9: Satellite link for direct and indirect access of a UE

Direct UE access via satellite

In this case, the UE is capable of receiving and transmitting signals directly from/to a spacecraft. The waveform used here can be 5G NR, enhanced to support non terrestrial networks as studied in 3GPP RAN [94]. It can also be a non-3GPP access at the condition that it implements the required interworking functions (N3IWF – Non-3GPP interworking function). The direct access case is not further addressed in the frame of this thesis.

Indirect UE access or backhaul

In this case, the satellite is used to provide backhaul to terrestrial services. The satellite link is typically between the access network and the core network. From an infrastructure perspective, the satellite terminal is therefore located as the gNB or other used access network. This case also includes the integrated access and backhaul (IAB) features (known as relay nodes in 4G systems). This positioning of the satellite link also matches which most of the use cases addressed in section §4.2. It

is therefore further analysed in this chapter and the requirements and implications of such positioning is also further analysed.

4.4.2.2 Generic backhaul architecture

Based on the use cases and scenarios as addressed in 4.2 and the positioning of the satellite link, a generic backhaul 5G integrated satellite-terrestrial architecture is proposed (Figure 4.10), with functional blocks ensuring identified key functionalities.

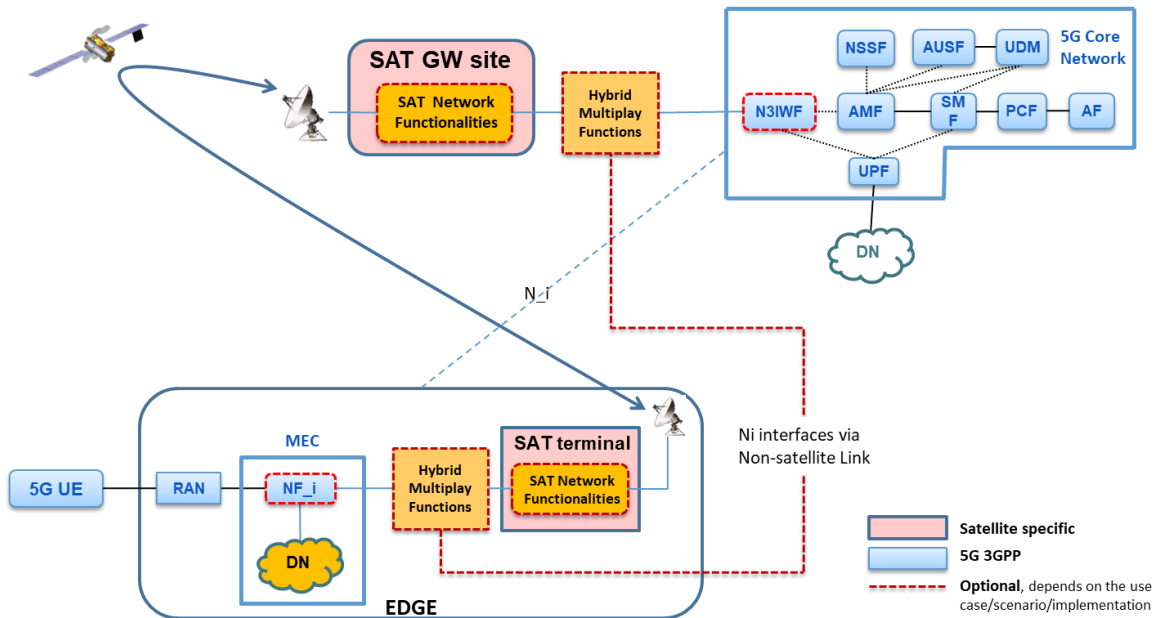


Figure 4.10: Generic 5G integrated satellite-terrestrial architecture

Hence, this generic architecture encompasses optional terrestrial backhaul links in complement of the satellite backhaul link. In addition to the classic 5G radio access network (RAN) and core network (CN) network functions, the following functions are highlighted in the architecture:

- Hybrid multiplay function(s): aims to address the backhaul multilink management. This can be traffic switching, splitting and steering (TSSS) at backhaul level, inspired from the access TSSS as defined in 3GPP at access level [99]. Thus, traffic can be redirected or shared among different links (e.g. satellite or terrestrial) following specific rules (e.g. latency sensitivity).
- Edge delivery function(s): for the management of edge delivery through the satellite link, and eventually in collaboration with hybrid multiplay functions when there is a combination of satellite and terrestrial links.
- Optional Non 3GPP Interworking functions: required if the protocol stack used on the satellite link is seen as untrusted non-3GPP by the 5G system.

4.4.2.3 Implementation options for satellite based 5G backhaul system

Following the use case specification and the satellite link positioning in the 5G system, another important step for satellite and terrestrial integration is the identification of the architecture implementation options. Figure 4.11 provides the different implementation options.

The direct UE satellite access can be based on a 3GPP access (enhanced 5G NR) on a non-3GPP access which can be trusted (i.e. known and accepted by the 5G system) or untrusted (requiring the implementation of non-3GPP interworking functions).

This categorisation is also applicable to the relay UE (renamed Integrated Access and Backhaul – IAB) and an implementation option for the indirect UE access or backhaul. Finally, the satellite transport network remains a basic implementation option for satellite based 5G system backhaul.

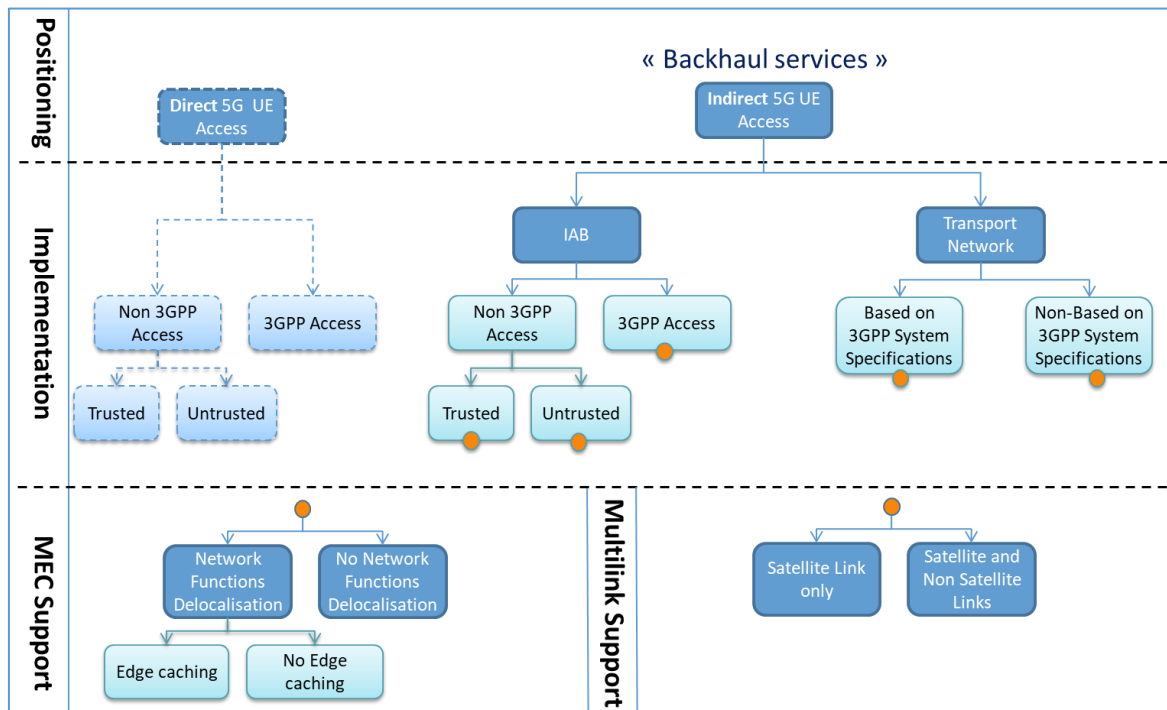


Figure 4.11: Defined implementation options

The implementation options are further detailed in my contribution to the 5G PPP Architecture whitepaper [100].

Table 4-3: Implementation options and key challenges for direct and indirect access

Positioning	Backhaul implementation option	Key challenges	Network management	Potential additional supported features	Timescale
Indirect Access (Backhaul)	Relay node with 3GPP Access	<ul style="list-style-type: none"> • NR over satellite • Adaptation of relay node mechanisms to satellite terminal 	Single integrated NMS	<ul style="list-style-type: none"> • Edge delivery • NF delocalisation • Hybrid multiplex (traffic steering at RAN level) • Enhanced User, Control and Management planes interfaces between satellite domain and terrestrial domain 	Long Term
	Relay node with Trusted non-3GPP Access	<ul style="list-style-type: none"> • Make satellite access a trusted non-3GPP access in standards • Adaptation of relay node mechanisms to satellite terminal 			Mid Term
	Relay node with Untrusted non-3GPP Access	<ul style="list-style-type: none"> • Implement untrusted access mechanisms as requested by 5G standards • Adaptation of relay node mechanisms to satellite terminal 			Short-Mid Term
	Transport Network based on 3GPP System specification	<ul style="list-style-type: none"> • Design a specific “5G ready” satellite transport network based on 5G system specifications 	3GPP NMS and Sat NMS working in coordination		Short-Mid Term
	Transport Network non-based on 3GPP System specifications	<ul style="list-style-type: none"> • Design an adaptation layer for existing satellite transport network 			Short Term

4.4.3 Integrated management and orchestration and end-to-end network slicing

An integrated management and orchestration solution is a key requirement for an integrated satellite-terrestrial network. The purpose of such features is to perform resource management, registration and access control and ensure the end-to-end quality of service.

In addition, the concept of network slicing is identified as a key 5G requirement. The network slicing is defined in 3GPP as a virtual network instance to fulfil a defined purpose, based on a shared physical network infrastructure. The network slicing aims to optimise data flow management and the support of such a feature is then also a key requirement for a 5G enabled satellite system.

The implementation options and the role models are the main drivers for the integrated management and orchestration and end-to-end network slicing requirements.

Thus, we identified two main approaches for management and orchestration and end-to-end network slicing.

The first approach is based on a single and unified network management system (NMS) managing directly all the components in the integrated network, including the satellite components.

The other approach is based on two NMS, one per domain (terrestrial and satellite) and both NMS working on coordination to meet network slicing requirements among all other potential requirements.

4.4.3.1 Network slicing with split but coordinated network management systems

Figure 4.12 provides an overview of the coordination between 5G system and satellite system. The Mobile Network Operator (MNO) will typically own an NMS to manage UE, RAN and CN. This NMS will work in coordination with a dedicated satellite NMS. This approach is particularly applicable to the backhaul use case based on satellite transport networks.

The SatCom NMS will then keep managing the satellite components in order to create specific SatCom slices to meet the end-to-end slice requirements provided by the MNO NMS. Several interfaces need to be defined to support this approach:

- Expository interfaces: where the SatCom NMS exposes the function and services that it can provide or support
- Slice and resources requirements: where MNO NMS can send a request to support an end to end service delivery
- Feedback and monitoring: where the SatCom NMS can confirm its ability to support a required end-to-end service delivery and provide a monitoring of the allocated resources to meet the requirements.

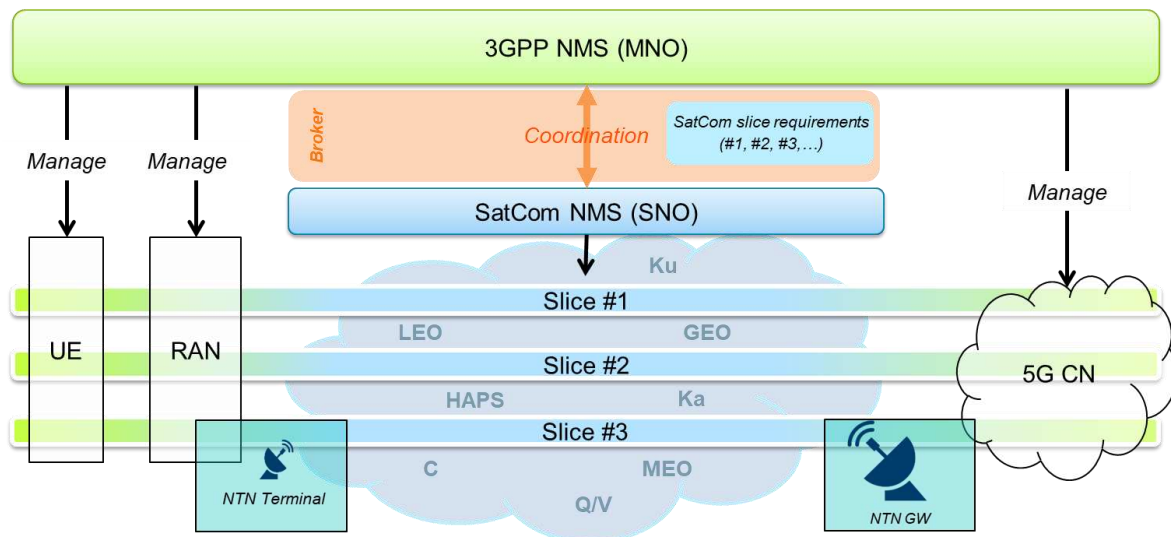


Figure 4.12: Management and orchestration in coordination

4.4.3.2 Network slicing with unique network management system

In this approach there is a single NMS, typically the mobile network operator (MNO) NMS. As represented in Figure 4.13, this NMS will manage the satellite domain in addition to the terrestrial domain which is the main domain it is built for.

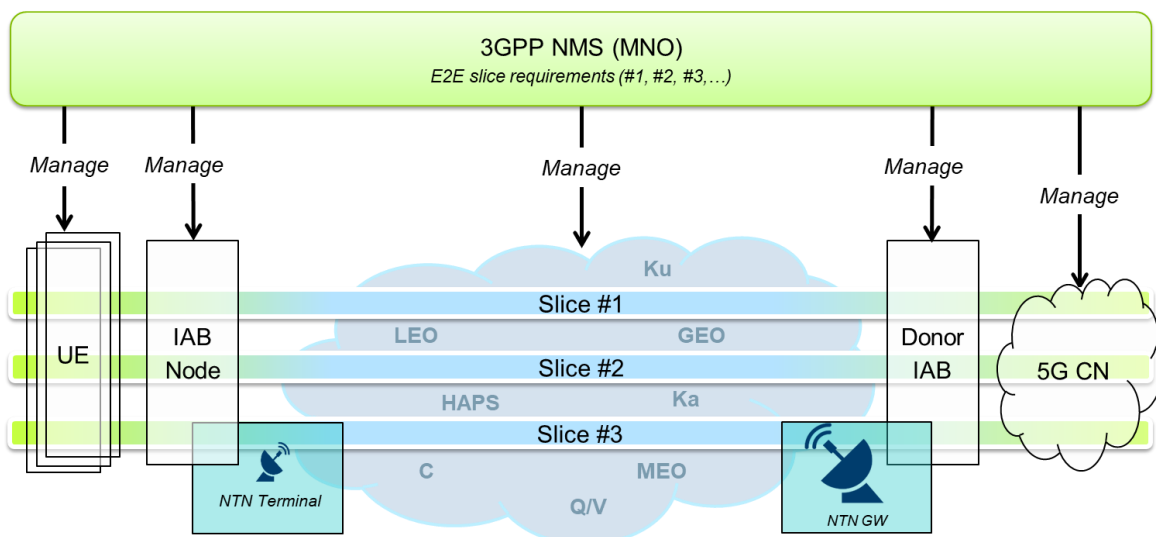


Figure 4.13: Unified Management and orchestration

Such an approach means that the satellite domain needs to be genuinely 5G ready and that all the satellite components are built based on 5G system specifications, e.g. by adopting the 5G NR, or they provide approved interfaces for direct management by a third-party system. Further challenges are the business impacts, and the required updated role model as satellite operator will then release the management of their very expensive assets to a third-party NMS.

Such an approach would be in line with the implementation options in the tree of indirect satellite access based on IAB nodes.

On the other hand, the fact that there is no intermediate NMS between the service requirements and the resources allocation and monitoring is also an advantage for efficient end-to-end service delivery. Typically, we can imagine that the resources

can be granted following a slice requirement regardless of the domain. Slicing interfaces and translation from one domain to another is then not required anymore. The technology readiness level (TRL) is however very low, and this approach cannot be expected in the first integration scenario, but it is definitely an option to consider for mid-term integration.

4.4.4 End-to-End QoS

4.4.4.1 QoS requirements in 5G systems

The QoS requirements in the 5G system are defined with details on the constraint of the 5G QoS specified in [98]. An overview is provided in Figure 4.14.

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget (NOTE 3)	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
1	GBR (NOTE 1)	20	100 ms (NOTE 11, NOTE 13)	10^{-2}	N/A	2000 ms	Conversational Voice
2		40	150 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3		30	50 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages (see TS 23.287 [121]). Electricity distribution – medium voltage, Process automation monitoring
4		50	300 ms (NOTE 11, NOTE 13)	10^{-6}	N/A	2000 ms	Non-Conversational Video (Buffered Streaming)
65 (NOTE 9, NOTE 12)		7	75 ms (NOTE 7, NOTE 8)	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g. MCPTT)
66 (NOTE 12)		20	100 ms (NOTE 10, NOTE 13)	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
67 (NOTE 12)		15	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
75 (NOTE 14)		25	50 ms (NOTE 13)	10^{-2}	N/A	2000 ms	V2X messages (see TS 23.287 [121]). A2X messages (see TS 23.256 [136])
71		56	150 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-6}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
72		56	300 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])

Figure 4.14: Overview of 5G system quality of service identifier (5QI)

Most of the 5QI represented in Figure 4.14 are related to service with packet delay budgets lower than 300 ms, which can complicate the support of such services by some satellite systems (in particular the GEO satellite).

However, the 5QI can then be a criterion to select the appropriate link in case of combination of satellite and a terrestrial link with lower latency.

Moreover, the entire table also shows that several 5QI have packet delay budget requirements that satellite systems can meet.

Figure 4.15 shows how the QoS is managed at different layers, from the service/application layers to lower layers. It can be noted that QoS flows marked 5QI are mapped to access network (AN) resources. A key question is then how to map QoS requirements to satellite resources.

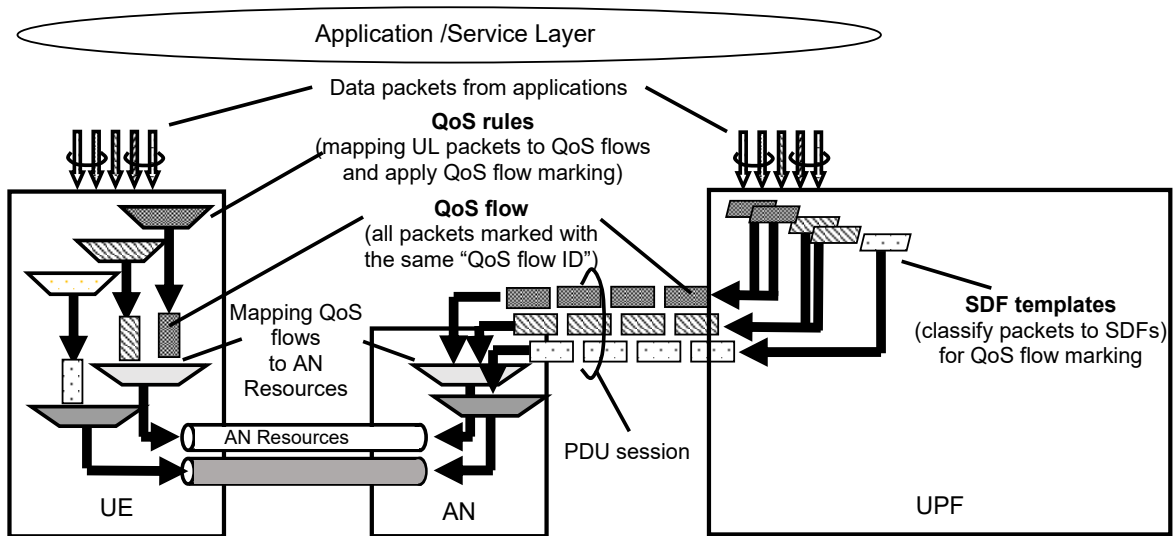


Figure 4.15: 5G quality of service management [98]

4.4.4.2 Satellite-Terrestrial QoS mapping

We focus on the mapping of QoS flow requirements and satellite resources in the context of the satellite network as a transport network [101].

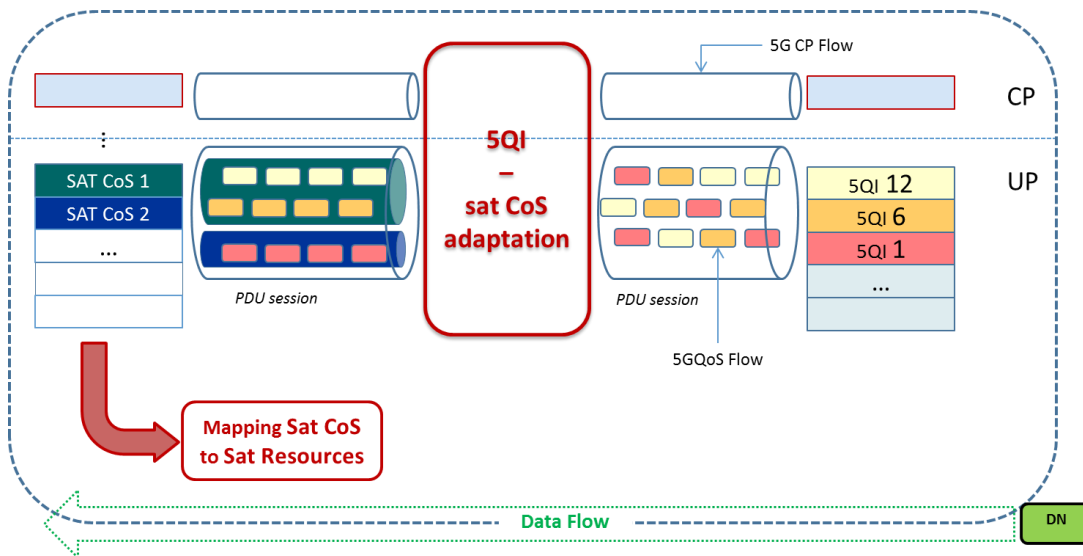


Figure 4.16: Satellite-terrestrial QoS Mapping through an adaptation layer

Indirect QoS mapping through an adaptation layer

Let us assume that the satellite (transport) network has its own quality of service identifier (let us call it satellite class of service – SAT CoS), the mapping can be done using the adaptation layer between the 5QI and the SAT CoS as represented in Figure 4.16.

Direct Mapping to satellite resources

In this approach, the mapping of 5QI requirements to satellite resources is done directly, assuming that 5G NMS has a direct access to manage satellite resources.

This approach requires advanced integration between satellite and terrestrial systems at NMS level. But for the first implementation, it can be considered that several 5QIs are mapped to the same satellite resources as represented in **Error! Reference source not found.** For 5QIs with non-GBR (Guaranteed Bit Rate), the mapping can be performed at lower layers considering SNR, modcod, allocated bandwidth, etc. For 5QIs with GBR the mapping might include additional elements (in addition to 5G QI with non-GBR) at network or upper layers such as QoS prioritization, advanced scheduling, etc to be further evaluated. Finally, further analysis are necessary to assess if some 5QIs with delay critical GBR can be addressed with recent low orbit satellite constellation systems.

Table 4-4: Direct 5G QoS Mapping to satellite resources

5QI		Satellite resources and constraints
non-GBR	{5, 6, 8, 9, 70}	high SNR, robust modcod, high bandwidth, ...
	7	low SNR, high bandwidth, high modcod
	79	low SNR, low bandwidth, low modcod
	{69, 80}	TBD
GBR	{1, 65, 66, 75}	TBD
	{2, 3, 67}	TBD
	4	TBD
Delay critical GBR	{81, 82, 83, 84, 85}	TBD

4.4.5 Multilink architecture and edge delivery management

4.4.5.1 Multilink backhaul architecture and management

The principle of multilink is depicted in Figure 4.17, with in this example the combination of a satellite transport network (TN) and a terrestrial transport network. But it can also be the combination of different types of backhaul transport networks (e.g. GEO satellites and non-GEO satellites).

It is highlighted that such integration yields to the transport by TN of interfaces of different planes of the 5G systems: the control plane, the user plane and logically it requires an interaction at NMS level as addressed in 4.4.3

We have defined two approaches to manage such multilink:

- Hard separation of the control plane interface to use one link (typically the terrestrial low latency link) and the user plane interface to use another link (typically the satellite high-capacity link)
- User plane traffic can use both links following a modified backhaul traffic switching, splitting and steering inspired by the 3GPP specification of access traffic switching, splitting and steering [99].

The latest approach was identified as a key issue to study in 3GPP SA2 TR 23.737 [86] and 3GPP SA5 TR 28.808 [87]. It was further investigated by SaT5G project partners labs and results are provided in [102].

The combination of both approaches is also possible, e.g. when several satellite links are available in addition to a terrestrial link.

This concept is not further addressed in the frame of this thesis.

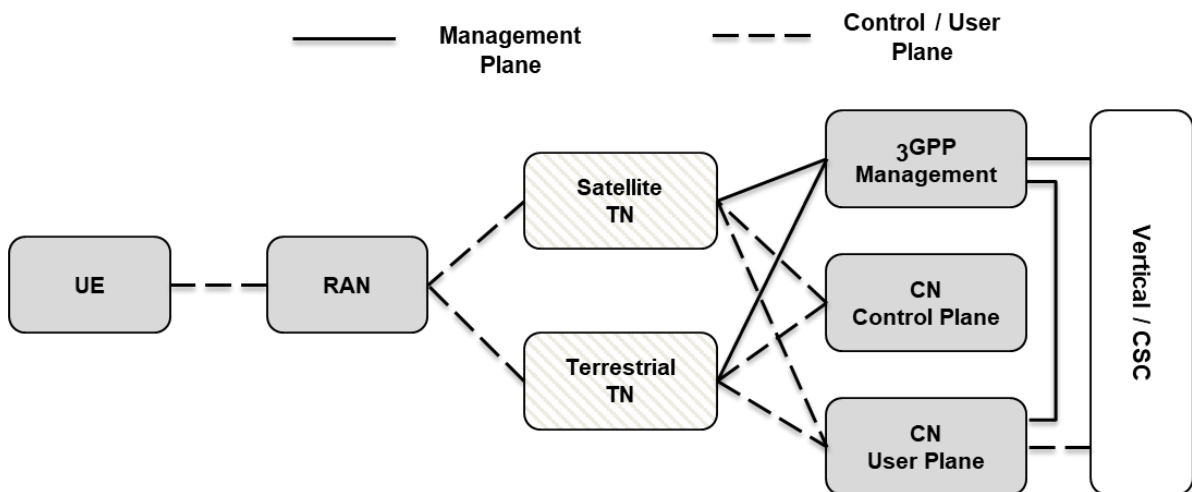


Figure 4.17: Multilink backhaul architecture

4.4.5.2 Multilink backhaul and edge delivery architecture

In a multilink backhaul model with a satellite link, we can imagine that satellite being very good to perform multicast and broadcast on a considerable coverage area, it can be used (mainly) for content delivery to the edge, close to the end-users.

Figure 4.18 provides the architecture concept of satellite link used for edge delivery.

- The addition of few functions are foreseen for such achievement:
- Content server with defined caching and prefetching policies
- Application function interacting with content server and running prediction algorithm for e.g. identify popular contents
- A local data network located at the edge of the network, typically close to the gNB and to the satellite receiver terminal
- Edge network functions (Edge NF) for local management of the delivered content and validation of the catching/prefetching in line with the AF and the popular content data network.

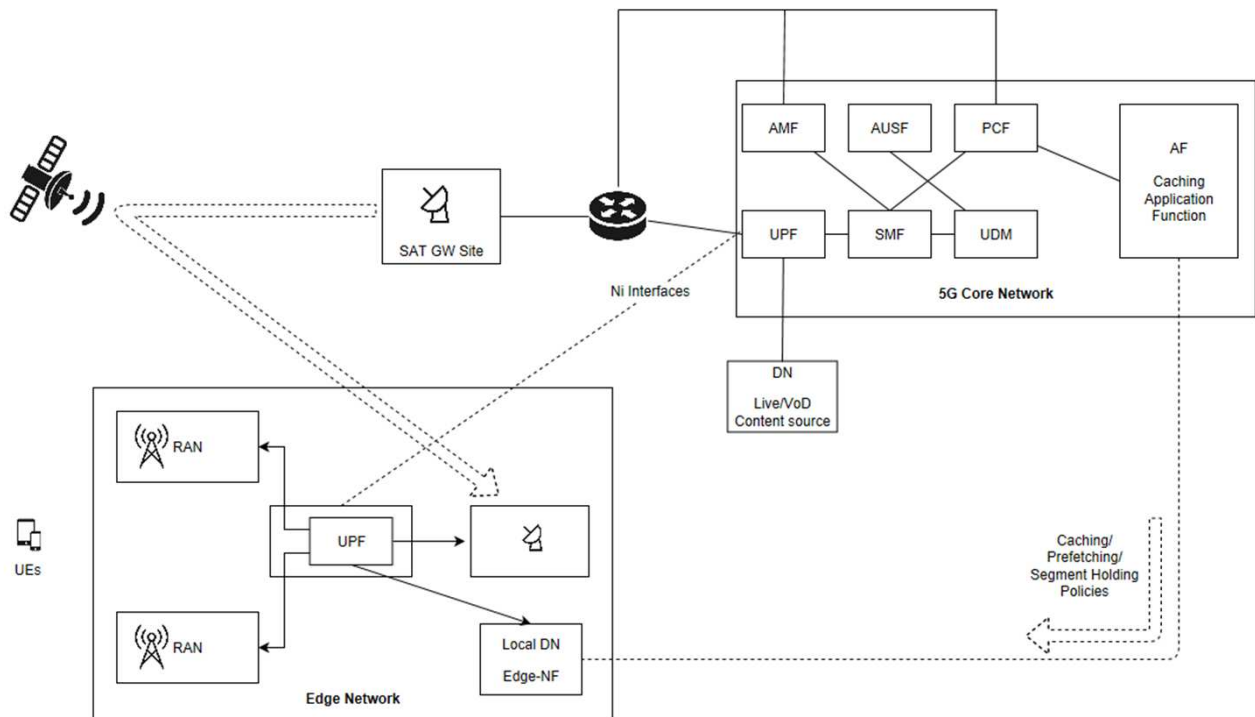


Figure 4.18: Edge delivery over satellite

4.4.5.3 Edge content delivery over satellite in 5G systems

Following the architecture provided in Figure 4.18, contents and media can be stored at the local DN under the direct management of Edge NF. The content is selected by prediction algorithms and are sent through a satellite link by the servers in the main DN. The idea of using the satellite to push content to the end is to use the broadcast capabilities of the satellite system to push the content to several locations at one. But it is also to avoid multiple transmissions of the same content when

required from different users from the same access network, and then reduce the load of the core network link.

It is then necessary when a content is requested by the users to check if it is already available in the edge, and when it is available, the content shall be delivered to the user directly from the local DN.

The two approaches were proposed to perform such availability verification and delivery from the local DN, with the constraints to have as little impact on existing standards as possible.

Solution 1- Uplink classifier

This solution proposes to use the “uplink classifier” (UL CL) standardised in 3GPP TS 23.501 clause 5.6.4.2 [98] and 3GPP TS 23.502 clause 4.3.5.4 [103]. A user plane function (UPF) supporting UL CL is selected and diverts the traffic which matches with traffic filters provided by SMF. This solution should prevent the satellite link from multiple content transmissions. However, this solution implies having a permanent PDU (Packet Data Unit) session between the UE and the remote DN, and thus having a satellite link always loaded because of the resource allocation to each PDU session till their release. The UL CL can be configured to steer all DNS requests to the local DN. Depending on whether the requested content is available at the edge, the UE’s DNS request can be either resolved in a local IP address (in which case all subsequent context fetching is performed from the local cache) or in a remote IP address (in which case all subsequent context fetching is performed from a remote content distribution server).

Solution 2- Multi-homing

A multi-homed solution defined in TS 23.501 clause 5.6.4.2 and TS 23.502 clause 4.3.5.4 can also be appropriate. The PDU session is associated with multiple IPv6 prefixes and a UPF supporting the Branching Point functionality is configured by Session Management Function (SMF). The Branching Point provides traffic forwarding toward the PDU session anchors. Thus, one anchor can route the traffic toward a local DN and the other toward the remote DN. UE has routing rules that tells the UE where to send the traffic and which IP address to use. This solution implies having a permanent PDU session between the UE and the remote DN, and thus having a satellite link always loaded because of the resource allocation to each PDU session till their release.

A contribution was submitted to 3GPP SA2, TR 23.737 [86] with both solutions and further experimentations are still expected to assess their performance, especially in terms of satellite resources consumption.

4.5 CONCLUSION

The research work addressed in this chapter mainly focuses on use case specification, architecture options and technical requirements for satellite and terrestrial integration in 5G context.

The topic is very large, and the research and contribution were mainly explorative in order to pave the way for many challenging subjects.

The main use cases and scenarios for integrated 5G satellite-terrestrial network, with two main categories: the direct 5G satellite user access and the indirect user satellite 5G access of backhaul.

After analysis of the role model in such evolving context, it was concluded that an agnostic approach on the role model should be considered for such integration, given the current vertical integration of several players in the satellite connectivity. Further analysis yielded the introduction of a new role, a capacity broker, in charge of provisioning and contracting satellite capacity for 5G usage, regardless of the satellite infrastructure owner.

For obvious reasons of technology readiness and potential maturity for immediate implementation in current 5G systems, the indirect access or backhaul was selected as the main use case category to be further investigated in the frame of my research and funding projects. Hence, all types of 5G satellite backhaul (fixed backhaul, mobile platform backhaul, multilink backhaul) and associated scenarios were defined.

Architecture analysis was then performed with the objectives to address the entire defined types of backhaul and associated scenarios. A generic 5G satellite-terrestrial integrated backhaul architecture was then proposed. Further investigation on the architecture aspects allowed to define various implementation options of satellite-terrestrial integrated in 5G context, which can be based on 3GPP access (using 5G new radio) or not (non-3GPP access based on e.g., legacy satellite waveforms). The most mature and ready for implementation approach was identified as the 5G satellite backhaul based on a satellite transport network.

Hence, following the analysis of such an approach, we defined two network management system integration options: the first approach considers a single NMS (typically the 5G system NMS) to manage both terrestrial and satellite domains. While the second approach considers two NMS, one per domain, working in collaboration. Once again, for technological maturity reasons, the second approach was identified for further analysis.

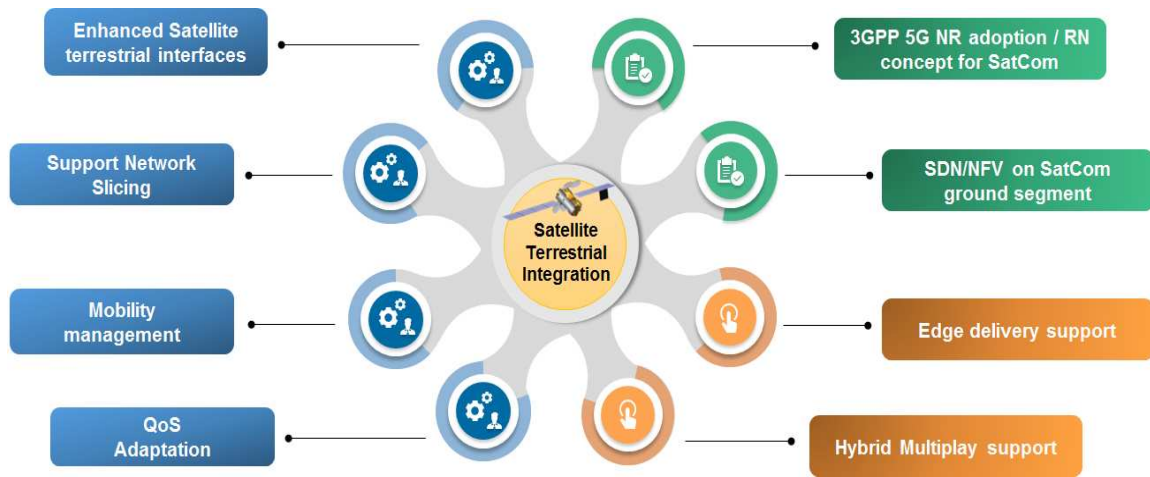


Figure 4.19: Challenges for 5G satellite-terrestrial integration

The next analysis was the identification of the further technical constraints related to the backhaul use case and selected implementation option (satellite as transport network, two NMS working in coordination). A summary is provided in Figure 4.19.

Among these challenges, three were further analysed in the frame of this thesis: the mapping of the quality of service between the satellite and the terrestrial domain, the multilink backhaul management, and the support of edge delivery.

The procedures regarding the QoS mapping were provided, either direct mapping of the 5G system QoS flow to the satellite resources, or indirect mapping through an adaptation layer between 5G QoS and satellite class of services. The edge delivery architecture and content delivery solutions were also defined. Few experimentations were performed for obvious reasons of the TRL of the propositions.

However, a testbed built by a research partner (University of Surrey) provided some demonstrations based on the defined specification such as MPQUIC based multilink proxy and live video streaming over local DN. Further details about these demonstrations can be found in [104].

Also note that most of the presented research outcomes have been published in two publications ([84] and [85]), and have contributed to several 3GPP and ETSI standardisations (3GPP technical report TR 23.737 [86] and TR 28.808 [87]).

Note that I have also contributed to several other satellite-terrestrial integration challenges, not addressed in the frame of this thesis, such as 5G satellite direct access study for the future European constellation, and support of network slicing by satellite systems.

Chapter 5. PERFORMANCE ASSESSMENT IN LIVE SATELLITE SYSTEMS

This chapter is a slightly modified version of the paper “Performance assessment framework and concept of operations in live satellite communication systems” [105] presented in the 40th International Communications Satellite Systems Conference (ICSSC), Bradford, United Kingdom, October 2023. The paper is to be published by the Institution of Engineering and Technology (IET) in 2024.

5.1 INTRODUCTION AND MOTIVATION

Satellite capacity supply is predicted to be increasing with demand as reported in *Figure 5.1*, [106] for GEO HTS in Ku-band. The system performances remain a key topic of optimization, either in terms of capacity increase, flexibility on the existing capacity or cost.

SatCom systems have a consequent chain of actors, which includes satellite and ground system designers and manufacturers, satellite operators, and final satellite connectivity and service providers (C&SP) [91]. The system performances can then be computed based on different assumptions and different frameworks by this multitude of players. The C&SP is the closest actor in the chain to the end user and actual connectivity consumer. As represented in *Figure 4.3*, the connectivity and service provider usually buys resources, as raw data or bandwidth, from operators, sources and delivers end-user terminals or remotes, installs, manages and maintains the user ground segment required to deliver the connectivity and managed services to end-users.

The C&SP would also develop and sell value added services. It is thus a key requirement for C&SP to have accurate performance assessment to optimise both purchases and sales. As the requirement might escalate, this is also applicable to satellite operators, especially with the new flexible satellites, in order to configure the satellite in line with the actual requirements and put the resources where they are needed. Finally, it is also applicable to the satellite manufacturer for the effective design of the spacecraft.

The capacity assessment today is performed differently depending on the actors. For the conception of the satellite system, satellite manufacturers and satellite operators will usually use a traffic prediction model to design and size the satellite and the ground segment, based on link budgets, defining specific coverage, beam layout and frequency plan [107]. Once a satellite is launched and/or the coverage and frequency plan are specified, this approach is not suitable anymore to assess effective capacity to sell, especially for C&SP with leases on given areas and given amount of bandwidth. Some tools like CST [108] can propose continuous capacity assessment based on user requirements and predictive remote performance. But the dynamic of the traffic is not considered and the mobility of the remotes add considerable uncertainty to the conditions of the link. Finally, the literature is very poor regarding accurate capacity assessment, probably due to the fact that the

systems could not efficiently manage exceeding capacity by lack of flexibility, which has changed with recent developments on multi-access technologies.

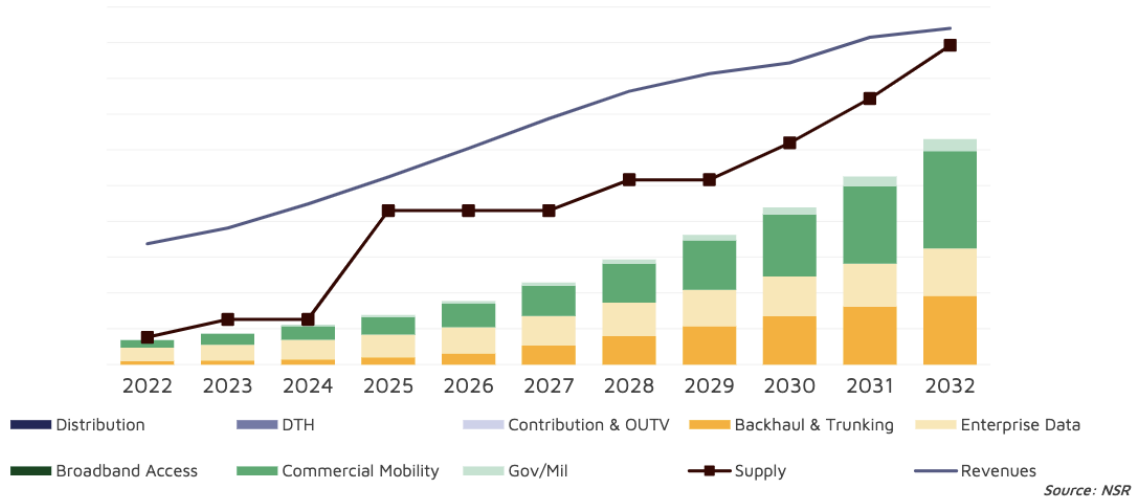


Figure 5.1: GEO-HTS Ku-band demand and total supply [106]

This chapter discusses a common framework for accurate performance assessment, from the live or operating SatCom system standpoint, driven by the C&SP.

The framework is based on various known measured satellite performances and actual remotes with known equipment capabilities and locations.

This work focuses on the estimation of the capacity as the main performance criteria at different moments in the lifetime of a satellite communication system (including ground and space segments), from its design to its implementation and exploitation. The proposal also includes a set of materials and algorithms for accurate capacity estimation, and definition of how a concept of operations (CONOPS) may use such an approach and related materials.

5.2 SYSTEM ASSUMPTIONS AND PERFORMANCE INDICATORS

5.2.1 Overview of performance indicators in satellite communication systems

As introduced in Chapter 2, despite the evolution of SatCom over the past decades, the main system performance indicators remain the following: coverage, availability, latency, capacity, and flexibility.

Many of these parameters are defined at conception and once the satellite is operational in orbit, they are not modifiable or when they are, it is at a considerable cost. We refer to these parameters as static and semi-static parameters. For instance, propagation latency is associated with the orbit of the satellite and the locations of the remote and the gateway, while coverage is associated with the shape of the antenna, especially with passive antennas. Note however that recent software defined satellites claim to be able to modify the footprint quite fast thanks to active antennas and on-board processing.

Other parameters, which can be referred to as dynamic parameters, can be modified based on actual system performances and constraints including propagation impairments, interferences, remotes distributions within the coverage, etc. The capacity allocation of a satellite network (SatNet¹), in MHz or in Mbit per second (*Figure 5.2*), is the main parameter of this category.

Accurate assessment of such static and dynamic parameters is thus important for several players in the satellite connectivity value chain to optimise the utilisation of the system.

5.2.2 Capacity as the primary performance indicator

Capacity can be defined as the achievable throughput of the network [109]. It is one of the main performance indicators that is linked to several other parameters, and this can bias the estimation and expectations.

As discussed in §2.3.4, the term capacity may also refer to the achievable bandwidth (MHz), but in the frame of this chapter, it refers mainly to Mbps.

Initial capacity assessment is usually made based on link budgets, and a performance table which provides the expected spectral efficiency given the signal to noise ratio as discussed in §2.3.4. It also depends on the distribution of the remotes in the coverage, the characteristics of these remotes, and the resource allocation to the remotes based on their service level agreement (SLA), actual traffic, etc [110].

¹ A satellite network (SatNet) in this context is the combination of (1) a specific forward carrier (thus a given gateway and satellite and user beam), (2) reaching remotes in a given are (user beam), (3) with a set of allocated return bandwidth, and (4) a control of resource allocation to the remotes.

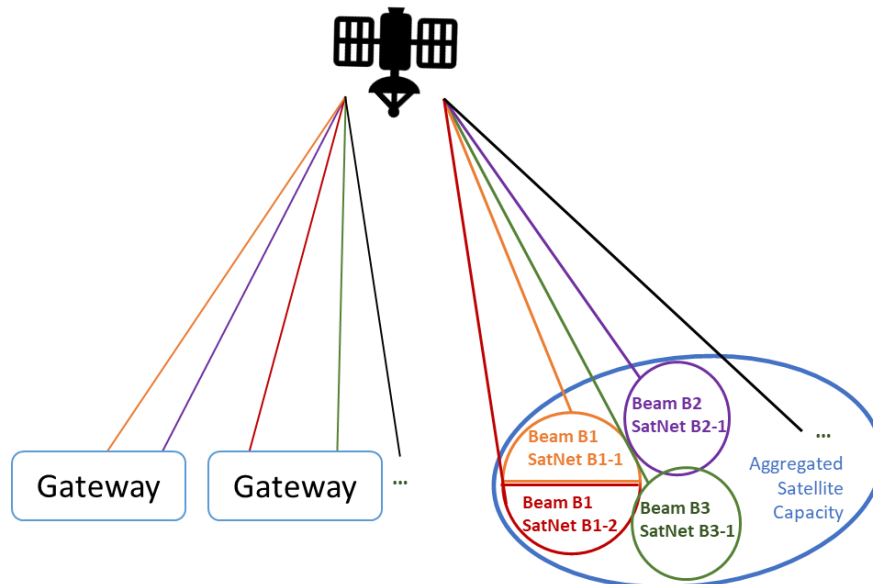


Figure 5.2: Capacity as different scales of a SatCom

The equation (eq. 3) in §2.3.3 provides the logic of initial capacity assessment which can easily be applied at SatNet level with the allocation of the SatNet bandwidth.

This capacity is based on the estimated CINR, which is based on well-known link budget models (combining carrier to noise ratio and carrier to interference ratio) [12]. It is an average of the computed CINR for remotes in a representative set of location (latitude and longitude) of a beam. The accuracy of this assessment approach is dependent on the accuracy of the representation of the type and location of the remotes.

The common link budget calculations to compute the CINR are described by the equations (eq. 1), **Error! Reference source not found.**, and **Error! Reference source not found.** in §2.3.3.

Computed CNIR is then used to derive the energy per symbol to noise density ratio (E_s/N_0) and to compare it to the threshold E_s/N_0 of the considered waveform and modem, and considering the potential link margin (LM_{db}) to complete the capacity assessment procedures [111].

For accurate assessment today, a set of remotes of different types, in different locations on the coverage can be defined based on the traffic prediction.

The capacity assessment can be a complex, time and resource consuming process in a dynamic operational live satellite communication system, where effective traffic and remote performances are difficult to predict and can vary substantially. It is based on global assumptions which can bias the assessment or limit the accuracy. We observed a deviation of ± 10 to $\pm 20\%$ between capacity assessed through this approach and the effective measured capacity.

Until development on multi-access technologies for both forward and return links, there was not actual need for further development of accurate capacity assessment since previous systems based on single channel per carrier (SCPC) were quite rigid and radical if a capacity adjustment were required (interruption of service for several carrier deactivations, resizing and reactivations).

Such capacity assessment needs to be accurate to master the service contracted by the end users and to adjust the resource allocation towards the remotes when necessary.

A common and more precise approach to assess system capacity is therefore necessary for several purposes, including the comparison between candidate satellite communication systems, the mastery, and the adjustment of traded capacity to meet the connectivity SLA, and the planning of future system configuration to deliver expected new commitments. It would also be the basis for an adapted and efficient CONOPS of a set of dynamic operational Satnets.

5.2.3 System assumptions

The system considered for the application of the proposed performance assessment framework and the resulting CONOPS is a SatNet based on a geostationary satellite, single beam, with single forward (FWD) and return (RTN) carriers as represented in *Figure 5.3*. We focus on the capacity as the main KPI, and the analysis is done at the SatNet level. It is assumed that the beam capacity and the satellite capacity can both be easily derived from SatNet capacity (eq. 22), (eq. 23).

$$C_{beam} = \sum_{i=1}^{N_{Satnet}} C_{(SatNetinbeam)} \quad (\text{eq. 22})$$

$$C_{Satellite} = \sum_{k=1}^{N_{beam}} C_{(beam\ in\ Satellite)} \quad (\text{eq. 23})$$

Where C_{beam} and $C_{Satellite}$ are aggregated capacity respectively of a beam, and a satellite. N_{Satnet} is the number of SatNet in a given beam, and N_{beam} is the number of beams in a given satellite.

Figure 5.3 represents the capacity tree with the overall SatNet capacity, potential segmentation of such capacity per pre-defined groups or sets, and allocation to the remotes.

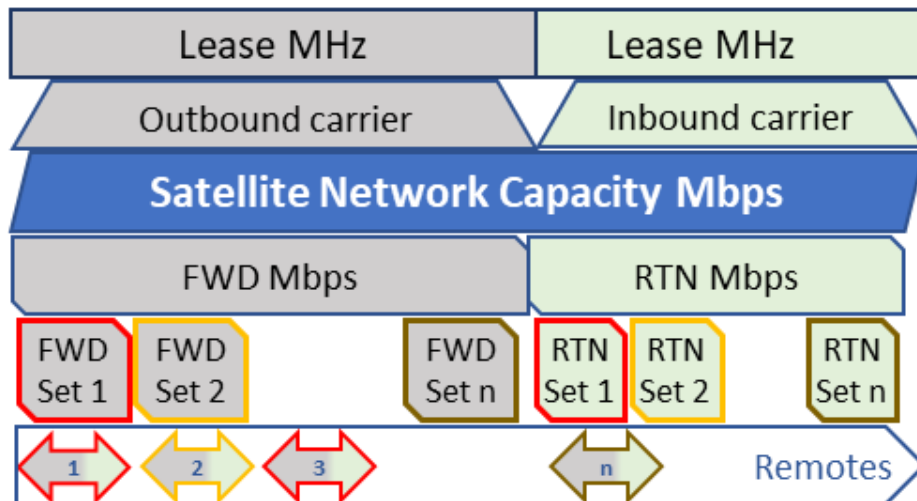


Figure 5.3: Distribution of assessed capacity to the remotes

The gateway (GW) can be based on the initial specification of the teleport that will support the GW beam. It is not expected to change often.

5.3 PERFORMANCE ASSESSMENT FRAMEWORK

As part of the performance assessment of a SatCom system and for the motivation provided in section §5.1, we introduce the MAPAN (Management and Performance of Access Networks) framework for performance assessment throughout the lifetime of a SatCom system.

The framework is inspired by operational performance objectives and business performance measurement concepts as discussed in [112] and [113] and which introduce five main operational performance objectives: speed, quality, cost, flexibility, and dependability.

In the frame of SatCom systems, the performance assessment is basically required to size the connectivity system and the proposed framework aims to address the five main performance objectives [112] and [113].

Hence, the proposed MAPAN framework is based on three types of performances: planned performance, actual performance, and predicted performance as shown in *Figure 5.4*.

Further details are provided in this section. The MAPAN framework is also the basis for the proposed CONOPS, which is presented in section §5.5.

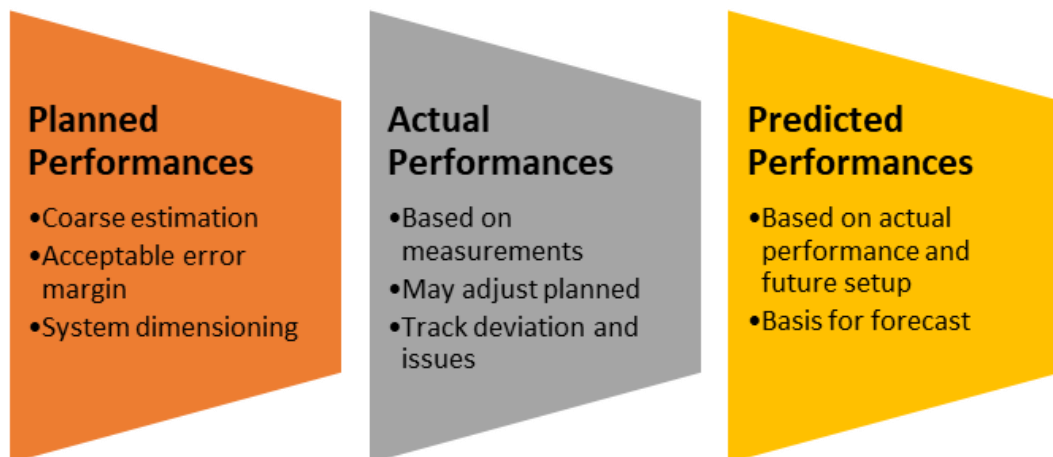


Figure 5.4: Concepts and purposes of the types of performances

5.3.1 Planned performance

Planned performance refers to the performance that can be expected from a SatNet based solely on initial raw parameters of the system. Planned performance is assessed based on initial configuration of the SatNet and includes physical beam characteristics such as allocated bandwidth, downlink EIRP, and distribution of the figure of merit of the satellite antenna over the coverage. It is also driven by the type of remotes and planned location set.

Planned performance is then necessary for the dimensioning of a SatNet prior to service commercialisation. It provides an overview of the performance that can be expected from a SatNet and can provide a good support for decision making and to evaluate the SatNet ability to address the expected demand.

5.3.2 Actual performance

Actual performance is the performance of the SatNet once remotes are in the network and generating traffic. Accurate estimation of actual performance is not obvious since it is not only the sum or average of measured performance of the remotes in the SatNet. Several other parameters need to be considered such as the fill rate of the network, the margin of the modulation and coding schemes on the user ground segment, and the priority associated with the SLA of the remotes or group of remotes.

Actual performance is necessary to monitor the deviation with planned performance and to ensure that the configuration of the SatNet is in line with the SLA of all the remotes in the network. It can also assist to identify potential issues or failures in the SatNet.

5.3.3 Predicted performance

Predicted performance is based on the actual configuration of the network (e.g., remote types and locations) and the projection of expected or desired events regarding the network or the remotes, on a real-time basis and in the future. These can be technical changes (e.g., modification of a remote equipment, remotes entering or leaving the SatNet, etc.) or commercial changes (e.g., customer bandwidth upgrade, traffic prioritisation, etc.).

Predicted performance can then be used for service adjustment once the network is activated. It can also support feasibility analysis following connectivity requests on existing networks and support the identification of potential SatNet issues or failures.

5.4 TOOLS AND ALGORITHMS FOR ACCURATE ASSESSMENT

For the assessment of the various types of performances, new tools and algorithms are introduced as part of the MAPAN framework. They are the basis for an integrated CONOPS of dynamic SatNet based on the proposed framework.

Those materials include the introduction of the reference terminal, the algorithm for averaging the capacity based on the performance variation within the coverage from beam peak (BP) to beam edge (BE), the introduction of the real-time link budgets for capacity prediction (for forecasting or what-if analysis) based on remotes actual and future performances and locations.

5.4.1 Reference terminal for planned performance

Concept

The proposed approach to perform the planned performance assessment is to use a logic reference terminal.

The reference terminal is a selected type of remote with known characteristics, which is considered to be located at the beam peak of the coverage, both for FWD and RTN directions. In reality, the remotes could actually be anywhere within the SatNet coverage.

As the purpose of the SatNet or remotes can be very different, with different characteristics and performances, the characteristics of the reference terminal needs to be aligned with those of the future remotes expected to operate in the SatNet.

The type of terminal and associated technical characteristics shall be in line with the purpose of the SatNet as proposed in Table 5-1 for a maritime Ku-band market.

Table 5-1: Reference terminal type per network type

Purpose of the SatNet	Selected Reference terminal
Premium Market	240 cm Antenna, 100 W BUC
Medium-High Market	150 cm Antenna, 25 W BUC
Common market	100 cm Antenna, 8 W BUC
Entry market	60 cm Antenna, 8 W BUC

Process

A link budget is computed following the logic provided in (eq. 1) and considering the reference terminal characteristics and location.

For the FWD link budget, it is considered that the entire bandwidth is allocated to the reference terminal.

For the return link budget, the theoretical power on the remote should not be exceeded. However, it is considered that the remote is not power limited when allocating the full return bandwidth.

The link budgets with the reference terminal will then provide the FWD and the RTN performance assessments.

In addition, in order to derive an effective capacity assessment of the SatNet based on the reference terminal, some link margins will be applied to the results based on the shape of the coverage and the delta between the BP EIRP (or BP G/T) and the BE EIRP (and BE G/T). Too optimistic assessment, based on rough link budget with the reference terminal at beam peak would then be avoided. Recommended FWD and RTN LM are provided by (eq. 24) and illustrated in Table 5-2 for the FWD link.

$$LM_{dir} = \begin{cases} 1dB, & \Delta_{dir} \leq 3dB \\ 2.5dB, & 3dB < \Delta_{dir} \leq 6dB \\ 3dB, & \Delta_{dir} > 6dB \end{cases} \quad (\text{eq. 24})$$

Where LM_{dir} is the link margin in a given direction (FWD or RTN) in dB and Δ_{dir} is :

- The difference between beam peak EIRP (in dBW) and beam edge EIRP (in dBW) for the FWD link; and
- The difference between beam peak G/T and beam edge G/T for the RTN.

For instance, the planned capacity of a SatNet will be computed based on the reference terminal with proposed characteristics and assumptions, by selecting the achievable modcod given the computed $EsNo$ (eq. 25), (eq. 26).

$$EsNo_{planned} = EsNo_{pb} - LM \quad (\text{eq. 25})$$

$$C_{planned} = BW_{SatNet} * \text{Max} \left(\begin{matrix} \text{Eff} \\ EsNo_{planned} < EsNo_0 \end{matrix} \right) \quad (\text{eq. 26})$$

Where $EsNo_{planned}$ is the resulting planned $EsNo$ of the SatNet in dB, $EsNo_{pb}$ is $EsNo$ at beam peak following the reference terminal specification in dB, LM the applicable link margin given the shape of the coverage as provided in (eq. 24), in dB. BW_{SatNet} is the allocated bandwidth a given direction in MHz and $C_{planned}$ is the resulting planned capacity of the SatNet in Mbps. Eff is the maximum achievable efficiency given based on the $EsNo_{planned}$.

Table 5-2: Recommended reference terminal FWD link margin

LM FWD & RTN	E.G. FWD downlink beam EIRP distribution (source ECM)
Delta BP vs BE delta ≤ 3 dB Recommended Margin LM = 1 dB	
Delta BP vs BE 3 < delta ≤ 6db Recommended Margin LM = 2.5 dB	
Delta BP vs BE delta > 6dB Recommended Margin LM = 3 dB	

5.4.2 Actual performances measurements

The actual network performance is based on the measurement of the performance of the remotes with traffic in the network. While it might appear easy and obvious to make an average or sum of effective performances of the remotes in the network to derive the network performances, it actually depends considerably on the fill rate of the SatNet.

For a given period (e.g., 15 minutes):

- Let us consider a SatNet with a given number of remotes across the coverage.
- Let us consider the throughput per remote is measured and provided.
- Let us consider the modcod per remote is measured and provided.
- The allocated symbol rate (SR) per remote is either measured and provided or easily computed, based on the remote throughput and the spectral efficiency (Eff) of the remote modcod.
- Let us compute the fill rate $f = \frac{\sum SR_{remotes}}{SR_{SatNet}}$
- Let us compute the equivalent percentage of symbol rate allocation per remote $p_{remote} = \frac{SR_{remote}}{\sum SR_{remotes}}$
- Let us assume that SatNet unused symbol rate $SR_{SatNet} * (1 - f)$ is prorated to the remotes.
- Assuming the remotes use the same modcod, the symbol rate would be:
 $SR' = SR + p * (SR_{SatNet}) * (1 - f)$
- Finally, the actual capacity of the SatNet would be :
 $C_{SatNet-Actual} = \sum_{remotes} SR'_{remote} * Eff_{remote}$

Figure 5.5: Capacity averaging process

Hence, a SatNet with a network fill rate close to 100% has quite small uncertainties on the remotes that will enter the network. It can then have a quite accurate performance measurement based on average (e.g., for the EsNo) or sum (e.g., for the throughput or capacity) of the remote.

As the fill rate decreases (and the event uncertainty increases) the actual performance measurement of the SatNet remains an estimation.

Let us focus on the capacity as the performance to monitor. The approach provided in *Figure 5.5* is a proposal for accurate actual capacity estimation.

Thus, when the fill rate is 100%, the capacity is actually the sum of the capacity of the remotes.

Note however that in the context of maritime network or any other types of SatNet with mobile user terminal, the future uncertainties remain considerable, even with high fill rate. This highlights the importance of the period selected for the analysis, which needs to be in line with the dynamicity of the network.

5.4.3 Real time link budget for predicted performance

The idea of real time link budget for predicted performance is to perform a link budget based on the actual setup of the SatNet, including the distribution of the remotes, their types, and locations.

For instance, the model can include known upcoming plans in the network in order to access e.g., what would be the network redistributable capacity, or the updated fill rate.

The process to compute the predicted capacity is similar to the process provided in *Figure 5.5* for the actual capacity computation. The only difference being that the modcod and the symbol rate will be provided by link budgets, and not remote measurements.

As represented in *Figure 5.6*, the live SatCom system may need to use a third-party system application programming interface (API) to compute on-demand link budgets, considering the actual and future location of the active remotes in the network, their actual data rate, their actual and future committed information rate (CIR), their technical installation (antenna and BUC details).

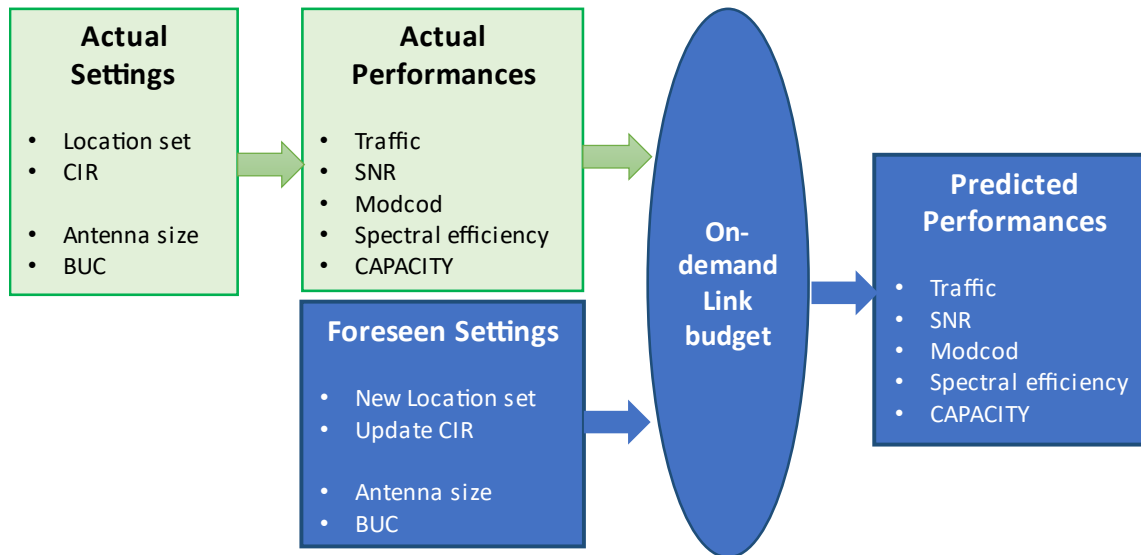


Figure 5.6: Process to compute predicted performances

5.5 CONCEPT OF OPERATIONS WITH THE MAPAN FRAMEWORK

5.5.1 Motivation and requirements

A concept of operations (CONOPS) aims to provide operational context and procedures of a complex system from the point of view of user. It can follow very procedural and detailed templates as proposed by the Joint Capabilities Integration and Development System (JCIDS) of the USA department of defence or NASA [114], [115].

In the context of the operation of a live satellite communication network, the proposed CONOPS aims to describe how the SatNet operates to deliver the service to end users, in line with their SLA while ensuring that the required operation performance objectives (e.g., fill rate, load balancing) are met.

Following the recommendation in [109], a CONOPS should not be complex and should describe a proposed system simply and without confusion. This section does not provide the full and detailed CONOPS as it is not the interest of this thesis. But it focuses on the employment of the MAPAN framework in the operation of a live satellite communication system.

5.5.2 Enabled CONOPS

The proposed MAPAN framework is considered with the capacity as the main KPI, given that is the most important performance indicator and the main parameter to optimise in the system configuration and thus CONOPS.

The logic of the CONOPS based on the mentioned materials is provided as a flowchart in *Figure 5.7*.

The CONOPS based on the MAPAN framework uses the three types of performance applied to the capacity, with the following logic:

- Setup the planned capacity as the expected capacity at the initiation of the SatNet.
- Establish and Maintain a MAPAN dashboard with the proposed three capacity definitions (planned, actual and predicted).
- Include the contractible capacity in the Dashboard as the capacity that can be contracted and expected by the customers (or the remotes).
- Use the MAPAN framework for troubleshooting by identifying capacity deviation and/or underperforming remotes, region, beams, or satellites.

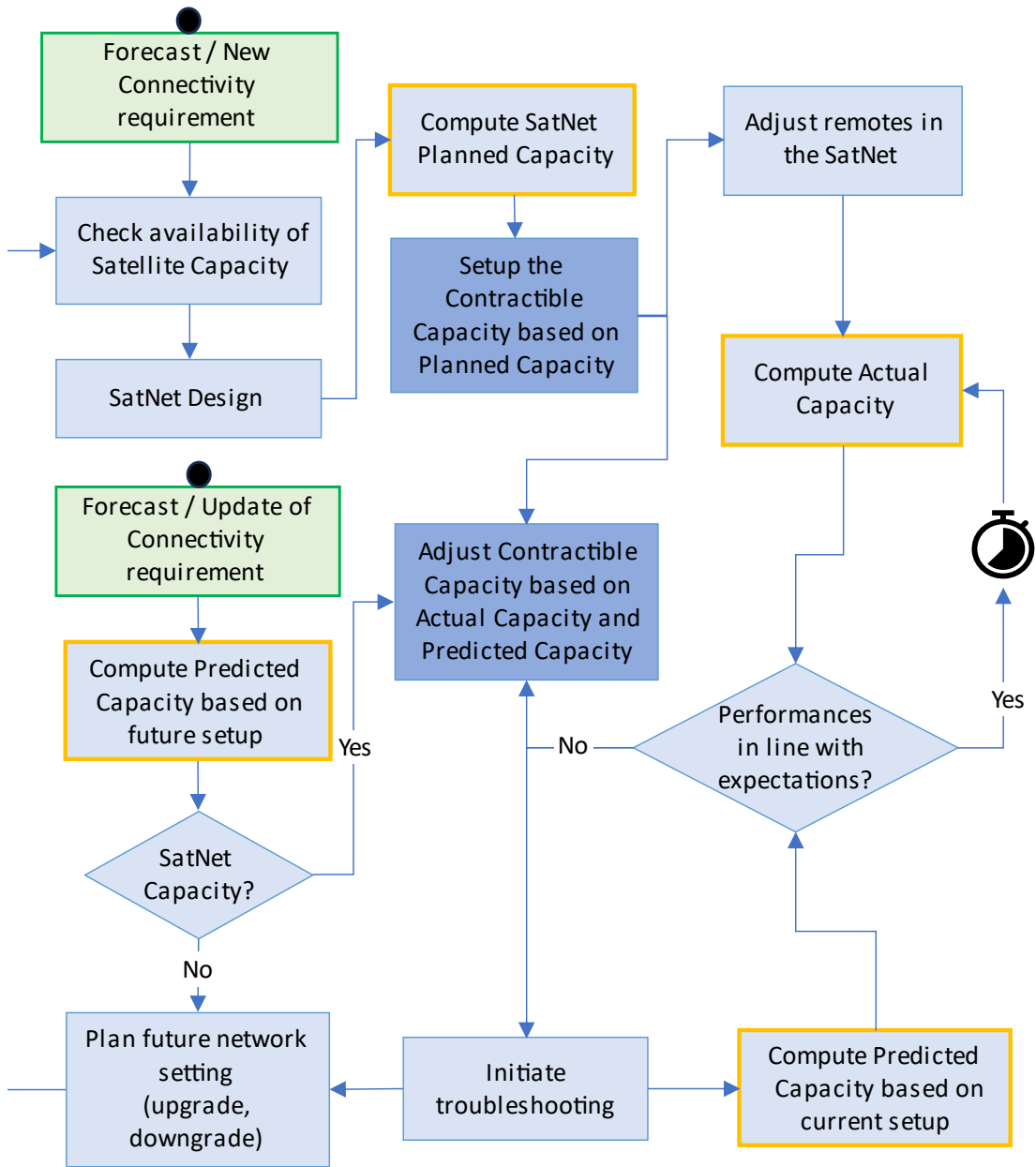


Figure 5.7: Flowchart of the capacity management with the MAPAN framework

5.6 EXPERIMENTATION

Based on actual traffic and history of an existing maritime satellite network, I made an evaluation of the different proposed types of performance defined in the MAPAN framework. The throughput capacity is used as the performance indicator in order to compare the accuracy of the proposed models for the performance assessment and system monitoring.

I collected the history of remotes measurements in the selected operational SatNet and applied the proposed models following the MAPAN framework and later emulated the CONOPS with the MAPAN framework.

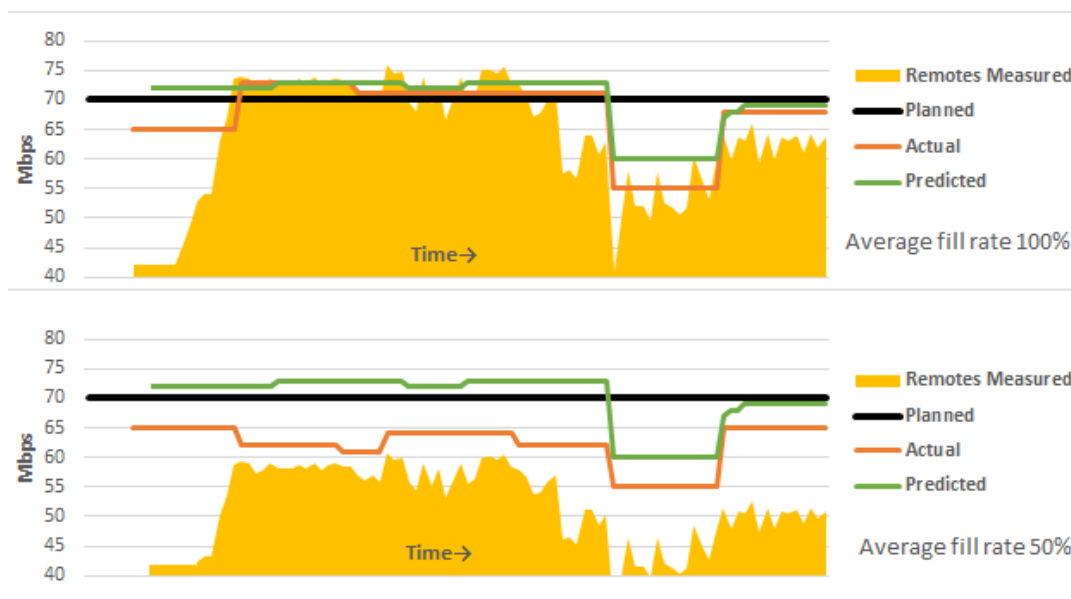


Figure 5.8: Planned vs Actual vs Predicted capacity

In Figure 5.8, I performed a comparison of planned, actual, and predicted capacity at identical system configuration.

The tests are done with the same SatNet but considering different fill rates: 100% and 50%.

The planned capacity is identical in both cases as this performance indicator is not based on the fill rate.

We can observe that the deviation between planned capacity and actual capacity can vary depending on the performance of the remotes in the SatNet and occurrence of potential failures.

But the delta between predicted capacity and actual capacity is most of the time negligible for the SatNet at 100% fill rate whereas it can be up to 20% for the SatNet at 50% fill rate.

An explanation of this delta is the fact that when the SatNet is not very loaded, the system tends to allocate larger symbol rates to the remotes while reducing the modcod in order to increase the robustness. This behaviour shall be taken into account for the definition of the contractible capacity, which should be a wise balance between planned, predicted, and actual capacity.

The experimentation continued with the CONOPS, with the objectives to see how the MAPAN could contribute to the effective operation of a SatNet.

To complete this analysis, I included the remote booking which refers to the committed information rate (CIR) of the remotes. The maximum information rate (MIR) was set at 130% of the CIR.

I also tracked the contractible capacity, which is updated throughout the lifetime of the SatNet based on the performance assessment from the MAPAN framework and following the concept of operations provided in section 5.5 and detailed in *Figure 5.7*.

In *Figure 5.9*, I can observe the adjustment of various types of the performance indicator (the capacity) following the voluntary triggered or known events (e.g., network upgrade / downgrade, remote itinerary) and involuntary events (e.g., remote increase or decrease of traffic, failure). Voluntary events are captured by the planned, booking, and predicted metrics, while involuntary events are captured in measured and predicted metrics. The contractible capacity is also tracked as an additional metric and we can observe that for both types of events, it is adjusted accordingly.

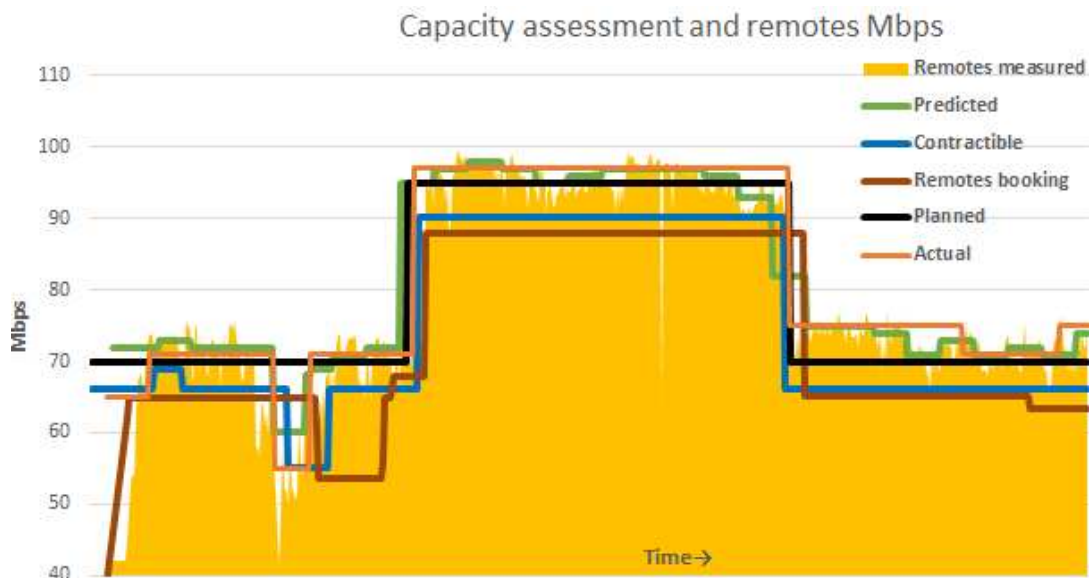


Figure 5.9: Capacity assessment with the MAPAN framework

5.7 CONCLUSION

This chapter introduced the challenge of performance assessment and the necessity to have an accurate performance estimation in live satellite systems. The proposed MAPAN framework introduces three types of performance and an additional type was introduced when applied the capacity as the selected performance indicator. Therefore, the four types of capacity are:

- Planned capacity, based on a reference terminal, can be used for initial system comparison, configuration and for dimensioning of the connectivity offer.
- Actual Capacity, used to track deviations, guide load balancing, and eventually adjust contractible capacity.
- Predicted capacity, based on real-time link budgets, is used for theoretical benchmarking and forecasting.
- Contractible capacity, which is the capacity that can be sold, and which is continuously adjusted.

The proposed model allows performing an initial capacity assessment (planned capacity) with an acceptable error margin (less than 20%), and a reduced computation effort. It may be less accurate than capacity assessment based on traffic plan as proposed in [107] but it has the advantage to be simple and applicable without any traffic plan and provide a basis which is acceptable for initial assessment of contractible capacity. It is then an advantage where traffic prediction is not provided. And combined with actual and predicted algorithms, it provides a good basis for an overall improved accuracy.

The proposed averaging algorithms combined with real time link budgets were demonstrated to provide accurate actual and predicted capacity assessments, which are used for continuous adjustment of contractible capacity, and can be used for network planning and traffic forecasting.

Future work may include the extension of the concepts to non-GEO systems and flexible systems and the embracement of machine learning for a more accurate and responsive MAPAN framework.

6.1 CONCLUSION

Satellite communication systems are continuously evolving with a strong focus on maintaining their position as the best option to provide connectivity to underserved areas, or in complement of terrestrial connectivity.

Capacity and connectivity cost optimization is an important focus area, at various levels: from the design of satellite systems, including the space segment and the ground segment, to the operation of satellite communication networks, independently or in integration with terrestrial networks.

The work presented in this thesis represents my main research activities in the satellite industry for the past 10-12 years.

In Chapter 2, we reviewed the main parameters of satellite systems and how they have been optimised recently. Hence, capacity, latency, availability, coverage and flexibility enhancement techniques were reviewed. We concluded that the flexible capacity remains the key parameter to optimise. And in line with my research activities, we focused on capacity optimization.

Hence, it is demonstrated in Chapter 3 that the continuous phase modulation can be therefore a solution to maintain a communication, even at very low signal to noise ratio (SNR) or it can allow the use of terminals with less precise amplifiers, reducing the cost. The combination of convolutional code and continuous phase modulation (CC-CPM) proposed in DVB standard was demonstrated to work with acceptable performances, but it had later to face the competition for very low SNR linear modulation waveforms, able to work at the same low SNR as the CC-CPM. Today, the technology is implemented in very few mass market products and when it is, it remains an optional waveform.

In Chapter 3 we also addressed the multicarrier predistortion and associated optimizations. We identified the throughput gain when implementing such techniques as a tangible and concrete gain for satellite operators. And we proposed a combination of coarse and fine search algorithms for the selection of the optimal operation point of the satellite high power amplifier and for the optimization of the carrier spacing. The gain related to the predistortion allowed to perform carrier overlapping as the resulting inter-modulations could be cancelled by the predistortion algorithm. This led to the increase of symbol rate and thus achievable throughput. The throughput gain resulting from all these techniques and algorithms was demonstrated on a live satellite to reach +10% throughput which is considerable.

In Chapter 3 and Chapter 5, we highlighted that accurate performance assessment is a key requirement for efficient resource allocation and to evaluate the impact of an optimization algorithm. We therefore discussed in Chapter 5 a proposal of a framework for performance assessment. It introduces the concepts of planned performance which is the expected performance at the initiation of the system, actual performance that is the current performance of the system and predicted

performance that is the expected future performance of the system. The framework was then applied with capacity as the performance indicator. A concept of operation was derived from the proposed framework in order to optimise the resource management in a live satellite system by detecting and troubleshooting issues, and/or adjusting the expected capacity according to the actual performances of the remotes in the system.

In Chapter 4, we focused on the relatively new subject of satellite and terrestrial integration in the context of the 5G system. The chapter was more explorative on different challenges of such integration. We provided a view of potential use cases and selected the multilink backhaul as the generic use case for further analysis. Then we studied the role model and the traditional value chain of satellite systems and we concluded that with a proposal of an open and agnostic role model where players can play different roles. We also analysed the challenges related to the introduction of a satellite capacity broker, in charge of capacity negotiation for mobile network operators.

Further investigations in Chapter 4 on key enablers for 5G satellite terrestrial integration were performed. Hence, we defined a generic satellite-terrestrial integrated architecture and the associated implementation options. We also proposed a model of QoS mapping between terrestrial 5G quality of service identifier and satellite class of service, or directly satellite resources in order to meet the requirements of 5G service delivery as much as possible with a satellite connectivity. We also introduced the concept of single-combined network management system or multiple-separated network management systems for terrestrial domain and satellite domain. Finally, we proposed an architecture and a protocol for content delivery to Edge of the 5G network, through a multicast satellite link.

The satellite system performance enhancement was demonstrated to be a key enabler for the integration of satellite and terrestrial networks in the 5G context. Accurate capacity assessment and various capacity enhancement techniques discussed in this thesis are important to provide required capacity and flexibility to support the 5G backhaul use case based on a satellite transport network immediately; and further use cases in the near future.

6.2 ACTUAL AND FUTURE WORK

The perspectives of the topics addressed in this thesis are as wide as the topics. We can mention further capacity improvement as well as flexibility enhancement and further embracement of “softwarization” by satellite systems to improve the connectivity offer, and the integration with terrestrial systems. This includes end-to-end management of the quality of service, and optimization of resource allocation. Since the completion of the research activities presented in this thesis, I have been involved or I am about to be involved in few related research activities as summarised below:

Machine Learning / Artificial Intelligence (ML/AI) for satellite networks operation

For operating systems, the challenge is to optimise the resource allocation considering the current load of the network, the user needs, the remote performance and the available capacity for network upgrade if necessary (thanks to system flexibility). In addition, load balancing is vital in such an environment and the number of parameters to consider is increasing considerably. Data on system performance history, prediction, capacity availability, user needs, etc, will be complex to be processed without ML/AI. My current work on this topic aims to address the following challenges:

- Automatic selection of the most suitable connectivity for a given mission
- Adjust the configuration of the system to the actual characteristics and constraints of the traffic (e.g., live transponder operation point adjustment driven by the multi-carrier prediction algorithm as discussed in §Chapter 3.
- Automatic identification and troubleshooting of issues
- Avoid human mistakes and typos.

The final objective is AI to allow SatCom networks to operate independently with minimal human oversight.

Beam hopping for increased flexibility

As discussed in Chapter 5, the available capacity in space will keep increasing faster than the demand, which means that the capacity availability tends to not be an issue anymore. But flexibility on coverage and allocation remain an important concern since the capacity distribution is not necessarily aligned to demand, in particular in a fast changing market. Study of implementation of beam hopping including on new software defined satellites can be an effective approach to address such challenges. The study can address space-ground synchronization as discussed in the ESA funded project Free HTS Hopper [116].

New Key Value/Performance Indicator for SatCom and integrated networks and improved cost model

For existing satellites, new performance indicators can be introduced in order to compare two or more systems, from cost perspective. Hence, beyond the actual cost

per bandwidth (\$ per MHz), or data rate (\$ per Mbit/s), or volume (\$ per Mbit), a new evolutionary cost model can be introduced at service level. The connected-service would be enabled by the satellite connectivity, eventually jointly with terrestrial networks and can then become another value to sell, monitor and optimise, beyond the connectivity. The units and metrics need to be defined and the approach will also support the transformation of players from infrastructure and connectivity providers to service providers.

Flexible terminal and Cognitive radio

The specification and adoption of the NTN 5G NR might be one the most studied areas nowadays. However, the evolution of the waveforms may not lead the replacement of legacy satellite waveforms (e.g. DVB S2X/RCS2), with several proprietary solutions, but rather the adoption of multiple waveforms with a flexible terminal, able to change or adapt the waveform depending on the system technology or conditions. Active antennas are already providing some flexibility at antenna level and the idea would be to seek for further flexibility at radio level. In addition, it can be combined with cognitive radio for opportunistic transmission and to allow spectrum sharing with terrestrial networks.

Other related research topics

Several other topics can be interesting as a follow up of the activities presented in this thesis. The satellite-terrestrial integration is probably one of the most active research topics in the satellite industry. Few examples of current research areas are:

- Completion of the 5G NR NTN specification for direct satellite access to 5G with solutions on identified key issues (time and frequency synchronization, optimization of HARQ processes, support of mobility and handovers, etc.)
- Management and orchestration of satellite access and backhaul in 5G
- 3D satellite connectivity: combination of Terrestrial-Satellite-LEO-MEO-GEO links to provide enhanced connected-services to a remote
- Embedding gNB onboard a satellite with all related studies on functional split between non-terrestrial and terrestrial components.

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ANNEXE A: ANNEXES RELATED TO RESEARCH ACTIVITIES

ANNEX A.1: LIST OF PUBLICATIONS AND CONTRIBUTIONS

BOOK CHAPTER (1)

A1.1: Satellite use cases and scenarios for 5G eMBB

Author(s): Konstantinos Liolis, Alexander Geurtz, Ray Sperber, Detlef Schulz, Simon Watts, Georgia Poziopoulou, Barry Evans, Ning Wang, Oriol Vidal, **Boris Tiomela Jou**, Michael Fitch, Salva Sendra Diaz, Pouria Sayyad Khodashenas, Nicolas Chuberre

Published in: 2018, Satellite Communications in the 5G Era, 2018, ISBN 978-1-78561-427-9

Publisher: The Institution of Engineering and Technology | **DOI:** 10.5281/zenodo.1402486

PEER REVIEWED ARTICLES (2)

A1.2: Use cases and scenarios of 5G integrated satellite-terrestrial networks for enhanced mobile broadband: The SaT5G approach

Author(s): Konstantinos Liolis, Alexander Geurtz, Ray Sperber, Detlef Schulz, Simon Watts, Georgia Poziopoulou, Barry Evans, Ning Wang, Oriol Vidal, **Boris Tiomela Jou**, Michael Fitch, Salva Diaz Sendra, Pouria Sayyad Khodashenas, Nicolas Chuberre

Published in: 2018, International Journal of Satellite Communications and Networking, 2018, IJSSN 1542-0973

Publisher: John Wiley & Sons Inc. | **DOI:** 10.1002/sat.1245

A1.3: An extensible network slicing framework for satellite integration into 5G

Author(s): Youssouf Drif, Emmanuel Chaput, Emmanuel Lavinal, Pascal Berthou, **Boris Tiomela Jou**, Olivier Gremillet, Fabrice Arnal

Published in: 2021, International Journal of Satellite Communications and Networking, 2021, IJSSN Page(s) 339-357

Publisher: John Wiley & Sons Inc. | **DOI:** 10.1002/sat.1387

INTERNATIONAL CONFERENCES WITH REVIEWING COMMITTEE AND PROCEEDINGS (6)

A1.4: An overview of multicarrier predistortion techniques and associated throughput gain for an actual hardware implementation

Author(s): Dieter Duyck, Alberto Mengali, MB Shankar, Konstantinos Liolis, Cedric Le Guern, **Boris Tiomela Jou**, S Cioni

Published in: 2017, Proc. AIAA Intern. Comm. Sat. Systems Conf.(ICSSC), Oct. 2017, Trieste, Italy, pp 352-362

A1.5: Architecture Options for Satellite Integration into 5G Networks

Author(s): **Boris Tiomela Jou**, Oriol Vidal, Joe Cahill, Fabrice Arnal, Jean-Michel Honssin, Mael Boutin, Duy Kha Chau

Published in: 2018, European Conference on Networks and Communications (EuCNC), 2018, Page(s) 398-9, ISBN 978-1-5386-1478-5

Publisher: IEEE | **DOI:** 10.1109/eucnc.2018.8442436

A1.6: Managing integrated satellite-5G networks: techno-economic evaluation of a brokerage role

Author(s): Asma Chiha Ep Harbi, Marlies Van der Wee, Michael Fitch, Keith Briggs, Simon Watts, Leonardo Goratti, **Boris Tiomela Jou**

Published in: 2019, the European Conference on Networks and Communications (EuCNC)

A1.7: Benefits and challenges of software defined satellite-5G communication

Author(s): Hamzeh Khalili, Pouria Sayyad Khodashenas, Carolina Fernandez, Daniel Guija, Konstantinos Liolis, Christos Politis, Gint Atkinson, Joe Cahill, Robert King, Mark Kavanagh, **Boris Tiomela Jou**, Oriol Vidal

Published in: 2019, 15th Annual Conference on Wireless On-demand Network Systems and Services (WONS)

Publisher: IEEE | **DOI:** 10.23919/WONS.2019.8795462

A1.8: Slice Aware Non-Terrestrial Networks

Author(s): Youssouf Drif, Emmanuel Lavinal, Emmanuel Chaput, Pascal Berthou, **Boris Tiomela Jou**, Olivier Grémillet, Fabrice Arnal

Published in: 2021, IEEE 46th Conference on Local Computer Networks (LCN), Edmonton, AB, Canada, 2021, pp. 24-31

Publisher: IEEE | **DOI:** 10.1109/LCN52139.2021.9524938.

A1.9: Performance assessment framework and concept of operations in live satellite communication systems

Author(s): **Boris Tiomela Jou**, Haug Torleif, Holmes Justin, Pascal Berthou, Roland Gautier

Published in: 2023, International communications satellite systems conference (ICSSC), Oct 2023, Bradford, United Kingdom

Publisher: Institution of Engineering and Technology (IET) | **DOI:** TBD

3GPP AND ETSI CONTRIBUTIONS

A1.10: 3GPP Working Group SA2, TR 23.737 - Study on architecture aspects for using satellite access in 5G

- [S2-1902443](#): Key issues Backhaul multilink
- [S2-1902883](#): Solutions for using satellite backhaul in content distribution
- [S2-1900326](#): The role of satellite backhaul in content distribution towards the edge
- [S2-1909749](#): Evaluation of Solution #6 for using satellite backhaul in content distribution towards the edge

A1.11: 3GPP Working Group SA5, TR 28.808 - Study on management and orchestration aspects of integrated satellite components in a 5G network

- [S5-212044](#): pCR 28.808 Reference architecture for the management of integrated satellite transport network for backhaul
- [S5-212045](#): pCR 28.808 Addition of two architecture scenarios for 5G networks with an integrated satellite transport network for backhaul

A1.12: ETSI SES SCN

- SESSCN(18)000025-Enhanced Interfaces for Advanced Satellite Transport Network

PROJECT DELIVERABLES AND OTHER SCIENTIFIC CONTRIBUTIONS

A1.13: D3.1, Integrated SaT5G General Network Architecture

Type: Research project Public deliverable, 2018 and 2019, 96 pages

Context: EC funded SaT5G Project (Grant agreement ID: 761413), Report ID: 7630038

Contributed as: Main editor

A1.14: Satellite Integration into 5G - Architecture Options and Integration Challenges

Type: Poster, 2018

Context: EuCNC 2018, SaT5G Booth, EC funded SaT5G Project (Grant agreement ID: 761413)

A1.15: D3.2, Integrated SaT5G Detailed Network Architecture

Type: Research project Public deliverable, 2019, 79 pages

Context: EC funded SaT5G Project (Grant agreement ID: 761413), Report ID: 6503809

Contributed as: Main editor

A1.16: 5G PPP architecture working group: View on 5G architecture

Type: Public document – Whitepaper, 2019

Context: Public project partnership for 5G Network

Contributed as: Main editor of the chapter on 5G satellite-terrestrial integration

Authors: Simone Redana, Ömer Bulakci, Anastasios Zafeiropoulos, Anastasius Gavras, Anna Tzanakaki, Antonino Albanese, Apostolos Kousaridas, Avi Weit, Bessem Sayadi, **Boris Tiomela Jou**, Carlos J Bernardos, et al.

A1.17: Key Enablers for Satellite-Terrestrial 5G Integration

Type: Poster, 2019

Context: EuCNC 2019, SaT5G Booth, EC funded SaT5G Project (Grant agreement ID: 761413)

Titre: Techniques d'amélioration et d'évaluation de performances de systèmes de communication par satellite et interconnexion avec les réseaux 5G

Mots clés : évaluation de performances, amélioration de performances, management de la capacité, satellite 5G, optimisation des ressources

Résumé : L'amélioration continue des performances des systèmes de communication par satellite est un enjeu permanent pour tous les acteurs de la chaîne de la valeur de la connectivité et du service par satellite. Cette amélioration peut s'effectuer à différents niveaux du système, avec des prérequis et des impacts différents et variés. L'évaluation de performances est une étape clé dans cette quête, avant la proposition de techniques d'amélioration de performance, mais aussi après, pour l'évaluation de la pertinence et de l'efficacité de ces techniques. Les travaux présentés dans ce manuscrit s'articulent en deux volets essentiels : le premier décrit plusieurs techniques d'améliorations de performances, au niveau des couches basses notamment, en s'attaquant à des problématiques bien connues telles que la distorsion. Mais surtout en proposant des méthodologies adaptées d'évaluation de performances.

L'autre volet traite de l'interconnexion de réseaux satellitaires et non-terrestres avec les réseaux terrestres dans un contexte 5G, en s'attardant sur les questions essentielles d'architectures, de livraison de contenu en bordure de réseau et de continuité de service. Enfin, ce manuscrit aborde également les questions de concepts d'opérations avancés, pour des systèmes opérationnels de fourniture de connectivité et de service par satellite. Ces concepts d'opérations se basent sur les cadres de travail proposés pour l'évaluation initiale et continue de performances.

Titre: Performance enhancement and evaluation frameworks for integrated 5G satellite networks

Keywords: performance assessment, performance enhancement, capacity management, 5G satellite, resource optimization

Abstract: Continuous improvement of satellite communication systems performance is an ongoing challenge for all players in the value chain of satellite-based connectivity and service. This can be achieved at different layers of the satellite communication system, with different and varied prerequisites and impacts. Performance evaluation is a key step in this quest, before proposing performance improvement techniques, but also after, for evaluating the relevance and the effectiveness of the proposed techniques. The work presented in this manuscript is divided into two essential parts: the first part describes several techniques, particularly at the lower layers, by tackling well-known issues such as the distortion; but above all by proposing novel frameworks made up of adapted performance evaluation methodologies.

The second part deals with the interconnection of satellite and non-terrestrial networks with terrestrial networks in the 5G context, focusing on the essential questions of architecture, edge delivery and service continuity. Finally, this manuscript also addresses advanced concepts of operations, for satellite connectivity and service delivery in live satellite communication systems. These concepts of operations are based on the frameworks proposed for initial and continuous performance evaluation.