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A Framework Implementing Multi-Criteria Least Cost Routing for IP Multimedia Services

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Présentée par **Sajjad Ali Mushtaq**

Département : Computer Engineering

Directeur de thèse : Antoine Beugnard

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Dedication

To my Family

Acknowledgments

First and foremost, I would like to express my gratitude to my advisors Assistant Professor Christoph Lohr and Professor Annie Gravey (HoD) for their support, help and patience towards the project and Ph.D that kept me going till the end. I am deeply indebted to them for their suggestions and guidance during this long journey. I also acknowledge my director Professor Antoine Beugnard for his support and the motivations he gave me on special occasions, whenever i walked towards him with the problem, he always has a solution.
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I am forever indebted to my parents and parents in law for their enormous love, support and prayers. I would like to give special thanks to my brothers and sisters for encouraging me with their best wishes, supporting me and being there whenever help was needed.

Words fail me to express my appreciation to my dear wife, Naheed whose encouragement, support, love and care enabled me to finish this long journey. I also would like to thank my kids Ayesha Ali, Muhammad Umar and Fatimah Zahra, who suffered a lot during this time span and i will never forget their innocent inquiry "" Papa Kab Finir Hoo Ga App Ka Thesis ""; they are powerful source of inspiration and energy and i pray for their good future and happy life. I dedicate this dissertation to my family.

Motivation en termes de pertinence industrielle et de recherche

La gestion et le contrôle de réseau basés sur des règles sont passés au premier plan des technologies de l'information et de la communication (TIC). L'unification des TIC et des télécoms, avec la promesse d'une infrastructure tout-IP, a apporté aux fournisseurs, de nouveaux marchés, produits, et plates-formes. Les opérateurs de réseau visent à minimiser le coût d'exploitation tout en désirant le meilleur retour sur investissement pour les équipements d'infrastructure. Les opérations et procédures de gestion et de contrôle, ainsi que les équipements réels ou virtuels (routeurs, commutateurs, les nœuds de raccordement, les équipements avec des interfaces multiples, les liaisons, etc.) doivent être vigilants vis à vis du service, de l'infrastructure, des contenus, du contexte, des coût, et ceci avec une évolutivité suffisante.

Les infrastructures et technologies réseau historiques ne peuvent pas garantir à la fois le niveau souhaité de qualité de service (QoS) ou de qualité d'expérience (QoE) et les exigences de performance des services divers (par exemple les services voix / vidéo et données), car ceux-ci ont besoin de ressources diverses avec des paramètres de QoS variables. De plus, la diversité des écosystèmes de contrôle et de gestion de réseau causée par l'unification des technologies sous-jacentes (c-à-d. flaires et sans fil), ajouté à la diversité des vendeurs, des solutions propriétaires, et des modèles économiques, introduit encore plus de complexité. Les principales sources de cette complexité sont les suivants: des services diversifiés eux-mêmes, des équipements divers, des technologies de transport et des protocoles hétérogènes, des vendeurs et des standards propriétaires multiples, etc. Pour surmonter la complexité sous-jacente et maîtriser l'hétérogénéité technologique et l'unification des services, la gestion des infrastructures et des procédures de contrôle doit masquer toutes les différences, afin de permettre une gestion efficace des ressources et un contrôle efficace sur la plate-forme.

La logique métier d'une entreprise est fortement dépendante de l'accès aux services et applications, de leur modification, et de la prestation de nouveaux services ou applications sur la plate-forme (par exemple des services triple/quadruple play, des services basés sur le cloud, des application de conférence, ou de VoIP, etc.). Le problème avec les systèmes de gestion et de contrôle existants est qu'ils ne sont pas en mesure de prendre en compte les règles de gestion de l'infrastructure. Toutefois, les systèmes tenant compte des règles d'entreprise ne peuvent pas s'adapter au changement dans les modèles d'affaires et préfèrent éviter un plus grand portefeuille de services pour ne gérer la dynamicité que des règles métier et d'exploitation.

La plupart des fonctions de contrôle et de gestion sur les infrastructures convergentes sont régies et manipulé par des entités qui doivent être configurés et administrés par différentes procédures bas niveau. Et souvent la configuration et l'administration

du service et de la logique métier ne se retrouvent pas correctement alignées avec les procédures précédentes. En outre, la gestion et le contrôle des entités au sein de ces environnements sont spécifiques à une technologie ou un vendeur particulier, et rendent difficile la réalisation d'objectifs multiservices, multi-fournisseurs et multi-domaines sur une plate-forme hétérogène. En outre, si par exemple le contrôle d'accès est fourni par un vendeur A, les services et applications sont offertes par un autre fournisseur B, et que la facturation et le contrôle sont externalisés à un prestataire tiers, tout ceci grâce à une architecture convergente, cela implique qu'un changement dans les règles métier et dans la logique de service doit être propagé de manière efficace vers tous ces acteurs tout en maintenant la multiplicité des objectifs et des critères. Lors du lancement de notre projet, le problème était axé sur l'acheminement des requêtes émanant des couches supérieures (c.-à-d. du point de vu OSI des couches couche applicatives), et ceci à la frontière du réseau public-privé et sur une infrastructure avec une certaine convergence des technologies d'accès. Mais, le projet évoluant, les besoins des partenaires et les fructueuses discussions internes ont élargit le cadre du problème et l'architecture du système dans son ensemble. Le problème de routage dans les couches supérieures avec une granularité différente (routage par appel / session / requête, plutôt que le routage des paquets dans la couche réseau) est différente du routage classique avec QoS. Le problème de routage sous-jacent doit prendre en compte les politiques classiques de gestion des données (par exemple en fonction du temps dans la journée, des profils utilisateurs, des priorités, des authentifications, des autorisations, etc.) en plus des principes d'ingénierie de trafic lorsque l'on se place à la frontière de la plate-forme (en ce qui concerne les liens externes qui établissent un lien entre le monde privé et le réseau public). Mais les politiques classiques de gestions des données, et la gestion et le contrôle du trafic réseau sont orthogonaux. En outre la voix, la vidéo, les services triple/quadruple-play ont des contraintes très diverses de QoS sur le délai, la gigue, le taux de perte, la bande passante, etc. De plus, lorsque l'on cible des objectifs multiples tant sur les couches de données inférieures et les couches applicatives supérieures, cela introduit des problèmes de décision multicritères. Il est important de mentionner ici que ce cadre doit appréhender des demandes dynamiques de routage de sessions provenant des couches supérieures sans perdre de vue le que la décision de routage ne porte seulement que sur le premier saut et qu'il ne traite pas le routage de bout-en-bout.

La solution proposée ici offre une meilleure maîtrise et une meilleur gestion et permet aux différents fournisseurs, aux multiples opérateurs de réseaux et fournisseurs de services, aux diverses fournisseurs de solutions et aux entreprises variées de gérer et opérer chaque fonctionnalité qu'ils apportent sur une architecture hétérogène mais convergente, avec un support du multihébergement à la frontière du réseau public-privé. Le routage dynamique des sessions multimédias et ses exigences dire ses racines du projet Companym@ges, avec des règles métier sur le service, le contrôle, le trans-

port, les accès, et des objectifs multiples sur la plate-forme. Un framework de prise de décision dynamique pour les infrastructures multihébergées incluant des aspects de convergence, de communication unifiée et d'hétérogénéité permet de résoudre la prise de décision de routage à la frontière du réseau public-privé, sur la base d'informations issues des plans mentionnés précédemment, en exprimant le problème sous l'angle de la décision multicritère. Au delà d'une solution au projet Companym@ges, ce framework peut être déployé pour des petites ou moyennes entreprises offrant des services de communication unifiée et diverses solutions applicatives. De plus sa version simplifiée et allégée peut être embarquée dans des équipements de bordure ou des équipement du domicile (routeur A/S-DSL et gateways supportant le multihébergement et ayant un ou plusieurs fournisseurs d'accès). De plus, son sous-système de prise de décision plus sophistiqué intégrant la gestion de l'énergie peut être embarqué dans des équipements nomades ayant plusieurs interfaces réseau et plusieurs technologies d'accès.

Position du problème

La gestion et le contrôle basé sur la prise de décision dynamique ont émergé comme une solution prometteuse pour la gestion des réseaux hétérogènes et convergents avec un support du multihébergement. Les caractéristiques fondamentales d'un tel framework d'aide à la décision est efficace en terme d'utilisation des ressources de l'infrastructure alliant la flexibilité de la plateforme et en accommodant les variation fréquentes dans les changements de gestion. Le but ultime est d'adapter le comportement dynamiquement sans réinitialisation ou redémarrage du système, en héritant de la base d'informations intrinsèques et extrinsèque des différents domaines ou plans de la plateforme hybride. Cette base de connaissance agrémenté des objectifs d'entreprise de la plateforme et des configuration d'administration sont exploitées par le calcule de politiques et de décisions. Ces décisions visent à régir le comportement de l'infrastructure de communication par l'application de ces décisions à différents niveaux de granularité de la plateforme (appel, session, requête).

Ce framework de décision/politiques requière un modèle d'information, des outils ou mécanismes pour appréhender les variations sémantiques ou les fluctuations comportemental, des procédures d'intercommunication pour partager ou disséminer l'information, des protocoles, essentiellement de protocoles de signalisation pour le contrôle et la gestion du partage de données à des niveaux micro et macro, et un langage sur l'infrastructure pour représenter les règles de la plateforme, les objectifs d'entreprises et les instructions de configuration et d'administration, d'une manière standardisée et compréhensible au travers d'une infrastructure convergente. De plus, la prise de décision dans un tel environnement n'est pas une tâche simple, spécialement lorsque des modifications ou variations dynamiques doivent être prises en compte avec un ensemble d'information et de paramètres conditionnels provenant depuis divers domaines de gestion (profile de services, information sur la fiabilité, heure de la journée,

objectifs d'entreprise, dernier état des liens, profils utilisateurs, Service Level Agreement (SLA), etc.). La situation devient encore plus compliquée lorsque les services distincts ont des exigences différentes : certains exigent une bande passante élevée et d'autres ont besoin d'un délai ou d'un taux de perte bas. Les besoins des utilisateurs sur l'infrastructure sont également divergents : certains désirent une meilleure expérience utilisateur, certains exigent la sécurité, et d'autres s'attachent au compromis coût/qualité. Les systèmes de prise de décision conventionnels prennent en compte des informations dépendantes de la technologie et d'autre informations indépendantes de la technologie (périphériques, interfaces, protocoles, architecture, topologie, etc. relatifs à l'infrastructure réseau, lorsqu'ils calculent une décision. Les ensembles de données orientées application, les attributs correspondants sur le plan de service et les objectifs d'entreprise sur la plateforme ne sont pas considérés ou sont pris en compte partiellement. Toutefois, les systèmes gérant les objectifs de l'entreprise peut ne pas être en mesure d'appréhender la granularité requise. Les systèmes accueillant les informations des services doivent être manipulés d'une manière abstraite vis à vis de l'évolutivité et l'extensibilité du service. Par-dessus tout, les derniers systèmes visant les questions mentionnées ci-dessus semblent ne pas être en mesure de fournir la dynamicité requise pour un contrôle efficace et une gestion efficaces sur une telle convergence et d'un système hybride de communication avec le support du multihébergement. En outre, les domaines d'information de la plate-forme qui sont pluridisciplinaire et multidimensionnelle (par plans ou couches) se trouvent synchronisés au niveau local et asynchrone au niveau mondial, formant ainsi un système Globalement Asynchrone Localement Synchrone (GALS). Les informations statiques et dynamiques (inter/intra domaines et multicouches) concernant la plateforme unifiée sont catégorisées soit comme intrinsèques ou extrinsèque au regard des différents plans ou domaines lorsque l'on pose le problème de décision multicritère avec des objectifs multiples. Il est alors nécessaire de pondérer l'accumulation d'effets multi-facettes causée par une grande diversité, une myriade de dimensions avec de multiples objectives concernant ce système GALS multi-plan. Les sources d'information représentant les différents domaines (p.ex. Les plans de service, de contrôle, de transport, de réseau) peuvent être fortement structurées et synchronisées localement (inter-domaines ou inter-plan), mais peuvent avoir très probablement des informations de représentation globale synchrones et non structurées (intra-domaine ou intra-plan). Les profiles de QoS des liens, les profils d'autorisation et d'authentification des utilisateurs, les profils et variantes de services, les objectifs d'entreprise, la dynamique courante d'une plateforme multihébergée et les questions de gestion du trafique à la frontière du réseau publique-privé constitue un problème pluridisciplinaire. Les informations provenant des différentes sources avec différentes unités reflètent la complexité du problème sous-jacent.

Les solutions conventionnelles pour appréhender des scénarios similaires d'un tel environnement convergent multihébergé sont soit centrées sur l'utilisateur ou mo-

tivées par une utilisation efficace des ressources de la plat-forme et/ou sont centrées sur l'optimisation des applications pour une QoS ou une QoE donnée. Cependant, pour prendre en compte à la fois les profils d'autorisation et d'authentification des utilisateurs, les objectifs d'entreprise, les SLA réciproques entre fournisseurs concurrents, les informations spécifiques ou indépendants d'une technologie de la plateforme convergente, la dynamique courante de l'infrastructure multihébergée et les questions de gestion du trafique à la frontière du réseau publique-privé, un système de décision efficace et performant est requis. En outre, l'évolutivité, l'extensibilité et la performance du système de décision sous-jacent doit être pris en compte même si la granularité de l'architecture proposée dans Companym@ges traite des appels ou sessions plutôt que des paquets individuels. Cette convergence au niveau service, contrôle, accès, transport et réseau requière des ajouts ou modifications et une mise à jour des ensembles de données pluridisciplinaire avec de multiples objectifs. La diversité et l'étendue des objectifs à multiples facette associée à des objectifs multiples sur la plateforme requière le recours à la théorie de la décision multicritères (Multi Criteria Decision Making) pour traiter toutes les questions mentionnées ci-dessus et calculer des prises de décision de routage à la frontière du réseau public-privé.

Contribution prenant en compte les différents modules et entités du framework Un framework de décision dynamique implémentant le routage multicritères de services multimédia à la frontière du réseau publique-privé avec des technologies d'accès convergentes et offrant une infrastructure multihébergée est présenté. Les ingrédients de ce framework s'étendent depuis le modèle d'information jusqu'à la gestion de la sémantique. Il embrasse la représentation de ses caractéristiques communicationnelles, comportementales et fonctionnelles des composants. Le contrôle et la gestion de l'infrastructure sont réalisés par la réorganisation des protocoles de signalisation (par exemple SIP, le diamètre et SNMP). Enfin un langue agrège toutes les constituants de la plateforme, les micro et macro règles, les objectifs ou instruction de l'entreprise, car tout ceci est profondément ancrée au sein de l'infrastructure. Les modules et sous-modules, les composants et sous-composants, leur intercommunication, le comportement de ces éléments, les relation de filiation, recouvrements, remplacement des concepts correspondants vis à vis du moteur de décision est développé et définit, tout en gardant en vu le calcul de décision et sa réalisation. Une approche en couches permet d'exploiter et de cartographier des informations spécifiques aux domaines et au plans, au regard de la théorie de la décision multicritères Le modèle d'information DEN-ng est étendu et taggé en accord avec les exigences du framework sous-jacent. La gestion des règles et politiques et leur spécifications sont en forte corrélation car elles doivent accommoder les changements de gestion et des processus d'entreprise en suivant la logique du business de l'entreprise. Les approches pour spécifier les règles et politiques va des langages de politiques formels qui peuvent être directement traitées par un ordinateur, jusqu'à des notations et construction de politiques fondées

sur des règles, et à la représentation des politiques comme des entrées dans un tableau à plusieurs attributs. Un langage de spécification de règles a été développé sur la base du framework permettant une spécification native des règles. Différentes méthodes de décision multicritères ont été expérimentées sur la plateforme pour appréhender la dimensionnalité des information, la dynamicité de la plateforme, les fluctuation des ensembles de données (bornes inférieures et supérieures), les informations contextuelles, et les variations sémantiques associées. Le moteur de décision de ce framework de communication unifié est en capacité de gérer le routage dynamique à la frontière publique-privé d'un réseau convergent. De plus, la solution est capable de gérer des décisions de transfert horizontal (handover) sans réinitialisation ou démarrage du système. La théorie de la décision multicritère est utilisée pour le calcul des décision et des méthodes adaptées sont exploitées en accord avec les scénarios et les modes de calcul de décision en prenant en compte les différents modes correspondant de mise en application. Le calcul des poids est crucial aux méthodes de décision multicritères car il caractérise l'importance relative de ces critères. Le calcul des poids des critères est appliqué et une échelle est revue en fonction des exigences de la plate-forme. Enfin une ontologie est intégrée avec ces méthodes multicritères afin de appréhender les variations sémantiques de la plate-forme.

Articles publiés au cours de cette thèse

$[C_1]$ Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " An Integration of Semantics in Multi Criteria Decision Making for Converged Multimedia Network Management ", In IEEE GlobeCom Dec, 5-9 Houston, Texas United States, 2011.

$[C_2]$ Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " Dynamic Decision Engine for Unified Communication", In 14th ACM International Conference on Modeling ", Analysis and Simulation of Wireless and Mobile Systems Miami Beach, Florida, United States, 2011.

$[C_3]$ Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " A Framework for Unified Traffic Dynamic Routing at Private-Public Network Border " in press for publication at IEEE ICC,, Conference; 10-15 June, 2012, Otawa Canada.

$[J_1]$ Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " Network Management and Control Framework for Hybrid Converged Environment ", Cyber Journals: Journal of Selected Areas in Telecommunications (JSAT), Vol. 2, No. 8: 45-55, 2011,ISSN: 1925-2676.

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[J_3] Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " Multi Criteria Decision Making Methods Adaptation, Enhancements, Integration and Comparisons for Dynamic Decisions Making Framework ". Springer Journal of Network and Systems Management, ISSN: 1573-7705, Journal no. 10922. (In Progress)

Contents

List of Figures **xv**

List of Tables **xix**

List of Tables **xix**

Abbreviations **xxii**

Abbreviations **xxii**

1 Introduction **1**

1.1 Extended Abstract 1

1.1.1 Motivation: In Terms of Industrial Relevance, Research and Benefits 1

1.1.2 Requirements: Problem Statement 3

1.1.3 Contribution: Contribution Taking Into Account the Different Modules/Entities Over the Framework 5

1.2 Thesis Outline 6

2 Background and Related Work **8**

2.1 QoS models and their connection with PBNM 9

2.2 QoS Information Sharing at device level using SIP 13

2.3 QoS mechanism Over Companym@ges Platform 14

2.4 Least Cost Routing as a Special Case of QoS 15

2.5 Policy/decision Framework Requirements 16

2.5.1 Policy Based Network Management (PBNM) 17

2.6 Related Work 18

2.7 Summary 25

3 Companym@ges Policy Based Network Management (PBNM) 26

3.1 Companym@ges Framework 26

3.1.1 Proposed Architecture and Decision Making Framework Requirements 27

3.1.1.1 Dynamic Decision Making Framework 31

3.1.1.2 Companym@ges Framework for Unified Communication 34

3.1.2 Proposed Architecture and IP Multimedia Subsystem Comparison 35

3.1.3 Rule Based Management and Control in Companym@ges Framework 36

3.2 Choice of Diameter, its Comparison with Other Protocols and its Revamping 42

3.2.1 COPS Vs Diameter Vs SNMP 44

3.3 Signaling Protocol (SIP) and its Revamping For The Platform 46

3.3.1 Handling incoming and outgoing calls 47

3.3.1.1 Outgoing Call 48

3.3.1.2 Incoming Call 48

3.4 Summary 50

4 Multi Criteria Decision Making and Corresponding Methods for the Framework 52

4.1 Choice of the Multi Criteria Decision Making Theory 54

4.1.1 Weighted Sum Method (WSM) 56

4.1.2 Weighted Product Method (WPM) 58

4.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) 59
4.2.1 Problem Formulation and Application of TOPSIS 60
4.2.1.1 TOPSIS MCDM Method Application Steps 60
4.3 Extended TOPSIS 64
4.4 Grey Relational Analysis (GRA) 67
4.5 Summary 70

5 Policy Engine in Companym@ges Framework 72
5.1 Decision Engine Modular Framework 73
5.2 Information Models for PBNM and Extracted Model for the Platform 76
5.3 Rule Specification Languages and the Followed Approach 78
5.3.1 Ponder 79
5.3.2 KAoS 80
5.3.3 Rei 81
5.4 Decision Computation and Management 81
5.5 Online and Off-Line Policy/Decision Computation 86
5.5.1 Provisioning Mode 88
5.5.2 Outsourcing Mode 88
5.6 Outsourcing and Provisioning Mode Comparison 90
5.7 Application of Decision Engine for Heterogeneous and Converged Environment 93
5.8 Test Bed for the Evaluation of Converged Architecture With Unified Communication 99
5.8.1 Horizontal Handover Decision Computation Using Same Decision Engine 103
5.9 Weight Computation for Corresponding Criteria in MCDM 106
5.10 MCDM and Ontology Integration 112
5.11 Summary 119

6 Conclusions **125**

6.1 Conclusions 125

6.2 Future Work 127

7 List of Author's Publications During the Thesis **129**

7.1 Publications During the Thesis 129

Bibliography **131**

List of Figures

2.1 Infrastructure Layered Model and the Corresponding QoS Mechanisms. 15

2.2 Infrastructure's Constituents Layered Building Blocks. 18

3.1 Companym@ges Proposed Architecture 28

3.2 Data and Multimedia Traffic Convergence Within Companym@ges Proposed Architecture 31

3.3 Unified Communication Architecture Layered Planer Representation and its Mapping 34

3.4 IMS and Proposed Architecture Layered Comparison 35

3.5 PS and SBC Modules and Their Inter-Communication 38

3.6 Vertical Pass and Horizontal Pass for Profile Selection and Information Processing Within PIP 41

3.7 Diameter Packet Format 43

3.8 Communication Between Diameter Server and Client at SBC and PS Respectively . 43

3.9 SIP Revamping Regarding Outgoing Call Flow. 48

3.10 SIP Revamping Regarding Incoming Call Flow. 50

4.1 Companym@ges Proposed Architecture Regarding Global, Local, Planer, Static and Dynamic Information Domains 53

4.2 Load Balancer Clustering Scenario 56

4.3 Candidate Links (Alternatives), Attributes (Criteria) and Objectives(Goals) Hierarchy 61

5.1 MCDM in the Context of Decision Engine. 74

5.2 Platform's Layered and Planer Representation and Their Corresponding Mapping to Goals, Criteria and Alternatives Hierarchy 75

5.3 Modular Framework of the Decision Engine. 76
5.4 Goal, Criteria, Sub-Criteria and Candidate Links Hierarchy. 79
5.5 Real Time Architecture for Corresponding MCDM Methods Evaluation. 82
5.6 Throughput of Each Link With the Corresponding MCDM Methods. 84
5.7 Aggregated Call Dropping Probability of the Links With Different MCDM Methods. 85
5.8 Delay (Milliseconds) Introduced by the System by Deploying the 5 MCDM Methods. 86
5.9 Information Flow in Provisioning Mode 87
5.10 Information Flow in Outsourcing Mode 89
5.11 Call Dropping Probability Introduced by the System in Outsourcing (Online and Off-line) and Provisioning Mode Respectively. 91
5.12 Delay (Milliseconds) Introduced by the System in Outsourcing (Online and Off-line) and Provisioning Mode Respectively. 92
5.13 Architecture for Unified Communication with Convergence. 95
5.14 Software Defined Radio Block Diagram. 96
5.15 Test Bed With 4 Links. 100
5.16 Throughput of Each Link With and Without Decision Engine. 101
5.17 Call Dropping Probability With OpenSIPS and With Decision Engine. 102
5.18 Delay (Milliseconds) Introduced by the System With and without Decision Engine. 103
5.19 Horizontal Handover Scenario. 104
5.20 Candidate GSM-cells, Attributes and Goals Hierarchy for Horizontal Handover Decision-Making. 105
5.21 Handover Call Dropping Probability With and Without the Decision System. . . . 106
5.22 GRA and AHP Integration for Decision System. 108
5.23 An Integration of TOPSIS and AHP for Decision System to Automate Weight Computation. 108
5.24 Throughput of Alternative Links by the Integration of TOPSIS, Extended TOPSIS and GRA with AHP. 109
5.25 Aggregated Call Dropping Probability by the Integration of TOPSIS, Extended TOPSIS and GRA with AHP. 110

5.26 Delay Offered by the System By the Integration of TOPSIS, Extended TOPSIS and GRA with AHP. 111

5.27 System Block Diagram With Modifications. 113

5.28 Architecture Used for MCDM and Ontology Integration Use Case. 114

5.29 SLA Ontology Model and Service/QoS Ontologies. 115

5.30 Throughput of Each Link With and Without Decision Engine. 117

5.31 Call Dropping Probability Without and With Decision Engine (Outsourcing Mode (Online and Off-line)). 118

5.32 Delay (Milliseconds) Introduced by the System Without and With Decision Engine (Outsourcing Mode (Online and Off-line)). 119

List of Tables

2.1 Voice, Video and Data Services Key Performance Expectations/Indicators (Courtesy ITU). 12

3.1 An IP SLA 39

3.2 VoIP SLS 40

3.3 Corresponding QoS Profile for VoIP 40

3.4 Switching Table for Dynamic Routing (At Higher Layer). 48

3.5 Addition of *Resource-Priority* in SIP INVITE for Outgoing Call. . . . 49

3.6 Addition of *Accept-Resource-Priority* in SIP 200 OK for Incoming Call. 49

4.1 Links With Corresponding Parametric Values 63

4.2 R Values and the Corresponding Grading of Alternative Links 64

4.3 Links With Corresponding Parametric Values 69

4.4 GRC Values and the Corresponding Grading of Alternatives (Links). . 70

5.1 Comparison of DEN-ng, SID and CIM 77

5.2 Resource Priority Type and Communication Type Mappings to Corresponding Profiles 83

5.3 Links With Corresponding Parametric Values. 100

5.4 R Values and the Corresponding Grading of Links. 100

5.5 Relative Importance of the Attributes and Their Corresponding Values Used for Pairwise Comparison. 108

5.6 Links With Corresponding Parametric Values 116

5.7 GRC Values and the Corresponding Grading of Alternative Links . . . 117

Abbreviations

IT	Information Technology
IP	Internet Protocol
QoS	Quality of Service
MONA	Module to Optimize Network Accesses
MPLS	Multiprotocol Label Switching
SBC	Session Border Controller
NGN	Next Generation Network
QoE	Quality of Experience
ISP	Internet Service Provider
CAPEX	CAPital EXpenditure
OPEX	OPeration EXpenditure
ETSI	European Telecommunications Standards Institute
IETF	Internet Engineering Task Force
RACS	Resource and Admission Control Subsystem
PDP	Policy Decision Point
PEP	Policy Enforcement Point
SLA	Service Level Agreement
DMTF	Distributed Management Task Force
MOF	Managed Object Format
TMF	TeleManagement Forum
ITU-T	International Telecommunication Union-Telecommunication
SG4	Study Group 4
NGOSS	New Generation Operations Systems and Software
eTOM	Enhanced Telecom Operations Map
BGP	Border Gateway Protocol
VPN	Virtual Provate Network
MIB	Management Information Base
SMI	Structure of Management Information
OIDs	Object Identifiers
MDD	Model Driven Development

MDA	Model Driven Archi?tecture
SLS	Service Level Specification
NAT	Network Address Translation
DNS	Domain Name Service
SIP	Session Initiation Protocol
GSM	Global System for Mobile Communications
VoIP	Voice over IP
IMS	IP Multimedia Subsystem
3GPP	Third Generation Partnership Project
PS	Policy Server
PIP	Policy Information Point
CDR	Call Detail Records
UDP	User Datagram Protocol
SNMP	Simple Network Management Protocol
GUI	Graphical User Interface
ECA	Event Condition Action
EPS	Evolved Packet System
AVP	Attribute Value Pair
COPS	Common Open Policy Service
EAP	Extensible Authentication Protocol
EPC	Evolved Packet System
AAA	Authentication Authorization Accounting
AAR	Auth-Application-Request
AAA	Auth-Application-Answer
ASR	Abort Session Request
ASA	Abort Session Answer
STR	Session Termination Request
STA	Session Termination Answer
DPR/A	Disconnect Peer Request/Answer
FQDN	Fully Qualified Domain Name
P2P	Peer-to-Peer
PPP	Point-to-Point Protocol
CMS	Cryptographic Message Syntax
COPS-REQ	COPS REQuest
COPS-DEC	COPS DECision
HTTP	Hypertext Transfer Protocol
URIs	Uniform Resource Identifiers

UAC	User Agent Client
LB	Load Balancer
LCR	Least Cost Routing
OWL	Ontology Web Language
RDF	Resource Description Framework
DEN-ng	Directory Enabled Networks - new generation
CIM	Common Information Model
SID	Shared Information/Data
LPDP	Local PDP

1

Introduction

1.1 Extended Abstract

1.1.1 Motivation: In Terms of Industrial Relevance, Research and Benefits

RULE-based network management and control has risen to the forefront of the Information Technology (IT) and telecommunication industry. The IT and telecom unification brought about vendors, network operators/service providers, solution providers and businesses over a platform offering the plans, packages and/or products while promising an all Internet Protocol (IP) infrastructure. Network operators are intended to minimize the ownership cost while desiring the return on investment for infrastructure equipment. The management and control operations and procedures along with the real and virtual devices (routers, switches, nodes, devices with multiple interfaces, individual links etc.) should be service/infrastructure/content/context/cost aware with enough scalability.

Legacy network infrastructures and technologies cannot guarantee the desired Quality of Service (QoS), Quality of Experience (QoE) and performance requirements of the diverse services (e.g. voice/video and data services) all together as they need diverse resources with varying set of QoS parameters. Moreover the diversity of network control and management ecosystem due to the subsequently stated technology unification (i-e wireline and wireless) alongside distinctive vendors following different business model with proprietary solutions introduce more complexity. The main sources of the aforementioned complexity are: diverse services themselves, diverse equipment, heterogeneous transport technologies and protocols, distinctive vendors and proprietary standards etc. To overcome the underlying complexity and to master the technology heterogeneity and service unification, the infrastructure management and control procedures should glue all the differences in order to enable effective resource management and efficient control over the platform.

Business logic of a company is highly dependent on the service/application access,

their modification and delivery of new services/applications (e.g. triple-play services, cloud based services, quadruple services, conferencing application, VoIP applications etc.) over the platform. The problem with existing management and control systems is that they are not able to take into account the business rules of the infrastructure. However the systems considering the business rules cannot accommodate the change in the business model so denying the larger service portfolio while withholding operational and business rules dynamicity.
Most of the control and management functions over the converged infrastructures are governed/handled by entities which have to be configured/administered through several low-level procedures/processes; moreover the service and business logic configuration and administration is not aligned properly with the former procedures/process. Additionally the management and control entities within those environments are technology and/or vendor specific negating and/or making the multi service, multivendor and multi-domain goal difficult that has to target the multiple business objectives over the heterogeneous platform. Furthermore if the access control is provided by vendors A, the services/applications are offered by another vendor B and billing and control is outsourced to the third party over such converged architecture. Then change in business rules and service logic has to be propagated effectively and efficiently with the underlying multiple goals posing multiple criteria.
At the launch of the subject/project, the problem is targeted and focused on the routing of multimedia calls/sessions/requests at higher layer (i-e OSI and/or TCP/IP Application layer) at private-public network border over the infrastructure with access technology convergence at the underlying border. But the evolutionary process, the demands and the requirements of the partners and fruitful internal discussions/meetings turned the problem into a full-fledged framework for the proposed architecture. The routing problem at higher layers with different granularity (call/session/request routing rather than packet routing at network layer) is different from conventional QoS routing. The underlying routing problem has to take into account the conventional traffic classification/policing/tagging data (e.g. time of the day, profiles, priorities, authentications, authorizations etc.) in addition to the traffic engineering principles (regarding the external links that are linking the private world to public network) while sitting at the border of the platform. But the former and later network traffic management and control mechanisms are orthogonal. Moreover voice, video, triple-play/quadruple services have very diverse QoS constraints on delay, jitter, loss ratio, bandwidth, etc. in addition to the lower layer data propagated to the higher layer (application) posing a multi criteria problem while targeting multiple objective and goals. It is important here to mention that the framework deals with the dynamic call/session/request routing at higher layer keeping in view the first hop only as it does not deal with end-to-end routing problem.
The framework delivers higher control and management and enables the distinct vendors, multiple network operators/service providers, diverse solution providers and dis-

tinctive businesses to drive their corresponding functionality and processes over the heterogeneous and converged architecture with multi-homing support at private-public network border. The dynamic routing of multimedia calls/sessions/requests and their requirements over the framework while driving its design roots from Companym@ges[1] project goals and business rules over the multifaceted service, control, transport and access planes along with multiple objectives over the platform. A dynamic decision making framework for multi-homed infrastructure with convergence, unification and heterogeneity orientation resolves the routing decision making at the private-public network border on the basis of information from aforementioned planer information while posing a multi-criteria problem. In addition to Companym@ges project solution, the proposed framework can be deployed from small to medium businesses offering unified communication services and diverse application solutions. Moreover its simplified and lighter version can be embedded within the edge devices of the home users (A/S-DSL routers and gateways supporting multi-homing having two or more links from distinct providers). Moreover its most sophisticated decision making sub-framework with energy/power aware adaptation can be embedded within the handheld devices having more than one interfaces with diverse access technologies.

1.1.2 Requirements: Problem Statement

Dynamic decision-based management and control has emerged as a promising solution for the management of heterogeneous and converged networks with multi-homing support. The fundamental characteristics of such decision making frameworks is efficient and effective resource utilization over the infrastructure by bringing flexibility to the platform while accommodating the frequent variation by change management. The ultimate goal is to adapt the behavior dynamically without resetting/restarting/stopping the system by inheriting the corresponding intrinsic and extrinsic knowledge base from different domains/planes over the hybrid platform. This knowledge base along with business objectives of the platform and administrative configurations are exploited for policy (decision) computation. These decisions are meant to govern the behavior of the communication infrastructure by enforcing these decisions at different granularity (call/session/request) over the platform.
Policy/decision framework requires information model, semantics variations/behavioral fluctuations capturing mechanisms/tools, information sharing/dissemination and inter-communication procedure, protocols especially the signaling protocols for control and management data sharing at micro and macro level and the language over the infrastructure to represent the platform's rules, business objectives and administrative/configurational instructions in a standardized and understandable fashion over the converged

[1]The Companym@ages project is a FUI project, which ran between 2008 and 2010, and was led by Alcatel Lucent. The present work was partially funded by Companym@ages.

infrastructure. Moreover decision making in such an environment is not an easy task especially when dynamic modifications/variations have to be taken into account along side a set of information and conditional parameters from diverse management domains (service profile, reliability information, time of the day, business objectives of the company, latest state of the links, user profiles and Service Level Agreement (SLA) etc.). The situation becomes more complicated when distinctive services have different demands, some require high bandwidth and others need lower delay/packet loss; user requirements over the infrastructure are also divergent, some desire better user experience, some require security and the others focus on cost-Vs-quality.
Conventional decision making systems take into account the technology dependent and technology independent information (devices, interfaces, protocols, architecture, topology etc.) related to the network infrastructure while computing the decision. Application oriented data sets, corresponding attributes over service plane and the business objectives over the platform are not considered and/or they are taken into account partially. However the systems meditating the business objectives may not be able to capture the required granularity. The systems accommodating the services information have to be handled in an abstracted way regarding the service scalability and extensibility. Above all, the latest systems targeting the aforementioned issues might not be able to provide required dynamicity for effective and efficient control and management over such converged and hybrid communication system with multi-homing support. Furthermore Platform's multidisciplinary and multivariate information domains (planes/layers) are synchronized locally and asynchronous globally forming a Globally Asynchronous Locally Synchronous (GALS) system. The static and dynamic information (inter/intra- domain and cross planer/layer) over the unified platform are categorized as intrinsic and extrinsic regarding those distinct planes/domains while posing the multi criteria problem with multiple objectives. It is thus necessary to mitigate the cumulative multi-facet effects due to disparate diversity, myriad dimensionality with multiple goals within GALS multi-planer system. The information sources representing different domains (e.g. service, control, transport and network planes) might be highly structured and synchronized locally (inter-domain/plane) but may have higher probability of asynchronous and un-structured information representation globally (intra-domains/planes). QoS profile of the links, user authentication/authorization profiles, service variants/profiles, business objectives of the company, fluent dynamics over the multi-homed platform and traffic management issues at private-public network border constitutes a multidisciplinary problem. The information coming from different sources with different dimensions reflects the complexity of the underlying problem.
Conventional solutions to handle similar scenarios over such multi-homed converged environment are either user-centric or motivated for efficient resource utilization over the platform and/or they are centered towards application optimization for desired QoS and QoE. However to cope with user authentication/authorization profiles, business ob-

jectives of the company, reciprocal SLAs with rivalry providers, technology specific and technology independent information over converged platform, fluent dynamics over the multi-homed infrastructure and traffic management issues at private-public network border all-together, an efficient and effective decision system is required. Moreover, scalability, extensibility and performance of the underlying decision system must be taken into account even although the granularity over the Companym@ges proposed architecture deals with calls/sessions/requests rather than individual packets. This convergence at service, control, access/transport and network level require modification/addition and updating of multi-disciplinary data sets with multiple objectives. Diversity and dimensionality of the multifaceted goals along with multiple objectives over the platform require Multi Criteria Decision Making (MCDM) theory to address all the aforementioned issues while computing the decision routing decision at private-public network border.

1.1.3 Contribution: Contribution Taking Into Account the Different Modules/Entities Over the Framework

A dynamic decision making framework implementing multi criteria routing of multimedia services at private-public network border with access technology convergence while offering multi-homed infrastructure is presented. The ingredients of the framework incorporate from information model to semantics capturing, it embraces the representation of its communicational, behavioral and functional features and components, the control and management of the infrastructure is carried out by revamping the sole signaling protocols (e.g. SIP, diameter and SNMP) and finally the language over the platform gluing all the constructs and micro/macro rules/business objectives/administrative instructions over the platform as it is deeply rooted within the infrastructure. The modules/sub-modules and the components/sub-components, their inter-communication, the behavior of the former and the later elements and the inheritance/overloading/overriding of the corresponding concepts regarding the decision engine is developed and defined keeping in view decision computation and its enforcement. Layered approach is followed in order to exploit and map the planer and domain specific information regarding the MCDM theory. DEN-ng is enhanced and tagged in accordance with the requirements over the underlying framework. Rule/policy management and its specifications have strong correlations as it accommodates the change management and business processes by following the business logic of the company. Policy/rule specification approaches ranges from formal policy languages that can be directly processed by a computer, to rule-based policy notations/constructs, and to representation of policies as entries in a table consisting of multiple attributes. A rule specification language is developed having its roots within the framework making the rule specification native. Different MCDM methods are adapted over the platform to

accommodate dimensionality of the info, dynamicity over the platform, fluctuations of data sets (upper and lower bounds), contextual information and semantics variations respectively. Decision engine over this underlying unified communication framework has the ability of handing the private-public converged network border dynamic routing. Moreover the solution has the capability of handling the horizontal handover decisions without resetting/restating the system. MCDM theory is used for decision computation/calculation and the adapted methods are exploited according to the scenario and decision computation mode while keeping in view the corresponding enforcement mode. Weight computation within those MCDM methods is crucial as it identifies the relative importance of the underlying criteria. Weight computation of the corresponding criteria is applied and a scale is revised according to the requirement over the platform. Finally ontology is integrated with the adapted MCDM methods in order to capture the semantics variation over the platform.

1.2 Thesis Outline

Chapter 2 introduces the QoS models, their interaction with PBNM, QoS information sharing among devices via SIP, QoS mechanism devised for Companym@ges framework, presentation of LCR as a tuned and special case regarding QoS, PBNM and the requirements of PBNM framework and finally the related work is presented in consent with the ingredients of the proposed framework.
Chapter 3 describes the Companym@ges architecture, the modules and their interaction for the control and management over the proposed platform, the protocols and the inter-communication among planes/devices via the underlying tweaked protocols, decision making framework adapted over the proposed architecture, Companym@ges framework for unified communication, comparison of the proposed framework with renowned IMS and the justification of the choice, entities, components, modules and their inter/intra-communication within the Policy Server (PS) and Session Border Controller (SBC) regarding the decision making, choice of Diameter (an AAA protocol) along with its comparison with other signaling protocols in addition to rebuttal for selection and finally the revamping of SIP for the information sharing between Call Server (CS) and SBC is illustrated besides incoming and outgoing traffic handling.
Chapter 4 presents the Multi Criteria Decision Making (MCDM) in consent with the proposed framework, choice of the MCDM methods for the corresponding issues (dimensionality, dynamicity, inappropriateness regarding the attributes and semantics variations) and in the end the MCDM methods (WSM, WPM, TOPSIS, extended TOPSIS and GRA) application steps while illustrating a simple use-case over the proposed architecture is presented.
Chapter 5 outlines the decision engine's modular framework in consent with the MCDM theory, distinctive decision engine's modules functionality and their interaction regarding the decision computation, information models with their pro and cons and rebuttal

for the choice, rule specification languages and the approach followed to have one that should be deeply rooted inside the proposed framework, decision computation and management regarding the test bed for stress testing and finally the proposed framework is tested regarding the adapted MCDM methods in different enforcement modes in addition to online and offline decision computation for the proof of the concept. Moreover the tests are performed for handling the horizontal handover decision making in addition to evaluations of the proposed decision engine for MCDM theory and ontology integration. Chapter 6 includes the concluding remarks along with future work and finally the authors list of publications during the thesis are presented.

2

Background and Related Work

QoS specification and its management is important in multi-service networks over the converged infrastructure with heterogeneous environment having support for multi-homing while particularly provisioning the multimedia applications. The emergence of multi-interface portable devices, the advent of handheld gadgets, nomadic service/application access irrespective of access and transport technology and service convergence has brought about the time to control individual private networks in/out traffic for even small to medium businesses by using QoS procedures and mechanisms. Conventional QoS is usually coupled with quantifiable metrics related to bandwidth, delay, jitter, loss rate and so on. QoS accommodation includes declaring the service authentication/authorization/classes, control and management signaling, Connection Admission Control (CAC). These aforementioned procedures are implemented via conditioning, e.g. policing, shaping, or dropping; queue management; e.g. random early detection (RED), queue scheduling, e.g. Weighted Fair Queuing (WFQ); and link-layer mechanisms. QoS management and control complements the PBNM as they both are integral part over the underlying converged infrastructure in order to carry out the efficient and effective operations for the heterogeneous devices/technologies offering unified operations. Rule/decision-based network management and control governs the proper provisioning of resources in consent with platform's business objectives and infrastructure's administrative and conditional state. The corresponding SLAs with peer providers and reciprocal agreements with rivalry setups has to obeyed and administrative rules in coordination with business logic must be respected by keeping in view the QoS mechanisms and procedures that go hand in hand for dynamic management and control.

QoS is presented here keeping in view the reliability, predictability, timeliness, volume, criticality, cost and security etc. Technology specific and technology independent QoS characteristics regarding the aforementioned parameters are elaborated. Proposed PBNM framework is discussed focusing on voice video and data services. Static and dynamic QoS in conduction with PBNM is also presented. Key performance indicators regarding the voice, video and data services/applications are compared. QoS mechanisms (DiffServ and IntServ) are compared and discussed regarding the platform's

requirements and the requirement of the new QoS model is realized by elaborating an example. Policy/rule control is a variation of network management. Signaling protocols are crucial as the relevant information sharing between devices and end points utilizing the services is accommodated via these signaling protocols rather than the bearer and other transport protocols. SIP, being the sole signaling protocol over the proposed framework requires to be tweaked and enhanced for information sharing and exchange between corresponding devices. QoS mechanisms over the proposed infrastructure are adapted over corresponding layers representing the service/application plane unification with the control and management plane functions mappings alongside the access/transport convergence. Least Cost r Routing is presented as a special case of QoS but rather than the cost the criteria includes multidimensional metrics i-e; delay, jitter, loss rate etc. for routing at higher layers. PBNM is elaborated and the paradigm's requirements in consent with the framework are discussed at the end of this chapter.

2.1 QoS models and their connection with PBNM

QoS management and control mechanisms and Policy Based Network Management (PBNM) techniques work hand in hand and they complement each other. Network management is essential to guarantee the communication and services with required QoS. Policy based management has been the subject of extensive research over the last two decades. It has been focused in Next Generation Network (NGN) like 3GPP [1] and TISPAN [2]. PBNM becomes more complex when multiple criteria has to be handled targeting diverse objectives while merging different paradigms and technologies with unified control and management requirement. IETF has been investigating policy based networking as a means for managing IP-based multi-service networks with QoS guarantees. They have proposed a policy framework [3] for management, representation and control of policies in an independent and interoperable fashion

Quality of Service is a combination of two open words i-e Quality and Service. These distinctive words leave room for free interpretations. Quality is often used to illustrate a superior performance in terms of probability of data loss, minimal jitter, minimal network delay, efficient use of network resources; but quality can also be considered synonymous with reliability and predictability of the service. The term service on the other hand carries implicit ambiguity, it is used to describe the communication capabilities offered to the end user of a network, but in another context it could have other meanings, e.g. in a layered architecture it assumes a more specific definition. The most important categories of QoS parameters for most of the applications are: reliability, timeliness, volume, criticality, cost, perceived QoS, security etc.

Reliability illustrates a range of issues, including the Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), percentage time a service is available, and

loss or corruption rates, measured in frames per second, bits per frame or other appropriate units. Timeliness is described in terms of the experienced delay between stimulus and response including deadlines, and earliest acceptable result times, latency, and the variation in that delay, or jitter. These characteristics are usually measured in milliseconds for multimedia communications. Volume or bandwidth characteristics illustrate the amount of data passed per time unit. It may be measured in Mbits/sec, but it is often more appropriate to present volume in terms of the content, e.g. frames of video per second, or discrete operations of a type per second. Criticality describes the value or importance associated with an interaction, e.g. priorities and authorizations (gold user service/access profile authorizations and priorities). It can also be used to provide a hierarchy of available choices when resolving conflicting requests. Cost is a slightly different category than the others described, as it could be a function of both service class and QoS value. It is not an intrinsic part of the visible results of most transactions. Cost is generally described in terms of a monetary value per interaction, or in terms of the time spent interacting. It is often the case that cost will be used to place upper and lower limits on other characteristics. Multimedia communications, triple-play services quadruple applications entail the concept of QoS, where there may be a scale of performance which is acceptable, and the boundary between success and failure of the system may be blurred or varying [4, 5]. For instance, a video may still be acceptable if presented with a lower frame rate, or reduced resolution, but be unacceptable for viewing if there are pauses or gaps in the film. Delay variations during voice communication is difficult to handle even by declaring larger local buffers.
QoS is focused here keeping in view the technology, user, and services. These are some of the key entities over the proposed framework and have strong ties with QoS. Reliability timeliness, and volume are the technology-specific QoS characteristics. Technology convergence over the multi-homed architecture requires an elaboration of the technology specific parameters. Reliability includes Mean Time To Failure (MTTF), MTBF, MTTR and loss rate etc. More reliability, minimizes the connection setup time, and allows capacity management and engineering. Moreover the underlying technology specific characteristics might be further classified by defining routing reliability, connection reliability and service reliability attached with different quantifiers. Timeliness in the context of technology characteristics includes renowned and common QoS parameters e.g. delay, jitter and response time etc. [6]. Volume termed as bandwidth is measured in bits/second or bytes per second. Mathematical models linking throughout, delay, jitter and loss-rate are specified in‘ [7, 8]. The alternative links over the proposed architecture have upper bounds regarding the traffic volume and it can be specified while setting the router interfaces representing these alternative links. Reliability is correlated with the application/service as the codec used during the voice/video communication is used as an indicator for required/available bandwidth.
User-based QoS includes cost, criticality, security, perceived QoS etc. Usual costing of per unit time and/or per unit bit/byte is ignored as the granularity of the cost is supposed

to be call/session/request based charging. Criticality over the proposed architecture implies the priorities/importance assigned to a different user profiles (e.g. Gold profile, Silver Profile, Bronze Profile etc.). The underlying parameter is also assigned to different flows and calls (voice on a specific alternative link is critically prioritized than the video on the same link). Perceived QoS is extracted from the Call Detail Records (CDR) and the analysis of the Simple Network Management Protocol (SNMP) traps captured from the alternative links over the platform. Security characteristics from user perspective envision the authentications and access control mechanisms regarding the presented framework.

Companym@ges proposed framework accommodates data, voice and video services over the hybrid infrastructure. But multimedia services (voice and video) are emphasized due to their stringent QoS requirements and control. Voice is characterized by convincing QoS requirements regarding end-to-end delay, jitter and packet loss. But a voice stream can sustain over a bandwidth of 64 Kbps and even a more sophisticated encoder can reduce this requirements to few Kbps. Video communication on the other hand has different QoS and network resources requirements as compared to voice. The table 2.1 presents the QoS requirements of the traffic specifically the multimedia traffic. It in important here to mention that the parametric indicators e.g. delay, jitter, packet loss etc. might also be used to declare the Service Level Specifications (SLS). The same sets of parameters are exploited to gauge the QoS of a certain link over the multi-homed network with reference to the proposed infrastructure. Moreover the similar set of attributes with an addition or subtraction of one or more parameters might constitute the QoS requirements associated to a certain profile (e.g. Gold profile). So this multi facet representation with multiple criteria while targeting multiple objectives has to be resolved and it will be discussed in more details in next chapters and the problem is resolved by proposing a solution.

QoS management can be divided into static and dynamic mechanisms, but the management framework with dynamic approach is mostly emphasizing on a specific issue [9]. The research efforts for QoS provisioning in connection with PBNM has been initiated by the Internet Engineering Task Force (IETF). Lets forget the granularity for the moment while discussing the QoS management frameworks (as proposed framework works at call/session/request level granularity). Integrated Services (IntServ [10]), an extension to the traditional best effort model and Differentiated Services (DiffServ [11]), which works on the basis of behavior aggregate (BA) classification are the two QoS mechanisms proposed at IETF. IntServ achieves end-to-end service guarantee on per-flow resource reservation basis, while the DiffServ focuses on traffic aggregation and provides per class prioritization. IntServ suffers from well-known scalability problems caused by massive storage costs at routers while retaining flow state information. Moreover it relies on signaling messages exchanged between terminals periodically, hence QoS provisioning is not easy in high-speed networks on per session basis. DiffServ model can simply provide a coarse end-to-end QoS gran-

Service	Applications	Degree of Symmetry	Data Rate	Key performance parameters and target values				
				End-to-end one-way delay	Delay variation within a cell	Information loss	BER	Traffic
Voice	Conversational Voice	Two-way	4-25 kbits/s	< 150 ms preferred < 400 ms limit	< 1 ms	< 3%	10^-3	Continuous
Video	Videophone	Two-way	32-384 kbits/s	< 150 ms preferred < 400 ms limit Lip-synch: < 100 ms		< 1%	10^-6	Continuous
Data	Interactive Web	Two-way		< 250 ms	NA	Zero	10^-6	Bursty
Data	Telnet	Two-way (asymmetric)		< 250 ms	NA	Zero		Bursty

Table 2.1: Voice, Video and Data Services Key Performance Expectations/Indicators (Courtesy ITU).

ularity that may result in a low resource utilization. Real-time data flows in DiffServ network are mapped to Expedited Forwarding (EF). If a real-time flow requires 100 ms delay and another flow needs 500 ms delay bound and they both are mapped to the EF service then there will be wastage of resources by allocating better-than-required QoS. Defining more classes can solve the stated problem but the code-points might not be standardized on the public networks. The granularity of the defining new classes cannot be fixed, so we need dynamicity and flexibility to take variations in the single parameter into account. Additionally, inside an enterprise, it is desired to prioritize the multimedia traffic to/from some specific user profile along with prioritization on the basis of applications/services. But still there is not enough granularity either in user profile or in usage characterization [12]. During congestion, DiffServ networks with multiple accesses to Internet (or different SLAs) do not define any scheme to differentiate between priority packets. They use static Policy Based Routing (PBR) and usually specify that traffic sent from the particular sub-network should be forwarded out to an interface, in order to restrict interface usage for only pre-configured source/destination IP. The discussion here is restricted to the context of enterprises with multiple accesses/SLAs to Internet through one or more ISP(s) despite the fact that multiple attributes with multiple objectives in content with multiple criteria have to be addressed. In some cases restrictions on utilization or topology in DiffServ networks is difficult to accommodate; so a number of advanced architectures have been proposed for delay sensitive multimedia applications. A flexible solution to support DiffServ over Multi-Protocol Label Switching (MPLS) networks is presented in [13–15], but it could not overcome the fundamental problem of DiffServ because the traffic engineering function is orthogonal to conventional DiffServ function. So the tuning and integration of existing solutions for QoS management and control address certain issue but give birth to another problem.

2.2 QoS Information Sharing at device level using SIP

SIP [16] is a signaling protocol for establishing and tearing down real-time calls and conferences over IP network. The sessions may include different types of data e.g. audio and video though currently most of the SIP extensions target audio communication. SIP resembles the conventional text based protocols; e.g. HTTP (hyper text transfer protocol) and SMTP (simple mail transfer protocol). SIP uses session description protocol (SDP) for media description. SIP natively has basic client and server architecture. User agent (client/server), SIP proxy server, the SIP redirect server, Back-to-Back-User Agent (B2BUA) and the registrar are some of the main entities in the SIP architecture. SIP offer scalability due to its open standards and works irrespective of access technology and transport protocol.
SIP was designed to setup a "session" between two points and to be a modular, flex-

ible component of the Internet architecture. It uses SDP that contains useful information for negotiation between the end points (e.g. codec negotiated between end points to be used during the session). But it does not define mechanisms to share and exchange information between devices (e.g. between Call Server (CS) and Session Border Controller (SBC)). Companym@ges framework solely used SIP as the only signaling protocol over the platform. QoS management and control mechanism e.g. Call Admission Control (CAC) requires information sharing and exchange between aforementioned devices. The openness of underlying SIP protocol is exploited here while introducing new headers for relevant information sharing and exchange between corresponding devices. The need to disseminate and exchange information between CS to SBC, adopted mechanism, and more details are available in [17].

2.3 QoS mechanism Over Companym@ges Platform

The term QoS is misunderstood leaving room for its diverse definitions: e.g. increase or decrease in bandwidth speed; superior performance in terms of probability of data loss, minimal jitter, minimal network delay etc.; efficient use of network resources and sometimes it can also be considered synonymous with reliability and predictability of the service. To the context of the proposed framework, QoS rather is meant the characterized, comprehended and deterministic treatment of certain set of metrics and/or services and/or profiles and/or applications. Different application and services require different set of parametric QoS requirements as voice requires different QoS as compared to emergency voice call. This requires effective and efficient QoS mechanisms under the dictation of certain set of business and configurational rules over the platform, hence forming rule/decision/policy-based management and control framework.
With the convergence of wireline and wireless access networks towards common IP-based transport technologies, the need to provide unified control and management infrastructure while provisioning QoS enabled services is becoming crucial. The inadequacy of traditional best-effort model of the IP-based transport to meet QoS of real-time applications such as voice, video triple-play/quadruple services and other real-time multimedia applications is intended to be addressed by new IP QoS architectures. Companym@ges framework adopted layered approach due to convergence of heterogeneous access technologies, diverse network and transport plane along with unification at application and service planes. Fig. 2.1 illustrates the architectural layered approach and the corresponding QoS mechanisms over the heterogeneous infrastructure with service and application unification while supporting access technology convergence. QoS parameters and attributes defined before are extracted from these mechanisms and procedures at different planes/layers shown in Fig. 2.1. These QoS procedures might have overlapping and conflicting set of parameters with the neighboring layers and/or corresponding/cross layers depicting diverse goals at different layers.

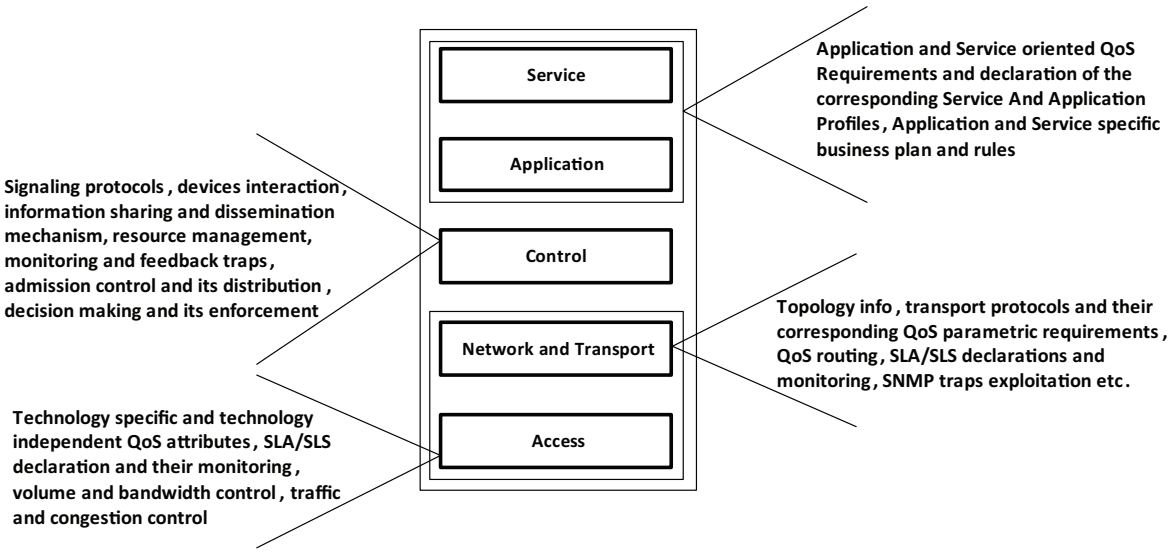

Figure 2.1: Infrastructure Layered Model and the Corresponding QoS Mechanisms.

As a matter of fact the underlying overlapping and/or multiple criteria with multiple goals arises due to the heterogeneity of the network, convergence of the technology requiring unified management and control plane functionalities in order to coordinate the converged transport infrastructure, adding to the complexity of QoS mechanisms and procedures.

2.4 Least Cost Routing as a Special Case of QoS

Least Cost Routing (LCR) is the process of analyzing, selecting, and directing the route of outbound communications traffic based on which path provides the most savings. It is thus optimized routing on the basis of cost natively. There are some mechanisms where cost is mingled with delay and other metrics to optimize the routing [18]. The authors in that work linearly combined delay, cost, and bandwidth metrics. The weights of these mentioned parameters are computed to find optimized route. This method involves computational complexities and does not suits if the LCR is being performed by talking into account more attributes at higher layers.
Conventional QoS routing is difficult due to several reasons. First, voice, video, triple-play/quadruple services have very diverse QoS constraints on delay, jitter, lose ratio, bandwidth, etc. Multiple constraints often make the routing problem intractable. In particular, finding the least-cost path with one path constraint or finding a feasible path with two independent path constraints is NP-complete. Second, converged networks is likely to carry both QoS traffic and best-effort traffic [19], which makes the issue of performance optimization a bit complicated. It is hard to determine the best operating

point for both sorts of traffic if their distributions are independent. Although there are mechanisms (resource reservation) by which the QoS traffic will not be affected, the throughput of the best-effort traffic will suffer if the overall traffic distribution is misjudged (an example illustrating a similar problem is quoted in 2.1). Third the network state changes dynamically due to transient load fluctuation, connections in and out, and links up and down. The growing network size makes it increasingly difficult to gather up-to-date state information in a dynamic environment, particularly when wireless communication is involved (VPNs, WiFi, etc). The performance of a QoS routing algorithm can be seriously degraded if the state information being used is outdated. The correlation of QoS mechanisms with LCR principles at the borders/edges in an enterprise is indispensable in this IP Multimedia Subsystem (IMS) era where access network technologies are integrated irrespective of the transport protocols providing unified communication while supporting multi-homed infrastructure.
Conventional LCR helps to optimize connections between telecommunication operators by minimizing costs for several demands and maximizing the operator income along with efficient use of the existing network infrastructure. This work address the generalization of LCR to Session Initiation Protocol (SIP) [16] based multimedia services enveloping a number of constraints (time of the day, profile priorities, service authorizations, business rules of the company etc.) and parameters (delay, jitter, loss rate, volume/bandwidth, etc.). The objective is to optimize the routing at higher layer (OSI application/service layer) while taking into account the aforementioned constraints and parameters while offering policy-based session/request/call management for multimedia communication, by using LCR principles at the network border point which provides public-private accesses to Internet through many Links/SLAs.

2.5 Policy/decision Framework Requirements

Before describing the Policy/decision framework, lets first elaborate the PBNM. It is a management paradigm that separates the rules governing the behavior of the system from its functionality and communication. So these three tears (behavior, functionality and communication) are constituents of the paradigm abstracting the management and control. PBNM promises lesser administrative and maintenance efforts while offering adaptability, reusability and flexibility. IMS adopted layered management approach while separating the service, control and transport planes in order to make network management and control easier while offering extensibility and scalability. Interfaces between the applications and the underplaying transport network are have been defined while offering efficient and dynamic rule-based management and control. This enables the delivery of carrier grade and QoS demanding services all together while using heterogeneous access and transport technologies. Multimedia and data communications networks are difficult to control and manage in the vicinity of the underlying PBNM. The business plan/model variations, technical diversity along

with the ambition to incorporate the best breed technology have resulted in increased complexity while requiring advanced/efficient management and control mechanisms. Information model embedding all the technology specific and technology independent; behavioral, functional and communicational data with all the intrinsic and extrinsic information over the platform is the basic building block of the policy framework. The information model does not have the capability to capture the dynamicity and behavioral semantics. So the information model has to be enriched with certain methodology in order to capture semantics variation and dynamics. The functional and communicational requirements are captured from the technology specific and technology independent knowledge along with the administrative rules and business objectives over the platform. The definition of policy model (e.g. ponder policy model to represent event, condition and action obligation rules) on the basis of information model while capturing the semantics variations in order to capture and govern the dynamic behavior is another step forward towards the framework development. Finally the extraction of a new policy language in order to represent the rules ultimately complete the policy/decision framework development.
Policy was originally described for access control of sensitive data [20]. Policies were firstly used by Moffett and Sloman for network management [21, 22]. The use of policy in network management attracted the community as it offered a solution to the management problem of large and heterogeneous networks [21, 23].

2.5.1 Policy Based Network Management (PBNM)

A policy based management system controls the state of the system and objects within the system using set of rules (policies) [23, 24]. The control paradigm used is based on finite state automata. The policy based management system is concerned with the installation, addition/modification and monitoring of policy rules, as well as ensuring the system operates in accordance to those policy rules. PBNM is in essence policy-based management as it is applied for network management and control. In such scenario the managed objects are networking devices, resources and services. Ultimately, the PBNM system is used to control the provision of services across a network in a predictable way. There are a number of terminology involved with policy based management [23, 24] that can be divided into two categories namely terms that describe a policy and terms that describe the management of those policies. The term policy and decision will be used from now onward interchangeably within the context of PBNM representing policy/decision. The decision computation and its enforcement is emphasized within Companym@ges framework for call routing at private-public network border of the company. The difference between the decision and policy lies in that the decision consists of a single rule to be applied (e.g. routing decision computation on the basis of multiple criteria with multiple attributes while targeting multiple goals, the single decisions thus may deals with individual calls/request/sessions and/or modules/devices etc. reflecting, dictating and/or enforcing the communication, func-

tionality and/or behavior locally). The policy on the other is a set of rules (more than one rules are defined as policy in our case; e.g. event condition action rules tuple constitute a policy, the policy however might also be used for control and management of corresponding entities having the global impact) that are used to manage and control the changing and/or maintaining the network resources (routers, links, gateways, border controllers etc.).

2.6 Related Work

Policy/decision framework requires information model, semantics variations / behavioral fluctuations capturing mechanism/tools, information sharing/dissemination and inter- communication procedure, protocols especially the signaling protocols for control and management data sharing at micro and macro level and the rule/policy specification system in order to stipulate the platform's business objectives and administrative / configurational instructions in a standardized and understandable manner over the converged infrastructure. The proposed framework encompasses all aforementioned ingredients required to built the dynamic decision making system. The related work however is discussed regarding the constituent building blocks (lying horizontally) of the decision system individually and the framework built by gluing all these building block to construct the framework (left hand side vertical unit). Fig. 2.2 illustrates the building block of the framework that are going to be focused regarding the related work as it motivates the development of the proposed framework. The

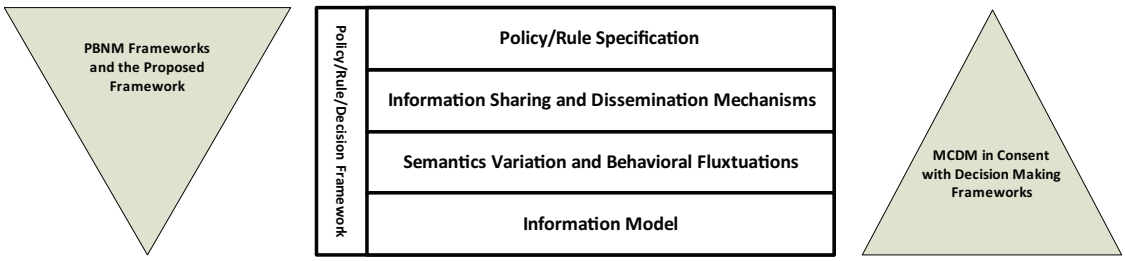

Figure 2.2: Infrastructure's Constituents Layered Building Blocks.

management of networked systems comprises all the measures necessary to ensure the effective and efficient operation of a system and its resources pursuant to an organization's goals [25]. Rule/Policy-Based Network Management (R/PBNM) is the ability of a network to provide an automatic response to network conditions according to predefined rules/policies and this approach appeases the network management and control involving the platform having heterogeneous combinations of resources, services and applications.

Management architectures also require information systems and functional imitation in order to model their communication and behavior respectively. The information model

defines the interaction between managed objects and sometimes is referred as management architecture. These information models are going to be discussed and presented in the context of Decision/Policy/Rule Based Management and Control Frameworks respectively that share the concepts of information model. Simple Network Management Protocol (SNMP) [25–28], an application layer protocol is still widely accepted and used for the management of network and devices. It uses Management Information Base (MIB) [29,30] that in turn uses Structure of Management Information (SMI), the group of standards developed by the IETF. MIB used Object Identifiers (OIDs) to record the hierarchical object information without object-oriented principles. OIDs uniquely identify managed objects in a MIB hierarchy. It has a hierarchical structure having static and fixed schema. There are two types of MIBs: scalar and tabular. Scalar objects define a single object instance whereas tabular objects define multiple related object instances grouped in MIB tables. Despite its legacy, MIB is still being utilized within management and control systems [31–33]

The MIB however does not comply with the information model required to accommodate the dynamic variations and fluctuations over the diverse planes and distinctive information domains. Moreover it describes the data objects to be managed by an agent within a device. MIBs are actually just text files, and values of MIB data objects are the topic of conversation between managers and agents. So one of the objectives to abstract the complex low level management and control is not going to be fulfilled by using MIB. Furthermore it has to be used with SNMP that lacks the division of public and private management data, which introduces interoperability problems by allowing different vendor-specific definitions of the same data in addition to its incapability of semantics and behavioral representation of network elements. However SNMP traps over the platform are exploited for probing the external links profiles.

CIM is a comprehensive set of object-oriented models that specify concepts about a computing or network environment; it comprises a core model that defines a basic classification of elements and associations for a managed environment (e.g., logical and physical elements, capabilities, settings and profiles) as well as common models that define concepts that are common to particular management areas (e.g., applications, systems, devices and policies) [34]. The core and common models together are referred to as the CIM Schema. It is designed to model computing systems in an enterprise environment but it is evolved now to be utilized for systems and network management.

CIM supports virtualization and it is introduced to the core specification via virtual system management capabilities and virtual system management service. It is basically designed to manage desktop computing environments. It is morphed into a Data Model that allows specifying distributed computing environments. Hence, the CIM model has a system view that impacts the definition of its entities. The network specifications and concepts are difficult to understand due to complex schema and terminology. It has two parts: the Visio UML-like graphical representation of the model and the Distributed

Management Task Force (DMTF)- Managed Object Format (MOF) textual specifications. It is thus a blend of information model and data model. CIM has its application roots in Energy Management Systems (EMS) to encompass distribution, markets, planning and systems integration but its evolution has led the model to an increased usage and adoption e.g. system planning, dynamic models, asset management, computer network management and control [35–37].
The mix of conceptual entities and their instances in CIM results in difficulties to understand the conceptual semantics independently of instantiation details that are related to a specific domain or platform. CIM does not support specifications for substantial network concepts e.g. separation physical of physical and logical interfaces, diverse QoS models and templates for network element classes (i-e routers, bridges, gateways etc.). CIM schema defines the models necessary for inferring properties about distributed systems, its specification as a semi-formal ontology [38] limits its ability to support important requirements of a dynamic decision making system including knowledge interoperability, knowledge aggregation and reasoning. Furthermore it is difficult to model the business logic and service layer with such a schema interpreting the low level functions and behaviors.
Shared Information and Data Model (SID), is standardized by the TeleManagement Forum (TMF) [39] and is starting to be standardized by ITU-T in Study Group 4 (SG4). The SID is part of the New Generation Operations Systems and Software (NGOSS) program and thus closely linked to the TMF's architecture and business modeling (enhanced Telecom Operations Map (eTOM)). It is considered a federated model deriving very substantively from DEN-ng model that in turn absorbed from DEN, DMTF and IETF models. SID, an object oriented model that uses UML to define entities and to define the relationships between them, as well as the attributes and processes that make up the entity or object. The information model as a framework, provides an information/data reference model and a common information/data vocabulary from a business as well as a systems perspective.
SID defines domains and entities on several levels of detail. It enables the design of services and network resources in conjunction with products and customers, thus providing the necessary associations to link all resources to business activities. It can also be used as a toolkit that allows modelers to adapt and select what they need to model specific applications. Most of the technical specifications of the model are contained in their own domain-specific [40] thus augmenting the policy framework. SID, however, is limited with regard to modeling dynamic environments due to its inflexibility compared to other information models (e.g. DEN-ng). Moreover business to network translation and vice versa is not realized in phenomenal and concrete form. Additionally the context is missing which is important from the Comanym@ges viewpoint. Furthermore, SID does not have the capability to model the behavior. Despite its inconsistent behavior regarding the proposed framework, SID is still in business with certain limitations and adaptations [41–43].

An information model is defined as a "representation of the characteristics and behavior of a component or system independent of vendor, platform, language and repository [44,45]. Conversely, a data model as defined in [46] is a lower level of abstraction and includes many details. Directory Enabled Network-next generation (DEN-ng), an object oriented information model is designed to represent the management information of large scale communications networks, from a business and system perspective (e.g. DEN-ng can represent information pertaining to a customer of an ISP service and its billing information and can also represent the services and resources required to enable the provision of the service within a communications network) [47]. It is built on two important concepts: patterns and roles in addition to its capability to use patterns. Similar to the SID, DEN-ng is designed as a toolkit, making it possible to derive domain-specific information and data models by means of selecting an appropriate set of features and extending them for a given domain. The DEN-ng is fully UML compliant and so can be used to automate the generation of management interfaces (via Model Driven Development (MDD) and Model Driven Architecture (MDA)) to the services and resources of the network, and therefore can be made compatible with all existing management technologies. The components of the DEN-ng information model describe the relationships and attributes of common business to networking entities. It describes concepts related to products, services, customers down to routing protocols and QoS services [48].
The SID and DEN-ng have diverged in recent past as DEN-ng is focusing more in communications network management, while the SID on the other hand emphasizing on the business orientation regarding the management and control. DEN-ng information model decouples the definition and design of services from the resources available over the network. Moreover it is a context aware model while supporting behavioral definition and orchestration. Furthermore it provides multiple abstractions and mapping among functionalities. These all features deemed appropriate to choose it for the Commapym@ges infrastructure with enhancement and adaptation.
The information sources over the corresponding layers shown in Fig. 2.1 (i-e. application, service, control, network/transport and access) might be highly structured and synchronized locally regarding the corresponding planes and/or domains (i-e. inter-domain/plane) but may have higher probability of asynchronous and un-structured information representation globally (intra-domains/planes). These highly dynamic, multidisciplinary and multivariate information domains (planes/layers) which are synchronized locally and asynchronous globally are behaving as GALS (Globally Asynchronous Locally Synchronous) system(s). Inter and intra domain/planer relationships between classes and/or instances within/over these GALS system(s) and the semantics among them are captured by using ontology.
Ontology has its significance in the filed of philosophy for a number of decades. Ontology use has exploded within the realm of computing particularly in fields of Artificial Intelligence, Agent-Based computing and more specifically the semantic Web

(WWW). The Semantic Web aims to revolutionize the Web by assigning explicit meaning to textual information to enable machines to automatically process and integrate information in a way not currently possible using plain text. Ontology can share vocabularies. It is defined as an explicit specification of a conceptualization [49]. It contains object types or concepts, properties and relationships. Ontology has some concepts in specific domain and its formal expression for their relationships. Generally, ontology has inference function aim at some properties of domain or to define the domain. In addition to ontology's native exploitation of inter and intra domain/plane knowledge representation while capturing the semantics while accommodating the variations and dynamic over the unified infrastructure. Ontology with inference engine configured with specific set of axioms is used for semantic matching between criteria for the application of MCDM theory.

Ontologies are used for the proposed infrastructure in combination with Multi Criteria Decision Making (MCDM) theory. MCDM helps in achieving the multiple objectives on the basis of multi-disciplinary information domains from distinctive planes/layers. The ontology, on the other hand, overcomes the semantic matching and reasoning issues using conventional object-oriented techniques with the help of inference engine [50, 51]. Ontology [52–54] and MCDM [55–59] is being utilized individually and independently for rule-based network management and control and dynamic decision making on the basis of multiple criteria respectively. To the best of our knowledge, [60–63] are the sole reported works that uses MCDM in coordination with ontology but in different domains (Health Care System, Decision Support System, Automotive System and the only exception where an automatic service composition algorithm is devised for globally optimized composite services with true and desired QoS respectively) rather than rule-based dynamic network management.

Companym@ges Framework addresses the multimedia traffic routing problem at private-public border network by taking into account all the variations and fluctuations over the converged platform. There are commercial and proprietary solutions available for multimedia traffic management while addressing the routing at higher layers (above OSI transport layer). Publicly available information does not reveal the decision-making mechanism and the LB algorithms. The core design and lower-level functionality are hidden because of commercial implications. However some vendors provide Software Development Kit (SDK) for customization of the specific solution with limited interaction and access to the core [64, 65]. Some products offer partial dynamicity with limited controls, while others are enforcing static decisions/rules. F5 networks [66] uses NAT for Load Balancing the SIP traffic to multiple links with static configurations. The proposed solution in this work accommodates the dynamic behavior of the platform and the context with the provision of decision enforcement mode choice in addition to the decision computation mode flexibility (online and off-line) by integrating MCDM theory and ontology.

Information sharing and dissemination mechanisms over the platform reflect the inter-

communicational aspect of the framework. These information sharing techniques and communication mechanisms are discussed here from the signaling viewpoint irrespective of the bearer and/or transport technologies, as the decisions computation and its enforcement over the proposed framework exploits aforementioned communicational techniques to get the relevant information regarding the context of the request/call/session and/or the latest dump of the platform. SIP, the main signaling protocol over the platform in being used and adopted protocol for multimedia communications [67–69]. It provides mechanisms and techniques for the creation, modification and termination of service sessions independently of the underlying data-link layer technologies and transport protocols. But it does not define mechanisms to share and exchange information between devices (e.g. between CS and SBC). Over the Companym@ges infrastructure, QoS management and control mechanism e.g. Call Admission Control (CAC) requires information sharing and exchange among devices. The native open architecture of the SIP protocol is exploited here while introducing new headers for relevant information sharing and exchange between corresponding devices. The need to disseminate and exchange information between CS to SBC, adopted mechanism, and more details are available in [17].
Diameter, a protocol with its native Authentication, Authorization and Accounting (AAA) functionality is used over IMS. Its AAA characteristics along with its enhancement orientations are becoming natural for decision-based network management [70, 71]. It supports large AVP space and reinforce large number of pending requests. Diameter is chosen for the underlying Companym@ges platform as it is intended to provide an Authentication, Authorization and Accounting (AAA) framework for diverse networks applications, distinctive multimedia services with unified control and management infrastructure while supporting the access technology convergence with multi-homing support.
Policy/Rule specification and representation should be deeply rooted within the infrastructure in order to avoid conflicts that ultimately leads to an effective, efficient and understandable inter-communication of instructions, commands, triggers and constructs among domains, planes and devices. But the premise of effective PBNM lies in unified policy description, specification and representation. To date there is neither the standard mechanism for management nor the rule/policies specification system for rule/policy specification. In [72] authors used models to specify Event-Condition-Action (ECA) policies at different levels of abstraction and consequently separate domain and policy aspects from each other. But the domain specific information is exploited by linking model while focusing on ECA tuple restricting the rule/policy representation. Author defines a flexible number of abstraction layers as the Policy Continuum [23]. Management rules and policies are defined at each layer of aforementioned policy Continuum by following domain specific terminology and are refined from business layer down to the technical level. But the emphasis there is on autonomic networking that is not desired regarding the focus of the presented work.

Each policy language has its own syntax and semantics and is connected to different building blocks constituting a policy framework enriched strongly with policy specifications and management mechanism. Three renowned policy languages that are used widely are discussed and compared with the corresponding pros and cons keeping in view the requirements of the presented platform in section 5.3.
Network Management and control is becoming more crucial as operators move towards converged wired and wireless IP-based networks. Conventional IP networks are supposed to be inadequate in order to meet the QoS requirements of the diverse services over the unified platform. The operators and service providers thus are migrating from legacy infrastructures to an all IP technology. The underlying all IP solution is thus becoming the cornerstone around which various access and transport technologies are converging with service unification. Moreover the conventional QoS service provisioning mechanisms are not sufficient to meet the QoS requirements of multimedia, triple-play and quadruple services over the these heterogeneous environments with multi-homed infrastructure. Policy-Based Network Management (PBNM) rather dynamic PBNM and control is emerging and materializing as an effective and important discipline to address the aforementioned issues.
Policy/Rule based management and control frameworks and architectures have been characterized by distinctive forums and standard bodies (i-e IMS by 3GPP, ITU and ETSI, Autol by EU FP7 IST, FOCALE etc.) [48,73,74]. IMS generates lot of signaling and control traffic due to its inherited and native layering, control interfaces information sharing and functionality at a fine granularity in addition to charging and accounting controls integration with other interfaces. Companym@ges can avoid this massive signaling and control traffic as sub-project MONA works at different granularity (i-e. call, session and/or request level rather than individual packets). Furthermore it deals with charging and cost at different level i-e the cost is represented/computed by counting the number of calls/request/sessions in/out and/or the total volume is accounted for rather than the monetary cost. Moreover the focus of MONA is at private-public border multimedia traffic management but IMS is adopted in the core of NGN while separating the control and bearer planes. Autol realizes the autonomic management architecture for the Internet, while aiming to develop a self-managing virtual resource overlay that can span across heterogeneous networks and supports service mobility, security, quality of service and reliability. Autonomic management and control requires closed loop and feedback mechanisms. But Companym@ges infrastructure deals with the multimedia traffic management issues at company's border while focusing on the first hop but not the end-to-end control, management and QoS issues. FOCALE isolate the operational and business support systems. It defines flexible number of abstraction layers as the Policy Continuum [23]. Management rules and policies are defined at each layer in consent with policy Continuum by following domain specific terminology. These rules are refined from business layer down to the technical level. FOCALE presents a complete framework for network management and control but again it deals

with the autonomic networking. However the proposed framework accommodates the dynamic decision making at private-public network border with access technology convergence over the multi-homed infrastructure. The decisions are computed by taking into all the technology dependent and technology independent attributes along with business logic and administrative rules over the platform. The underlying decisions are enforced in order to accommodate the routing at higher layer (i-e. application layer; the conventional terminology LCR is used within the document but in addition to its native parameter, cost, LCR principle is generalized to SIP based multimedia traffic routing while taking delay, jitter, loss rate, volume/bandwidth and other attributes into account). In addition to the dynamic call routing at the border, the system has the ability of handling the horizontal handover decisions without resetting/restating the system.

2.7 Summary

This chapter includes the conventional QoS models and their limitations regarding the proposed framework. The QoS is then discussed in connection with PBNM keeping in view the variations and fluctuations in consent with certain set of metrics. The QoS requirements for data and multimedia differ a lot, so to use the resources over the platform effectively and efficiently; the later and former services are discussed within the bounds to attain certain QoS. Key indicators regarding the important parameters are presented and compared for voice, video and data communications. SIP modification for information sharing and dissemination at device level is described. QoS mechanism over different layers for Companym@ges framework representing the corresponding service, application, control, network/transport and access planes are presented. Least Cost Routing is outlined as a special case of QoS but taking into account multimedia communication sensitive parameters (e.g. delay, jitter, loss rate etc.) in addition to the cost. Requirement of PBNM and ingredients of PBNM framework are discussed in consent with proposed framework. Finally the state of the art keeping in view the proposed framework in presented.

3

Companym@ges Policy Based Network Management (PBNM)

3.1 Companym@ges Framework

COMPANIES nowadays are approaching towards an all Internet Protocol (IP) paradigm by subscribing different access technology links from several service providers for reliability, redundancy and availability while providing good Quality of Service (QoS). Diversity and dimensionality of the company's service, control, transport and network planes along with multiple objectives over the multi-homed platform brings forth the challenge of devising a framework for such converged hybrid infrastructure. Unified Communication over such a platform promises an IP solution. Access technology convergence with heterogeneous network infrastructure, service unification, applications convergence with centralized control and management procedures are the main driving forces for stepping forward towards this unification and an all IP goal. The convergence of voice, video and data services onto the company's network demands that the underlying infrastructure deliver high performance with resilience. Moreover, the infrastructure must provide effective QoS to ensure that latency sensitive traffic (e.g. multimedia traffic) is getting enough resources it requires even in the face of congestion. This is what is targeted in one of the modules in Company@ges project. It integrates different services, binds versatile control interfaces, combines a number of signaling, control, access and transport protocols in addition to unification of access technologies. Companies providing diverse services over the platform are linked to the rest of the world via different network accesses (links) and users of the platform may even access the services in a nomadic manner. It is therefore necessary to enable the company to implement policy rules for optimizing the utilization of its different access links while targeting the private-public network border traffic management issues. Proliferation of diverse networks and services providers (heterogeneity of networks and increasing number of services, vulnerabilities etc.) highlights the imperative role of traffic management and control issues at private-public network border. Convergence, unification and heterogeneity orientation of the multifaceted planes (service, network,

transport etc.) along with multiple objectives over the platform require dynamic management and control.
Today's business model expedites companies that are linked to the public network (Internet) via diverse accesses with multi-homing support. The users over such platform therefore must have to choose an appropriate access (link) for services access. It is therefore necessary to enable the company to implement policy rules for optimizing the utilization of its different access links. The goal of MONA, a subproject of Companym@ges, is to manage all the issues related to traffic management at private-public network border of the company. MONA is in charge of enforcing security for all the network traffic at the network's border. For data traffic, it is done by a firewall. For multimedia traffic, the Session Border Controller (SBC) equipment that is a key element in IP multimedia architectures does it. MONA is also in-charge of controlling the routing of multimedia flows/requests/calls over the available network accesses.
Network Management and control has always been a challenging task over such multi-homed and converged environments with heterogeneous infrastructure. Traffic mix, heterogeneous wireline/wireless access technology, fixed-to-mobile and vice versa convergence difficulties, versatile data representation, diverse QoS requirements and variations/dynamics over the network are some of the main complexities involved for network administration and control. A dynamic decision making framework for multi-homed infrastructure with access technology convergence, service unification, heterogeneous with multi-homing support is required to address the traffic control and management issues at private-public network border effective and efficient resource utilization offering good QoS and Quality of Experience (QoE). These subsequently mentioned issues are addressed by proposing a network management framework while taking all the variations and fluctuations into account over the infrastructure. An architecture is proposed in consent with the underlying framework while supporting the dynamic decision making resulting in an effective and efficient resource utilization.

3.1.1 Proposed Architecture and Decision Making Framework Requirements

The QoS-centered architecture shown in Fig. 3.1 provides a cost effective unified communication platform offering versatile access technology convergence while highlighting network traffic unification framework emphasizing private-public network border traffic management issues. It integrates devices and modules from different vendors over a single platform while offering diverse services for public and private (local) networks. The global objective is the accommodation of dynamic modifications/variations into the policy-computation (decision-making) criteria for control and management of a multi-homed platform by using enhanced general methods/techniques and protocols. Service, control, network/transport and routing issues posing a multi-criteria problem are handled together without affecting the standard

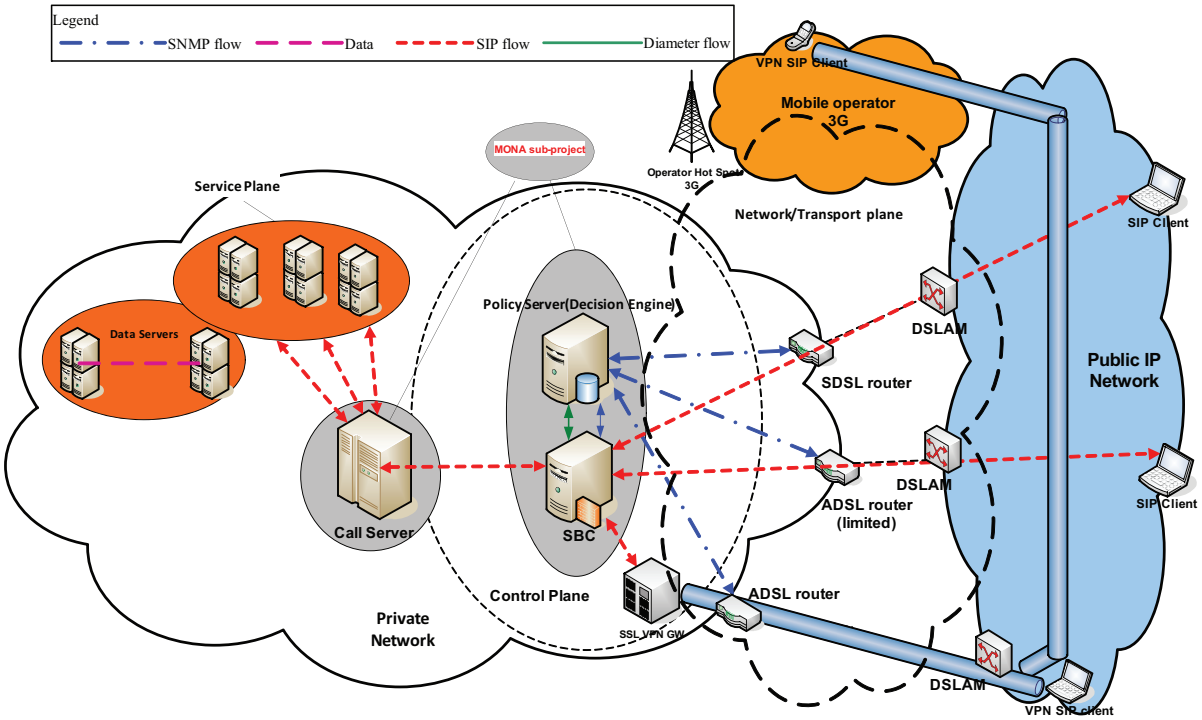

Figure 3.1: Companym@ges Proposed Architecture

mechanisms and classical layered approach. The underlying platform stems from multi-homed competitivity cluster with technology convergence especially at the private-public network border for handling dynamic routing (at higher layers e.g. session and/or application layer routing) in either direction (inbound and outbound traffic) and network management and control issues over the framework. Application Servers (AS); constituting the service plane and Call Server (CS), Session Border Controller (SBC), Policy Server (PS); forming the control plane and wireline/wireless access technology convergence at the private-public network border incorporating the network/transport plane are the main building blocks of the proposed architecture for MONA (Module to Optimize Network Accesses) sub-project.

CS is an important component of IP based PBX/Softswitch. It may also support proxy, registrar, redirect and location services. Most of the CS solutions are proprietary and support wide range of services. CS here provide registration, user profile management, service control and user profile Call/Connection Admission Control (CAC) functionality. CS is connected directly to SBC and they communicate via SIP protocol. There is no direct communication between CS and PS and it is declared as one of evolutions in the project to split and manage the profile and resource/service related policy controls (CAC) directly at two distinct places i-e. CS and SBC respectively. CS is modified to

handle the user profile based CAC functionality.
SBC is another key module of the proposed architecture. It is a session aware device. The primary functionality of the SBC is Network Address and Port Address Translations (NAT/PAT) and firewall traversal. The term SBC is not specific since its functionalities are not yet standardized or defined anywhere [75]. SBC provides a variety of functions to enable or enhance session based multimedia services (e.g. Voice over IP (VoIP)). The main functions of SBC are: Perimeter defense (access control, topology hiding, DOS prevention and detection), functionality not supported at the end points (protocol interwork, media repair) and network management (traffic monitoring, shaping and QoS). SBC can handle both signaling and media depending upon its functionality and deployment. SBC over the proposed platform also embeds: a SIP/SDP (Session Description Protocol [76]) analyzer, a communicator function (used for policy/decision and information exchange between PS and SBC), network QoS monitoring and the policy/decision enforcement module. In addition to the functionalities mentioned subsequently, SBC is tweaked to act as a Local Policy Decision Point (LPDP) to support provisioning mode policy/decision enforcement.
PS is the core module in proposed architecture. Policy based management system is emerging as the promising technology to address the challenging tasks in the converged Next Generation Network (NGN) [77]. IETF policy framework terminology and concepts has been adopted and extended to formulate an enhanced framework capable of taking into account high variability and dynamicity. A Policy/decision-making framework keeping in view integrity and compatibility is proposed over the underlying architecture. Conventional policy based systems do not allow dynamic control, management and extensibility [78, 79]. Although some policy based systems have been proposed for managing telecommunication and enterprise network services [80, 81], but those systems were specifically designed for a certain set of services and environments with limited dynamicity. A policy/decision-system is proposed here in this work that supports converged network services with dynamicity emphasizing on access network optimization. PS being an intelligent and key player in the architecture formulates the brain of the framework. It has to obey the Service Level Agreements (SLA) and reciprocal agreements with peer providers. The business objectives of the enterprise must be fulfilled while the users and applications should get assured QoS. The system also address the access optimization by taking into account the information narrated along with routing rules and configurations entered by the administrator. In order to provide required QoS for multimedia services, PS provides a decision for every request by considering static information and dynamic information (e.g. time of day, context of the external links, Statistical analysis of QoS information or Call Details Records (CDRs), etc.).
The policy system supports multi-service and multi-vendor environment having diverse technology convergence with high variability while isolating the service, control and network/transport planes. The decoupling of three planes leads to distribute CAC

functionality into profile and resource related functions being carried out at two distinct points; CS and SBC respectively. The policy/decision computation takes SLAs, business objectives, routing rules, services information, QoS of the accesses (links) and profiles into account. The SNMP [78] flows presented in figure 3.1 are used by the policy server to gauge the QoS of the external links by performing statistical analysis on captured metrics (delay, packet loss etc). Further description of the PS and its behavior is explained in the section 3.1.3. Moreover detailed information about the PS framework, the functionality and its behavior alongside the information required for dynamic policy/decision-based control and management is available in chapter 5. The protocol chosen to communicate the information/decisions between PS and SBC is Diameter [82–84] with newly defined and developed Attribute Value Pairs (AVPs). Diameter is natively an Authentication Authorization Accounting (AAA) protocol. Due to its AAA characteristics, its enhancement orientations are becoming natural for decision-based network management. It has large AVP space and supports large number of pending requests.

Legacy network management/control techniques and technologies cannot guarantee the required QoS and desired QoE requirements for voice/video and data services (FTP, Web, Mail) all together as they need diverse resources with varying set of QoS parameters. Service, control and network information are to be shared within those distinct domains and across these planes for network management. The attributes and parameters related to resources, profiles, services and dynamics taking place over those planes are disseminated and exchanged via different interfaces and protocols. The information sharing and exploitation process becomes more delicate when its control and management has to be performed under the dictation of certain set of pre-configured rules and business objectives. Fig. 3.2 illustrates the separation of multimedia and data traffic from architectural view point over the converged infrastructure. It allows multimedia service providers, carriers, operators, Internet Service Provider (ISPs), and emerging transport/ network operators to unify voice, video, data, triple-play and quadruple services over a single platform with diverse resource and QoS requirements. The business, technical, functional and operational procedures/phenomenon over the hybrid architecture demands a global solution merging the access/transport/network planes horizontally manipulating the layered planes (application, service, control etc.) vertically while sharing/disseminating the inter and intra domain information for dynamic network management and control issues. This led us to investigate and devise a hybrid decision-making framework. The convergence of voice, video and data services onto the company's network requires that the underlying infrastructure deliver high performance with resilience. Fig. 3.2 integrates multimedia, triple-play, quadruple and data services all together over the platform. These services are being offered by different service providers requiring diverse resources with varying set of QoS parameters. Data servers offer conventional web (HTTP, streaming HTTP), FTP and mailing services (irrespective of access protocols and technology) over the normative unified

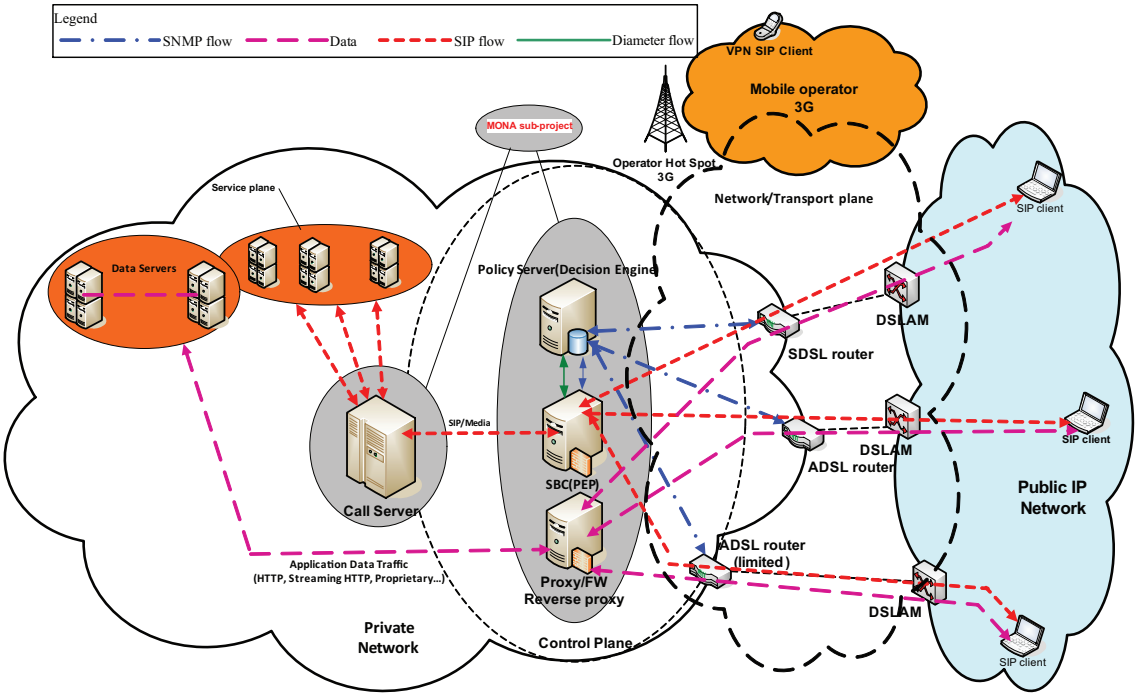

Figure 3.2: Data and Multimedia Traffic Convergence Within Companym@ges Proposed Architecture

architecture. After the introduction of the architecture regarding the multimedia and data services, the service, control and network/transport planes isolation and their interaction and the protocols exploitation over the platform, lets have an illustration of the inter/intra-domain and inter/intra-planer dynamism, information fluctuations over the infrastructure, decision making framework requirement to capture these variations over the platform along with the state of the art in the underlying area.

3.1.1.1 Dynamic Decision Making Framework

Network management and control is becoming more complex requiring more CAPital EXpenditure (CAPEX) and OPeration EXpenditure (OPEX) with increased human interaction and intervention as the operators move towards an all IP infrastructures while converging the wireline/wireless access/core/transport networks. This paradigm shift requires effective and scalable control and management solutions to address the complexity introduced by their heterogeneity diversity and dimensionality. Dynamic network management enables emerging access technologies to be agnostic to transport plane allowing applications/services to work independently. It equips networks with an ability to provide an automatic response to network conditions according to pre-defined set of business rules and policies actively and in a reactive

fashion. There are growing number of research and development efforts [85, 86] targeted towards policy-based control and management architectures to meet the challenges imposed by hybrid and converged infrastructure. (e.g. Telecoms and Internet Converged Services and Protocols for Advanced Networks (TISPAN) technical committee of the European Telecommunications Standards Institute (ETSI) [87], Third Generation Partnership Project (3GPP) [88] and the Internet Engineering Task Force (IETF) [89]. These architectures define functional blocks, interfaces and protocols that allow for interoperability between devices/interfaces from different vendors. 3GPP and TISPAN architectures share some similarities in the employment of policy decision entities that act as policy servers for the policy enforcement points in the transport plane. TISPAN defines a Service based Policy Decision Function (SPDF) as part of its Resource and Admission Control Subsystem (RACS) while one of 3GPP's policy framework defines a Policy Decision Function (PDF). These architectures indeed are aligned with the IETF policy based model which specified: a Policy Decision Point (PDP), Policy Enforcement Point (PEP), central policy repository, and the policy management tool [90]. Companym@ges sub-project architecture follows similar naming convention with some of the IETF native functionality inherited along with newly add-on functions and tweaking accordingly.

Vendor specific functionality, enterprise oriented business goals, dynamic variations in service attributes, distributed application development and wired-wireless network convergence have raised the complexity and concerns requiring new technologies and paradigms for rule based network management. Conventional network management techniques [91–93] deal with the device level control/configuration and/or are centered for specific goals (e.g. security, traffic classes, QoS etc.) while focusing on technical and operational aspects of devices (routers, switches, gateways, domain controllers etc.). There are hardly any links between business objectives, service requirements, network resources and embedded set of rules. The static abstracted relationships among the aforementioned information domains even increase the complexity and become almost impossible to manage for possible operational scenarios over such multi-homed and converged communication systems. Traditionally, these systems have been centrally controlled, deployed and accessed. Such paradigms are inflexible, as exclusively the service provider or administrators of the system possess centralized customization/addition/modification. Rules have emerged as a method of controlling such converged networks, providing sophisticated management, but allowing static or partially dynamic control without extensibility. A dynamic rule based framework with scalability and extensibility support for multi-homed hybrid network management is required to cope with the mentioned challenges. Information representation that is rooted in information model and in turn is correlated with policy model must be expressly constructed for capturing dynamism. An existing and already developed information model is adapted and tagged for the posed problem.

Layered information representation and sharing is adopted within the architecture shown

in Fig. 3.1. Application, control and network information are to be shared within those distinct domains and across these planes for network management. The attributes and parameters related to resources, profiles, services and dynamics taking place over those planes are disseminated and exchanged via different interfaces and protocols. The information sharing and exploitation process becomes more delicate when its control and management has to be performed under the dictation of certain set of pre-configured business objectives and rules. There are some frameworks [78, 79, 94] for rule-based management and control but they are static and/or semi-dynamic and are limited to device level configuration and control with different granularity. Moreover, in heterogeneous unified communication systems, there are vendor-specific concepts and implementation dependencies with different means of information representation and processing. These systems take into account a few information among the set of available parameters over the platform, while computing the rules (service profile, reliability information, time of the day, business objectives of the company, latest state of the links, user profiles and Service Level Agreement (SLA)) e.g. SLA management in Diffserv enabled environments, DiffServ over Multi-protocol Label Switching (MPLS). Moreover, a system capable of taking into account Service Level Specifications (SLS), e.g. susceptible delay, jitter and packet loss may not accommodate the technology specific information. Systems considering user, service and QoS profiles do not compensate for dynamic context of the request.
The information stated above for rule-based network management and control comes from different sources with different dimensions, hence formulating a multi-faceted problem. The first challenge is to utilize the available information over the platform maximally so that the network management reflects dynamic control and effective resource utilization with good QoS and QoE. Moreover, the objective is to capture the variations and dynamics over the platform that requires semantics diversity capturing among these distinct domains (inter-domain and intra-domain) with all the fluctuations in order to avoid the conflicts, similarities and overlapping. Directory Enabled Networks-New Generation (Den-ng) [23] is tagged with customization accordingly for inter/intra-domain and inter/intra-planer information representation. Justification about choosing this method is presented in next chapter. Network management and control rules/decisions computed on the basis of aforementioned distinctive information while taking all the inter-intra domain/planer variations and dynamism into account reflect the efficient resource utilization enforcing the true business objectives over the platform. Finally, the calculated rules/decisions are enforced by using the existing standards (e.g. Network Address Translation (NAT)ing, Domain Name Service (DNS) Cycling, Hashing, Proxying etc.) without introducing overheads in the protocol stack over the unified converged platform. The mentioned targets and objectives are heading towards the unification of services and applications while complimenting the private-public network border technology convergence presented in the next section.

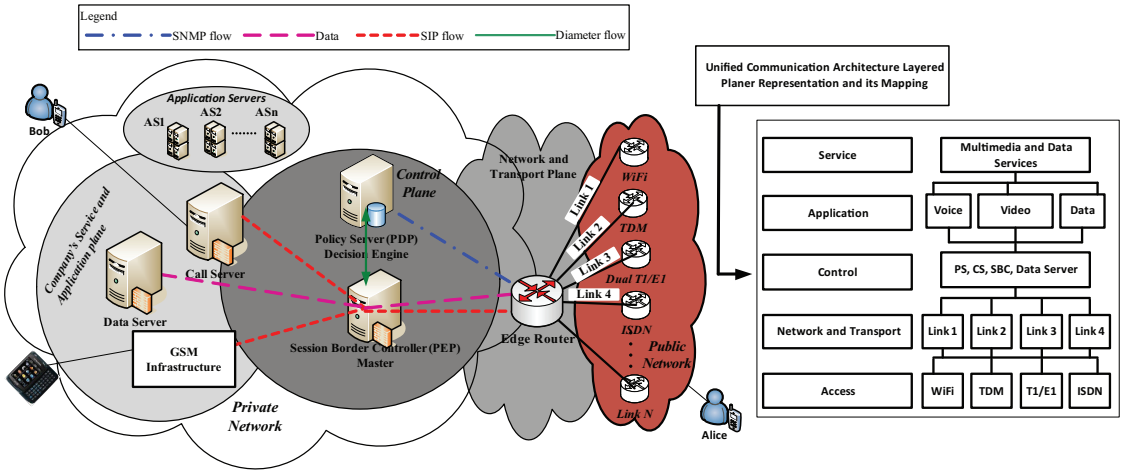

Figure 3.3: Unified Communication Architecture Layered Planer Representation and its Mapping

3.1.1.2 Companym@ges Framework for Unified Communication

Unified communication promises cost reductions and productivity benefits across a number of administrative and control domains. It maximizes the use of existing infrastructure, streamlined communications, increased operational efficiency while eliminating the device and media dependencies. Enterprises use Internet to deliver unified services. They subscribe different access technology links from several service providers to accomplish this unification goal. As mentioned before, multimedia traffic especially Session Initiation Protocol (SIP) based multimedia traffic is emphasized in the Comapnym@ges sub-project (MONA). So the system discussed over here is in the context of unification while highlighting the multimedia traffic (particularly the voice traffic) with multi-homing support. The telecommunications industry driven by new rich service innovations is in the midst of the megatrend of an all IP solution. The telecom business is motivated to achieve an all IP setup goal while converging towards unified communication. Global System for Mobile Communications (GSM) to multi-homed Voice over IP (VoIP) network and vice-versa unification is one of the core steps while moving towards this converged and an all IP platform. This unification enables operators to lower their overall operational and management costs while offering innovative advanced services with improved QoS to the end users. Each level of the value chain is benefitting directly or indirectly: fixed operators have the benefit of a reduced infrastructure and maintenance expenditure; mobile operators can accelerate fixed-mobile substitution by offering services previously available only for fixed lines. Companym@ges unified architecture and its corresponding layered mappings are shown in Fig. 3.3. The corresponding service, application, control, network and transport and access technology layers are mapped to the service (application and ser-

vice), control and management (control) and network and transport (network/transport and access) planes respectively. These layers work independently isolating the functionality while abstracting the low level complications. The hierarchy of the items on the extreme right of the Fig. 3.3 provides a comprehensive and rational framework for structuring the corresponding layers into sub-layers/items respectively. Inter/Intra-domain and inter/intra-planer Information and data has to be shared and exchanged for the network management and operations which in turn reflect the layered communication over the framework. The hierarchy of the corresponding building blocks complements this inter-communication and information sharing. Layered approach followed over the underlying infrastructure is then compared with the IP Multimedia Subsystem (IMS) regarding the modules, components, protocols and the functionality over the platform is coming in the next section.

3.1.2 Proposed Architecture and IP Multimedia Subsystem Comparison

IMS is defined by 3rd Generation Partnership Project (3GPP) that defines IMS standards as a network domain dedicated to control and integration of multimedia services [95]. It is a promising solution for facilitating, creating, deploying and tearing down the multimedia services while supporting the interoperability along side the convergence. The focus of IMS is to facilitate the network management while making it easier and comfortable. It separates the signaling and control from bearer functionality. It is intended to be access technology agnostic. The layered comparison for IMS and the proposed architecture is shown in Fig. 3.4. The layered approach followed in

Layer	IMS		Proposed Architecture		
	Interfaces / Servers	Protocol	Interfaces / Servers	Protocol	Functionality
Application	AS	H323/SIP/ Diameter	AS	SIP/Diameter	Rule based application , group, profile, presence and service management
Service	PS, SIP B2BUA, HSS	H323/SIP/ Diameter	SIP B2BUA, SIP UA	SIP/Diameter	
Control	P-CSCF, I-CSCF, S-CSCF	SIP/Diameter / COPS	CS, SBC, PS, Data Server	SIP/Diameter	Rule based session control and management
Transport and Network	Routers, Switches and Media Gateways	SNMP, IPV4, IPV6,SCTP, UDP, TCP etc.	Routers, Switches and Gateways	SNMP, IPV4, IPV6,SCTP, UDP, TCP etc.	Rule based network and transport optimization and management
Access Technology	xDSL, WiFi, GSM, Ethernet etc.		xDSL, WiFi, GSM, Ethernet etc.		Rule based access technology, convergence, management and optimization

Legend

AS Application Servers	HSS Home Subscriber Server	P-CSCF Proxy Call Session Control Function
PS Presence Server	xDSL A/S Digital Subscriber Line	I-CSCF Interrogating Call Session control Function
WiFi Wireless Fidelity	SIP B2BUA SIP Back to Back User Agent	S-CSCF Serving Call Session control Function
TCP Transmission Control Protocol	SCTP Stream Control Transport Protocol	COPS Common Open Policy Service Protocol
UDP User Datagram Protocol	IPV4/6 Intenet Protocol Version 4/6	GSM Global System for Mobile Communication

Figure 3.4: IMS and Proposed Architecture Layered Comparison

the previous section is adopted here and the corresponding layers here are mapped to distinctive interfaces/servers with protocols used over those layers keeping in view the IMS and then same set of interfaces/server and protocols are presented in consent with the Companym@ges framework along with functionality at those horizontal layers.
IMS involves a large number of devices (controllers, servers, gateways (signaling and media), routers, switches etc.). It binds different application, service, control and transport protocols focusing on multimedia traffic. Services can be accessed seamlessly irrespective of the control, transport and access technology. These mentioned objectives are very much similar to our targeted goals as there are number of partners involved in the Companym@ges project which their dedicated devices for customized and specialized functionality. The information about applications, services, and user profiles has to shared and disseminated between interfaces and devices using agreed upon protocols. Companym@ges platform provides unified communication with scalability and extensibility offering seamless transport and access convergence. But IMS generates lot of signaling and control traffic due to its inherited and native layering, control interfaces information sharing, fine granularity and policy and charging control merger. Companym@ges can avoid this massive signaling and control traffic as sub-project MONA deals with charging and cost at different granular level i-e the cost is represented/computed by counting the number of calls/request/sessions in/out and/or the total volume is accounted for rather than the monetary cost. MONA deals with routing issues at private-public network border emphasizing the multimedia traffic (routing at higher layers, i.e. application layers routing). Moreover the granularity handles the multimedia sessions/request/calls over the platform without introducing overheads in the standard interfaces and protocols. Above all IMS is still its evolution phase as the Policy and Charging Control are merged together in its latest release. Policy/Rule based network management and control for NGN infrastructures is complemented by IMS framework and the interfaces and control components are designed keeping in view the convergence and heterogeneity irrespective of the access technology and transport protocols but at different granularity (i-e packet level). Next sections includes the rule based management and control over the Comapnym@ges platform emphasizing the multi criteria problem formulation, the dimensionality of the information over the distinct domains and dynamic behavior of the underlying framework

3.1.3 Rule Based Management and Control in Companym@ges Framework

Rule based management and control has emerged as a promising solution for the management of heterogeneous and converged networks with multi-homing support. This approach has been adopted in several network management and control paradigms, such as in the QoS and security management. However, although rule-based management has been the subject of considerable research, the proposed solu-

tions are often restricted to static and/or partially dynamic event-condition-action tuple rules where conditions determine when actions should be performed. The static and/or partial dynamic rule configurations require manual intervention to cater for configuration changes and to enable policy deployment. However, changes in the system such as QoS violations, network conditional and environmental parameters, service/network failures or denial of service attacks in a secured network may require adaptation of existing rules to new circumstances. Thus, policies/rules themselves need to be managed and adapted with dynamicity support.

Rule (decision) computation and its enforcement are the two important mechanisms that involve different devices, interfaces and protocols over the platform shown in the Fig. 3.3 (lefthand side) while sharing/disseminating information within and across different planes (inter/intra-domain). The hybrid multi-homed platform links the company's private network (where service providers are offering versatile services (voice, video, data, triple-play/quadruple services etc.)) to public network (the internet: similar sort of aforementioned competitive services might also be available there) via different access links. One of the objectives is the accommodation of inter/intra-domain dynamic modifications/variations by using enhanced general methods and techniques while handling service, control and transfer layers issues.

Policy Server (PS) is the main controller in the proposed architecture. It acts as a PDP. It computes all the decisions by taking into account the static configurations and dynamics taking place over the platform, in addition to the policy enforcement supervision. The dynamic decision engine partly constitutes the core of PS. IETF policy framework has been followed and tweaked accordingly keeping in view integrity, scalability, extensibility and compatibility. Conventional decision systems are developed and deployed from the functionality (algorithmic) and performance implications viewpoints. Decision-making, within these systems is usually static and/or semi-dynamic. Moreover, these systems take into account few attributes among the set of available parameters over the platform, while calculating the decision ((service profile, reliability information, time of the day, etc.), business objectives of the company, latest state of the links, user profiles and Service Level Agreement (SLA)). A system capable of taking into account Service Level Specifications (SLS), e.g. susceptible delay, jitter and packet loss may not accommodate the technology specific information. Systems considering user, service and QoS profiles do not compensate for dynamic context of the request. The system considering the technology specific information might not accommodate the business objectives of the company during the decision-making process. The first challenge is to utilize the available information over the platform maximally, which comes from different sources with different dimensions so that the final decision for link selection reflects dynamic control and effective resource utilization with good QoS. The use of existing standardized technologies without introducing overheads for decision enforcement is another aim over the unified converged platform while targeting the integrity and compatibility.

PS is an intelligent module in the proposed framework; has to enforce the SLAs and follow the reciprocal agreements among various service/access providers. The business objectives of the company must be fulfilled while the users and applications should get good and agreed upon QoS and QoE. PS Block Diagram is shown in Fig. 3.5. PS shown in Fig. 3.5 has various modules interacting with each other to

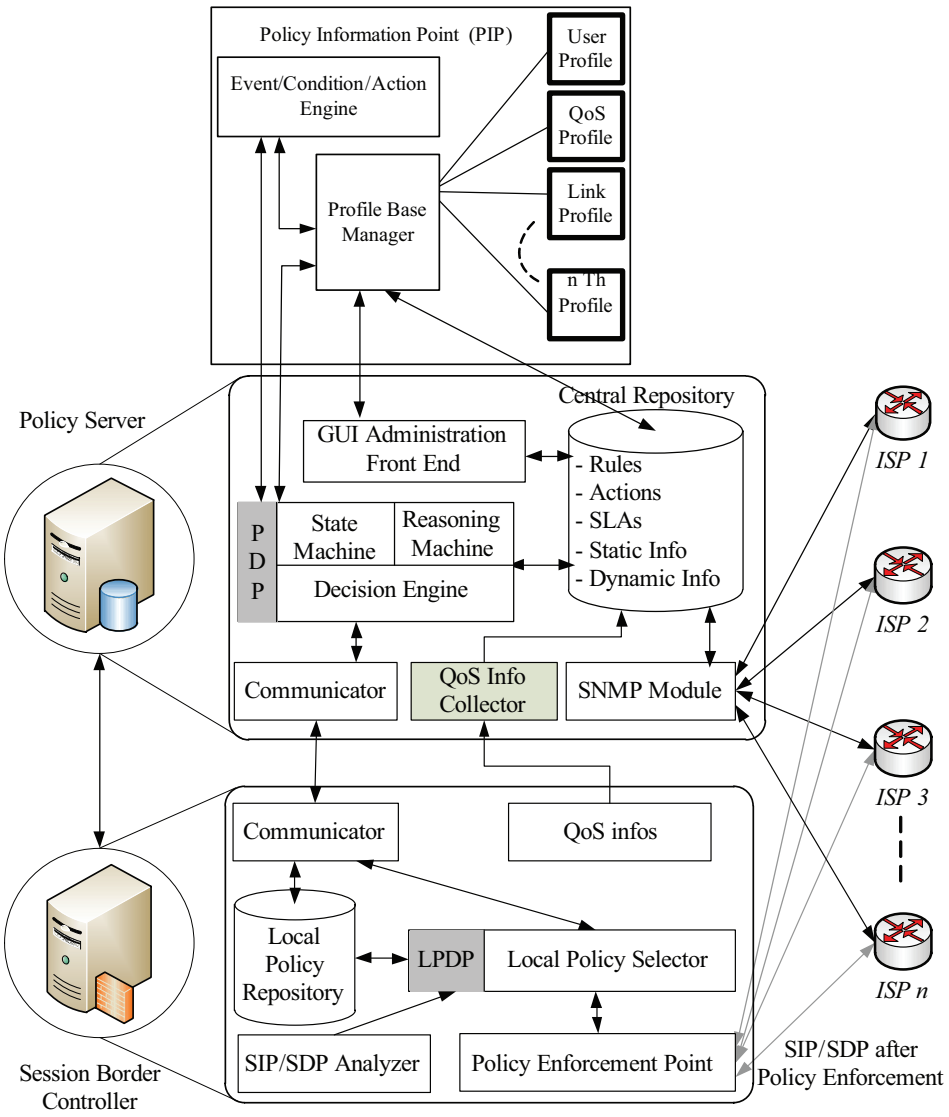

Figure 3.5: PS and SBC Modules and Their Inter-Communication

share and manage necessary and required information. Event Condition Action Engine at Policy Information Point (PIP) has the capability to sense the triggers (event request and/or modification/updation trigger etc.) and take/supervise all the neces-

sary steps accordingly (loading of the corresponding profiles from the central profile base, updating/modifying the profile in the repository etc.). The profile matching and selection process is not within the scope of the current work but a flow chart elaborating the mechanism briefly is presented later on in this section. Administrative front end is used for rule/policy/info/profile specification, modification and addition. Policy Repository contains all the static and dynamic information along with set of pre-defined business rules, routing strategies, SLAs, technology independent and technology dependent infos, overloaded set of profiles to be used in decision making etc. Decision Engine is the brain of policy system and takes decisions along with policy computation, conflict detection and resolution along side policy enforcement supervision. Communicator used for policy/rule and other information exchange between PS and SBC over Gq interface using diameter protocol [82]. User Datagram Protocol (UDP) Socket gathers QoS info from SBC(Call Detail Records (CDR)s etc). Simple Network Management Protocol (SNMP) Module is used to gather the latest information of access router interfaces (links) by collecting delay, loss, jitter metrics (SNMP alarms/traps). PIP contains all the profile related data sets and whenever an addition and/or modification is carried out via the dedicated Graphical User Interface (GUI), it is being added at PIP info base. Profile Base Manager keeps the track of all the profiles. User Profile base contains different profiles according to the offered service plans (might be extracted from plan creator, plan administrator and to some extent from Service Level Agreements (SLAs) with authentication and authorization parameters (translation of SLA competencies into business goals and objectives). A user profile may include identified services (different granularity) and a data plane devised on the basis of these services. Assigned QoS and gating information along with charging model information (Volume base charging, Time base charging event base charging etc). QoS profile base also contains the corresponding QoS parameters (delay, Jitter, Packet Loss, Burstiness) and thresholds (susceptible QoS parameters) values extracted/defined from Service Level Specifications (SLS) Defined by Admin. An example of an IP SLA, VoIP Service Level Specification (SLS) and QoS Profile are shown in table 3.1 ,3.2 and 3.3 respectively. Link profile might have network type

Parameter	**Value**
Network Latency	50-100 ms
Packet Loss	1.0 E-09-1.0E-06
Jitter	50-60 ms
Downtime	2 S
Charging	Cumulative (Per byte)

Table 3.1: An IP SLA

SLS	Type/Attribute Value
Delay	50ms
Packet Loss Ratio (PLR)	0.1%
Jitter	1ms
Traffic Conformance (TC)	VoIP TC 1
Throughput (TP)	VoIP TP
Global Consumption Limit	VoIP Global
Individual Consumption Limit	VoIP Indiv TI
Scope	Faculty
Schedule	24x7
Service ID	VoIP

Table 3.2: VoIP SLS

QoS-Profile	G.729	
QoS-Semantics	Minimum QoS	
QoS-Parameters	Rate	40000 (40kbps)
	Bucket-size	1024 (1KB)
	Peak rate	40000 (40kbps)
	Minimum policed unit	1024 (1KB)
	Path Latency	50000us (50ms)
	Path Jitter	1000 us (1ms)
	Path Packet Loss Ratio	0,001 (10-3)

Table 3.3: Corresponding QoS Profile for VoIP

(wireline, wireless, etc.), access technology type (GSM, Ethernet, WiFi, etc), upper /lower bounds, over-utilization/under-utilization, charging methodology, current status (QoS, Up/Down, etc). Dedicated ports and services (if defined) and business rules for the link (Time of the day and bit/byte count mechanism: flow, application and/or protocol based). Bandwidth and traffic burstiness might also be important parameters in the link profile. System can also accommodate additional profiles if required according to the platform's configurations, settings and obligations in consent with core decision engine to obey the pre-configured business objectives and routing rules in order to achieve the desired QoS and QoE, e.g. application profile (triple-play and quadruple application services requirements, the important metrics involved, their threshold values, accounting policy etc.). Platform's administrator can add new profiles along side the provision of modification/removal of existing entities.
On receiving an event from the decision engine, the Event Condition Action (ECA) engine loads the corresponding profiles from the PIP according to the context then

horizontal filtering process is being performed on individual profile category (e.g. QoS Profile) to select the matched profile (the profile that can be closely mapped to the requirements of the ongoing context/request/session). Those filtered profiles from different categories contain chunks of information that has to be utilized at central repository at PS for decision computation. The profile sorting, filtering and processing is shown in Fig. 3.6 . Three profiles are considered in each category i-e., User (UP1, UP2 and

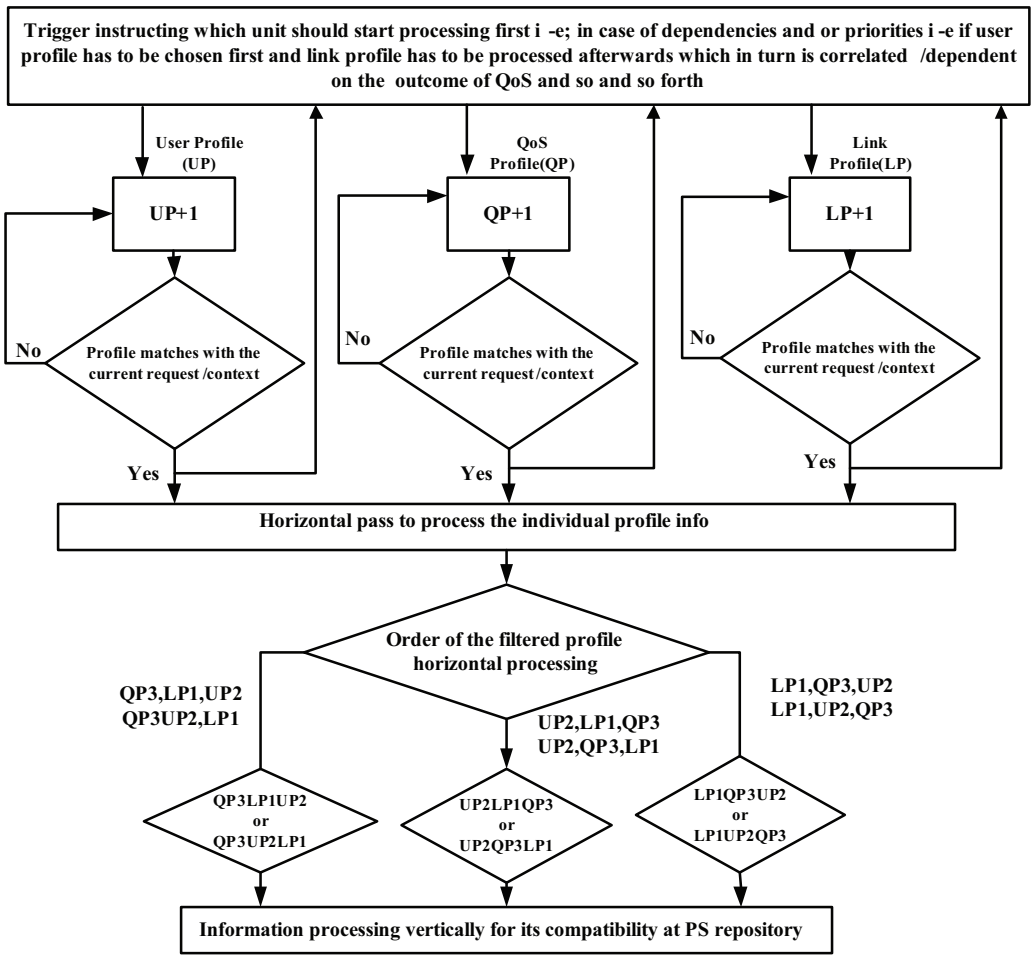

Figure 3.6: Vertical Pass and Horizontal Pass for Profile Selection and Information Processing Within PIP

UP3), QoS (QP1, QP2 and QP3) and Link (LP1, LP2 and LP3) Profiles respectively to avoid complexity. The horizontal sorting and filtering is accommodated first and the chosen profiles information is processed in vertical depth to make the information compatible and understandable for central repository at PS.

The inter-communication between PS and SBC is important and decision dissemination for their enforcement at SBC has to be reliable by following the standardized

mechanisms. The choice of the key signaling protocol and its comparison with the corresponding candidates is explained next.

3.2 Choice of Diameter, its Comparison with Other Protocols and its Revamping

The current paradigm of communication assumes the flexible network access driven by any service, anytime, anywhere, over any-network concept while offering diverse services over converged hybrid platform. Multi-vendor, multi-service and multi-operator environment harmonize the infrastructure irrespective of geo-location while maximizing the provider's revenue and customer's satisfaction. Moreover companies want to have such systems with optimized and superlative use of resources offering simplicity, nomadic accessibility with personalization. In such scenario there is a need to debate on some AAA protocol supporting the intended infrastructure offering the desired QoS and QoE to the end users/services/devices while facilitating the administration and control from provider perspectives. Diameter [82] consists of a base protocol and different extensions and applications like Diameter Network Access Server Application [96], Diameter Mobile IPv4 Application [97], Diameter Extensible Authentication Protocol (EAP) Application [98], Diameter Command Code Registration for the Third Generation Partnership Project (3GPP) Evolved Packet System (EPS) [99], Diameter Policy Processing Application [100] and Quality of Service Parameters for Usage with Diameter [101]. All the basic functionality common to all applications and services is implemented in the base protocol while all application specific functionality exists within the different applications. The Diameter base protocol is intended to provide an Authentication, Authorization and Accounting (AAA) framework for networks applications such as network access or IP mobility. Diameter is also intended to work in both local Authentication, Authorization Accounting and roaming situations. The Diameter base application needs to be supported by all Diameter implementations. The communication between PDP and PEP is accomplished via Diameter with newly defined and developed Attribute Value Pairs (AVPs).

Diameter packet format is shown in Fig. 3.7. Version field indicates diameter version, message length is used to indicate the total message size of diameter message (including header fields) and flags are represent the type of the message. Normally the first 4 bits in the flag header are used and the rest of 4 bits are reserved for future use. Fully Qualified Domain Name (FQDN) or host IP address uniquely identifies the diameter (server/client) running on a hybrid environment. This field is used in diameter to indicate the type of message (AAR, ASR, STR, etc.). Requests and answers are combined to get one code i-e., AAR = AAA = 265, ASR = ASA = 274, STR = STA = 275, and the flags are used to determine which type the message is (Request or Answer).

Traffix OpenBlox [102] Diameter stack has been tweaked and adapted accordingly (IMS Gq interface). It is an implementation of the IETF's Request For Comments

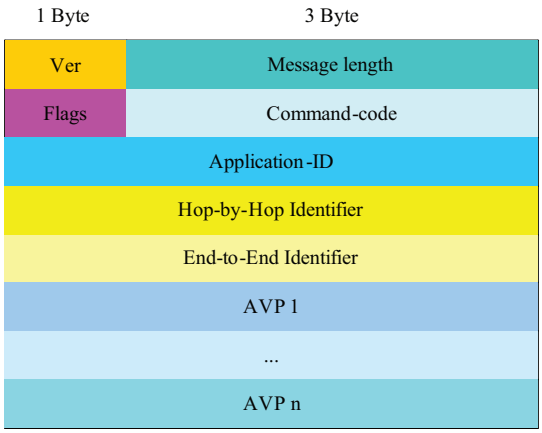

Figure 3.7: Diameter Packet Format

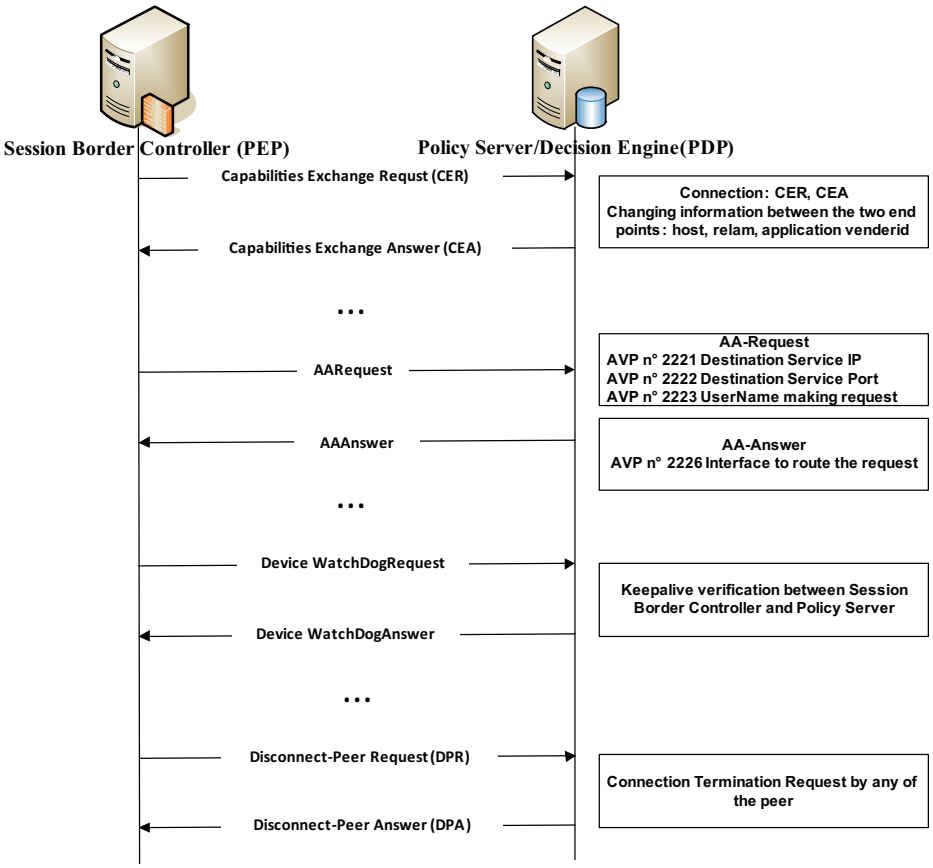

Figure 3.8: Communication Between Diameter Server and Client at SBC and PS Respectively

(RFC) 3588. It is used for the communication between PS (Decision Engine (PDP)) and SBC (PEP). Diameter Attribute Value Pairs (AVPs) have been developed and used for the required mechanism following the standardized header format. However, the AVP numbers adopted here are non-registered, i-e., these AVPs are understandable onto the platform and within the partners environment only. This methodology has been adopted to avoid the delayed and long AVP registration and approval process however, in the near future; the administrative requirements will be followed. Capability Exchange Request (CER) and Capability Exchange Answer (CEA) messages initiate the communication between the Diameter client at SBC and Diameter server within the PS. Negotiation for secured connection (TCL or IPSec) is then performed. The communication starts immediately after the negotiation using Diameter protocol over the Gq interface. WatchDog request/answer messages are often sent to check the keep-alive status of the Diameter client and server. The peers must disconnect formally by sending/receiving the Disconnect Peer Request/Answer (DPR/A). The communication flow graph is shown in Fig. 3.8. Non-standard AVP identifiers 2221, 2222 and 2223 are chosen for service IP, service port and username respectively. The triplet service IP, service port and username is exploited at PS. The development and behavior of diameter in different policy computation and policy enforcement scenarios will be presented discussed in next chapter.

3.2.1 COPS Vs Diameter Vs SNMP

COPS protocol is able to support policy control in an IP network through simple request and answer messages. It is used for exchanging network policy information between the PS (PDP) and different clients (policy enforcement points, PEPs) in a network. It allocates the network traffic resources as a part of overall QoS. COPS was originally intended to be a policy dissemination, control and enforcement protocol but due to some IETF extensions [103], it may also be considered partially as a AAA protocol. Using COPS policies related to Authentication, Authorization and Accounting along with QoS can be distributed and enforced but on the system level not on the user or service level. COPS message has an 8-byte-long packet header. A typical COPS-REQ message is 24 bytes long and a DEC message has the size of the decision object plus 32 bytes.

The design of the diameter protocol is initiated by the 3GPP to be used for IMS. The basic protocol is designed to provide a framework for services requiring AAA support, at the access technology level. The protocol is intended to be flexible enough to allow services to add building blocks to the base Diameter protocol to meet their requirements. Unlike other AAA protocols for access technologies such as Point-to-Point Protocol (PPP) dial in, Mobile IP and others, Diameter uses a Peer-to-Peer (P2P) architecture rather than a more classic client/server scheme. It is recognized as a P2P protocol since any node is free to initiate a request at any time. Diameter is also meant to operate both with local and with roaming situations. Diameter is not a complete

protocol by itself, but it needs application-specific extensions from the technology, or architecture, used to access the network. Diameter can be used from small to very large networks with the scalability in mind (can handle huge number of requests simultaneously). Diameter protocol is backwards compatible with RADIUS that makes its agents able to act as RADIUS gateways sending RADIUS messages through the network without any conversion. By using the diameter protocol, applications are able to support interfaces such as Cx, Dh, Dx, Rf, Ro, and Sh. The Diameter protocol uses a binary header format and is capable of transporting a range of data units called AVPs. The Diameter base protocol specifies the delivery mechanisms, capability negotiation, error handling, accounting and extensibility of the protocol, whereas individual Diameter applications specify service-specific functions and AVPs. Diameter is still evolving and there are number of extensions and enhancements in the base protocol (e.g., [104]).
SNMP is an application layer protocol that implements communication between a management console and the managed agents. It implements 5 messages: messages for information request (GET, GETNEXT, GETBULK), a message for information writing (SET) and a message for event notification (TRAP). The messages are coded in small size packets and transported using UDP in order to allow a lightweight message transport in overloaded networks. Version 3 [105–109] includes some enhancements in terms of security and remote configuration. SNMP protocol is widely used today in network management as well as in the equipment management areas, mainly as an equipment monitoring tool but it does not support AAA.
Diameter, an inherited AAA protocol is natively adopted in IMS. Due to its AAA characteristics, its enhancement orientations are becoming natural for decision-based network management. It has large AVP space and supports large number of pending requests. Common Open Policy Service (COPS) [79], a strong candidate for Policy Based Network Management (PBNM) [100] has not been chosen for decision(policy) provisioning and dissemination, as it is specifically designed for device-level configuration and management. However, dynamic session/call/connection management is required while taking into account the variations/dynamics, pre-configured rules and business objectives and the context of the ongoing session/call/connection over the converged and hybrid platform with unification support. SNMP has sometimes been proposed in the literature to be a candidate for PBNM [78]. SNMP-based information in our system is exploited to gauge the QoS parameters of access router interfaces (links).
The signaling protocols explained up till now are restricted for information exchange and sharing at device level only but a protocol is required which in addition to signaling capabilities at device level must share and exchange information between end points (devices) of service users at application and service level. There exits no such protocol but SIP, a signaling protocol is tweaked to do the job and is presented next.

3.3 Signaling Protocol (SIP) and its Revamping For The Platform

SIP [16] is the main signaling protocol used for multimedia communication over the converged multi-homed platform. It is a Hypertext Transfer Protocol (HTTP) like request response signaling protocol used for creating, modifying and tearing down sessions independently of the underlying data-link layer technologies and transport protocols. Its infrastructure is highly open and flexible facilitating the services.
SIP is extensible in terms of methods, headers, and message payload in accordance with numerous standardized extensions matching specific needs. SIP is inherently dynamic supporting mobility relying on Uniform Resource Identifiers (URIs) abstracting the terminal network address while referring to agents. The URI shields the application code from runtime configuration changes in the environment.
Service provider has to take care of QoS requirements of the ongoing flows, before accepting a new request that may degrade the performance of ongoing flows over the hybrid platform. Flow control/management mechanisms such as Call/Connection/Session Admission Control (CAC) are typically applied during the signaling phase especially over the unified platform while handling multimedia services. The CAC mechanism is not within the scope of the SIP (except a special case of an outbound proxy used for outgoing calls, that proxy may control the firewall and thus restricts outgoing calls), being used as the signaling protocol over the proposed architecture. In order to observe active CAC mechanism during signaling phase, some information needs to be disseminated and shared among corresponding devices involved in the communication (e.g., Call Server (CS), SBC etc.). At present SIP does not provide/support such mechanism to share and exchange information between devices. A specific way of information sharing/dissemination among devices is adopted to accomplish the requirements. Standard SIP messages are used to share and distribute required information between different devices over the network.
An efficient CAC function over the Companym@ges proposed architecture should take account of many factors, including user profile, call type and the state of the available access links. It is proposed to distribute the CAC function between the CS and SBC; the CS handles issues related to user profile and the SBC handles issues related to resource availability. The collaboration between CS and SBC is made possible by using the SIP Priority header to share and exchange information during Call Setup. This mechanism helps in abstracting the service, control and transfer planes issues while sharing and disseminating the required attributes and parameters.
In order to illustrate the basic problem, consider the following situation in which Bob's SIP User Agent Client (UAC) is registered on the CS and it initiates a call to Alice by sending an INVITE to the proxy server at CS (Fig. 3.3). SIP proxy at CS can identify the profile (user type) of the call sent (received) to (from) a given UA, by querying the

profile database. The SBC can identify the communication type (audio, video, etc.) by analyzing the SDP [110] payload of INVITE message. Therefore, the call server knows the profile type, while the SBC on the other hand, have the communication type information. In fact, the call server does not analyze the message payload and does not have any idea about the communication type while the SBC does not know the user type. Therefore, an information exchange and sharing is indispensable for rule based decision computation at PS (Decision Engine) in order to accomplish dynamic call routing while enforcing the decision at SBC.
One of the solutions to this problem is that SBC accesses the profile database at CS and caches/mirrors the information within a duplicated database at SBC. This solution does not sound efficient because the call server also accesses profile database frequently to filter incoming and outgoing calls. Hence the system has to access the profile base twice for each call, which is neither efficient nor elegant. Moreover this solution requires one extra communication between SBC and CS's database introducing more add-on delay.
Our preference is the following: proxy server within the CS marks the INVITE with specific field that identifies the *user type*. *Resource-Priority* and *Accept-Resource-Priority* are defined according to the semantics in [111]. It is intended to describe a structure for fields inserted in the header of INVITE message. The fields are used to communicate a priority level for accessing the resources. The structure of the priority field used in our implementation is *name.number*. The name identifies the resource, and the number identifies the priority level. A name can be defined (e.g. company) and different priority levels corresponding to the different user types (e.g. boss, administrator, trainee student, gold, silver bronze etc.) can be declared. These header fields are used to transport the user priority which is taken into account when a policy decision is computed. The *Resource-Priority* field will be used in INVITE messages while the '*Accept-Resource-Priority*' field will be used in 200 OK messages.

3.3.1 Handling incoming and outgoing calls

The user type is set up and stored into the users profile database at CS. The CS looks at the user profile database to accept or reject the call. If accepted, it add a proprietary SIP header to carry the user type info. The proprietary SIP header will be removed by the SBC once it got the user type. A communication type is computed according to media & codec used by the UAC. Such information is described by the SDP message between user agents. The user type information is extracted from the *Resource-Priority* and *Accept-Resource-Priority* header fields, while the communication type is computed by the SIP/SDP analyzer at SBC (SDP offer/answer messages). This information is bundled into a pair and is compared with the switching table shown in table 3.4 (policy based QoS routing), computed from policy database.

Call Type	Access
(User Type-1,Communication Type-A)	1
(User Type-1,Communication Type-B)	3
(User Type-3,Communication Type-C)	2
(User Type-2,Communication Type-A)	1

Table 3.4: Switching Table for Dynamic Routing (At Higher Layer).

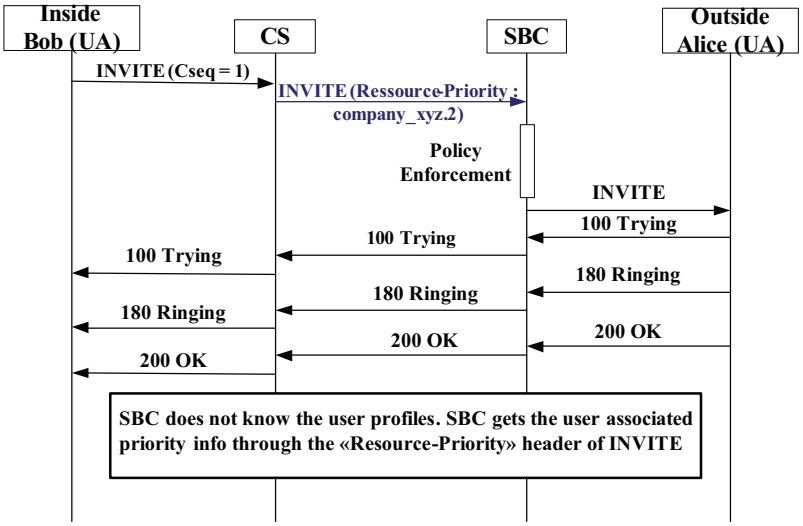

Figure 3.9: SIP Revamping Regarding Outgoing Call Flow.

3.3.1.1 Outgoing Call

For outgoing calls (i.e. for INVITE sent from platform to outside), the *Resource-Priority* header must be added to the INVITE message as shown in table 3.5. For an outgoing call, policy enforcement will be done on the INVITE response (200 OK). It should trigger on SDP offer/answer as shown in Fig. 3.9.

3.3.1.2 Incoming Call

For incoming calls (INVITE from public to the private network), the *Accept-Resource-Priority* header must be added to the 200 OK message as shown in table 3.6. Policy enforcement in case of incoming call is applied in 200 OK response, as shown in Fig. 3.10.

INVITE sip:bob@xyz.com SIP/2.0
Via: SIP/2.0/UDP 192.168.1.156:5060;branch=xxxx
Session-Expires: 86400
From: “Alice” <sip:alice@xyz.com:5060>;tag=xxxxx
To: <sip:bob@xyz.com:5060>;tag=xxxx
Call-Id: XXXXXxxxxx
CSeq: 1 INVITE
Resource-Priority: compagny_xyz.2
Contact: “Alice” <sip:Alice@xyz.com:5060>;tag=xxxx
Max-Forward: 70
Allow: ACK,BYE,CANCEL,INVITE,NOTIFY, . . .
User-Agent: useragent name
Content-Type: application/sdp
Content-Length: xxx

Table 3.5: Addition of *Resource-Priority* in SIP INVITE for Outgoing Call.

SIP/2.0 **200 OK**
Via: SIP/2.0/UDP 192.168.1.156:5060;branch=xxxx
Session-Expires: 86400
From: “Alice” <sip:Alice@xyz.com:5060>;tag=xxxx
To: <sip:bob@xyz.com:5060>;tag=xxxxx
Call-Id: XXXXXxxxx
CSeq: 1 INVITE
Accept-Resource-Priority: company_xyz.1
Contact: “Bob” <sip:bob@xyz.com:5060>;tag=xxxx
Allow: ACK,BYE,CANCEL,INVITE,NOTIFY, . . .
Content-Type: application/sdp
Content-Length: xxx

Table 3.6: Addition of *Accept-Resource-Priority* in SIP 200 OK for Incoming Call.

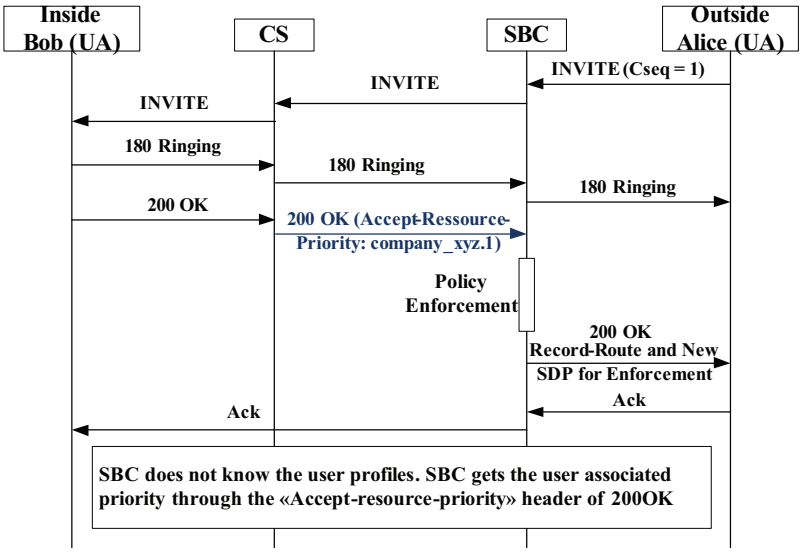

Figure 3.10: SIP Revamping Regarding Incoming Call Flow.

3.4 Summary

This chapter presents the Companym@ges framework. Architecture constituting the core of the platform is characterized regarding the multimedia and data communication. The isolation of the planes over the architecture representing multiple criteria and objectives over those distinctive planes is illustrated. The underlying architecture is then linked to the decision-making framework by describing the inter-intra communication between different modules over distinct domains. Signaling protocols used for the control and management of the infrastructure and their revamping for inter/intra-domain/plane multidimensional information dissemination is then elaborated. Layered approach is followed for application, service, control and network functions and operations. Hierarchy of the underlying layers reduces complexity of the multi criteria problem with multiple goals in addition to the technical and non-technical representation over the multi-homed infrastructure. The linkages, relations and interaction between different modules over these layers, their corresponding functions are simplified by the hierarchical representation. Granularity of the targeted platform is in consent with the network management and control is explained and is compared with IMS. Rule based management while keeping in view the information sharing and exchange between two core components over the platform is depicted. Inter/Intra communication, tagged information flow and the sequence of operations between different modules regarding these components (SBC and PS) are introduced. Choice of the protocols, corresponding modifications/additions of the headers, according to the requirements over the platform are highlighted. Finally, the information sharing at device level using SIP;

the main signaling protocol over the platform keeping in view the incoming/outgoing communication is presented.

4

Multi Criteria Decision Making and Corresponding Methods for the Framework

EMERGENCE of wire-line and wireless network infrastructures, fast changing network topologies with dynamicity support, varying data-link/network layer technologies, diverse user requirements, distinctive service and application types, etc. are all inciting the need for an all-IP solution that integrates various sorts of networks, providing a converged and hybrid environment with multi-homing support fulfilling the global business objectives and multiple administrative goals while handling multitudinous attributes and parameters from application/service/control/network planes all-together. The all-IP backbone provides an integrated heterogeneous platform supporting ubiquitous and unified communications across various access technologies. Decision making in such an environment is not an easy task especially when dynamic modifications/variations have to be taken into account along side a set of information and conditional parameters from diverse management domains (service profile, reliability information, time of the day, business objectives of the company, latest state of the links, user profiles and Service Level Agreement (SLA) etc.). The situation becomes more complicated when disparate services have different demands, some require high bandwidth and others need lower delay/packet loss; user requirements over the infrastructure are also divergent, some desire better user experience, some require security and the others focus on cost-vs-quality.

Conventional decision making networking systems take into account the technology dependent and technology independent information (devices, interfaces, protocols, architecture, topology etc.) related to the network infrastructure while computing the decision. Application oriented data sets, corresponding attributes over service plane and the business objectives over the platform are not considered and/or they are taken into account partially. However the systems meditating the business objectives may not be able to capture the required granularity. The systems accommodating the services information have to be handled in an abstracted way regarding the service scalability

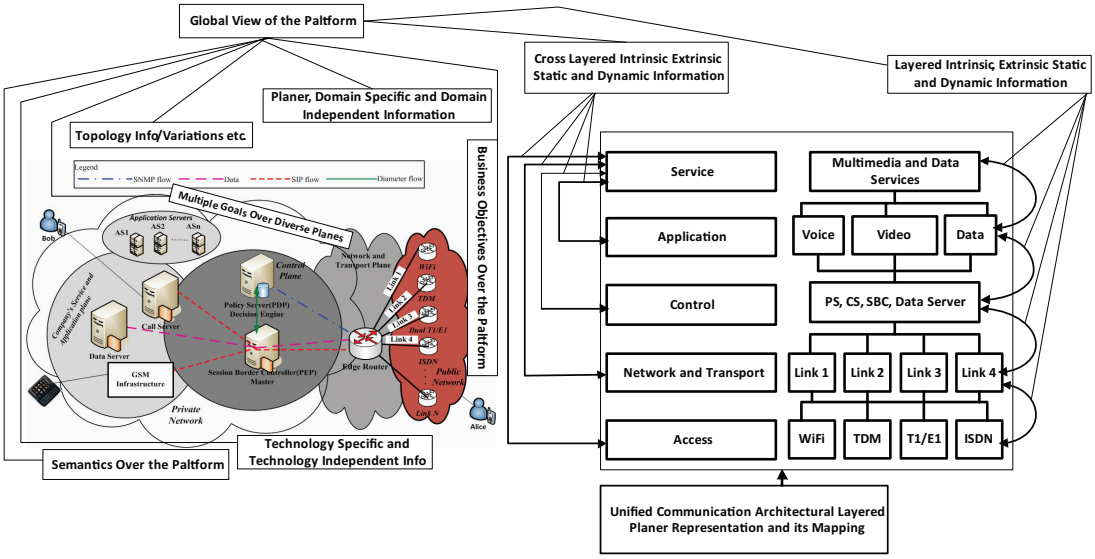

Figure 4.1: Companym@ges Proposed Architecture Regarding Global, Local, Planer, Static and Dynamic Information Domains

and extensibility. Above all, the latest systems targeting the aforementioned issues might not be able to provide required dynamicity for effective and efficient control and management over such converged and hybrid communication system with multi-homing support.

Platform's multidisciplinary and multivariate information domains (planes/layers) are synchronized locally and asynchronous globally forming a Globally Asynchronous Locally Synchronous (GALS) system. The static and dynamic information (inter/intra-domain and cross planer/layer) over the unified platform are categorized as intrinsic and extrinsic regarding those distinct planes/domains while posing the multi criteria problem with multiple objectives. It is thus necessary to mitigate the cumulative multi-facet effects due to disparate diversity, myriad dimensionality with multiple goals within GALS multi-planer system. The information sources representing different domains (e.g. service, control, transport planes etc.) might be highly structured and synchronized locally (inter-domain/plane) but may have higher probability of asynchronous and un-structured information representation globally (intra-domains/planes). QoS profile of the links, user authentication/authorization profiles, service variants/profiles, business objectives of the company, fluent dynamics over the multi-homed platform and traffic management issues at private-public network border constitutes a multidisciplinary problem. The information coming from different sources with different dimensions reflects the complexity of the underlying problem.An illusion of the abstracted information domain over the presented architecture is given in Fig. 4.1

Conventional solutions to handle similar scenarios over such multi-homed converged environment are either user-centric or motivated for efficient resource utilization over the platform and/or they are centered towards application optimization for desired QoS and QoE. However to cope with user authentication/authorization profiles, business objectives of the company, reciprocal SLAs with rivalry providers, technology specific and technology independent information over converged platform, fluent dynamics over the multi-homed infrastructure and traffic management issues at private-public network border all-together, an efficient and effective decision system is required. Moreover, scalability, extensibility and performance of the underlying decision system must be taken into account even although the granularity over the Companym@ges proposed architecture deals with calls/sessions/requests rather than individual packets. This convergence at service, control, access/transport and network level require modification/addition and updation of multi-disciplinary data sets with multiple objectives. Diversity and dimensionality of the multifaceted goals along with multiple objectives over the platform require multi criteria theory to address all the aforementioned issues. MCDM is elaborated regarding the routing decision making at private-public network border and the corresponding MCDM methods are adapted over the environment for their application and decision making functionality. First simple scenario is emphasized while addressing the large data sets involved in the routing of request/calls/sessions in a multi-homed infrastructure. Then peculiarities that are important to the routing decision making but comes from diverse domains reflecting multi dimensional nature of these underlying attributes and parameters are focused by choosing another method. The former methods are not able to capture the dynamicity over the platform so another method is adapted over in order to overcome the dynamic behavior and diverse fluctuations issues. Information abnormalities and data representation issues over the converged environment with heterogeneity support are tackled by an extension of MCDM method. Context of the incoming/outgoing requests is important while computing the decisions dynamically; a different method is adapted over the platform. Choice of these methods and their application in the context of simple use-case over the proposed architecture is presented next.

4.1 Choice of the Multi Criteria Decision Making Theory

Decision-making is a key element in a number of disciplines of knowledge, technology and even in our daily life. In common practice, its scope ranges from the individual to the largest groups and societies including nations and ultimately organization at the global level. It considers situations ranging in complexity from the simple to the most complex involving multiple objectives. Multi Criteria Decision-Making Method (MCDM) involves making preference decisions (such as evaluation, prioritization, selection, and so on) over the available alternatives that are characterized

by multiple, usually conflicting, criteria targeting diverse and conflicting/overlapping objectives. The criteria are often interdependent and/or correlated in a complex and uncertain way reflecting the complexity of the system. Moreover, the value of a criterion for a given action can be affected by many factors that are external to the decision system and cannot be controlled by the decision maker (Extrinsic Info). For instance in case of Internet Service Provider (ISP) selection problem, the cost, which is a criterion, can be influenced by external factors (e.g. time of the day, congestion hours etc.) MCDM technique is affected by tangible and intangible criteria requiring a combination of monotonic and non-monotonic functions aiming diverse objectives with optimization. Multiple goals over the individuals planes over the converged network, intentional business objectives influenced by service scalability to comply an SLA extensibility over multi service environment, frequently changing business logic, rule management over the infrastructure in accordance with the traffic volume, routing rule at private-public network border reflecting the globally multi-facet goals and objectives, addition/modification/updation of services/carriers/VPNs and technology specific and technology independent diversified knowledge are some of the stimulating factors encouraging us to use MCDM theory.
MCDM pertaining to Companyma@ges is initially augmented with a self-explanatory use-case. Lets take the example of load balancing at private-public network border with four links. SIP-based multimedia traffic (voice calls) will be distributed to different servers on the basis of simple criteria. One of the criteria of the Load-Balancer (LB) module is based on call routing on the basis of real-time load of the peer modules (links). LB is able to keep the load status (as number of ongoing calls) of each destination link. It is aware of the capacity of each destination as it is preconfigured with the maximum load accepted by the destinations. Conventional LB chooses the less loaded destination not the destination with the smallest number of ongoing calls, but the destination with the largest available slot. But by introducing MCDM theory, load balancing is fine tuned as more attributes has to be taken into account. Moreover the weight assignment introduces more control offering dynamicity to the LB. A typical LB clustering scenario is shown in Fig. 4.2. LB can handle both incoming and outgoing class/request/sessions but the emphasis is on SIP based outgoing call routing in consent with the decision computation on the basis of multiple criteria while targeting multiple objectives in addition to accommodation of dynamicity and fluctuations. The remote server cluster representing the public network contains SIP server having different flavors of Asterisk (an open source soft switch) emulates the alternative links for outbound call routing. Private network on the other hand emulates the service and control infrastructure but the intensions here are to present a simple architecture for the adaptation of the MCDM methods accordingly. Cost is the second criterion, which is taken into account while choosing a link from the cluster that falls into Least Cost Routing (LCR). The third and the final criteria for choosing the best link among the available choices are number of dropped calls (total number of calls a link can accom-

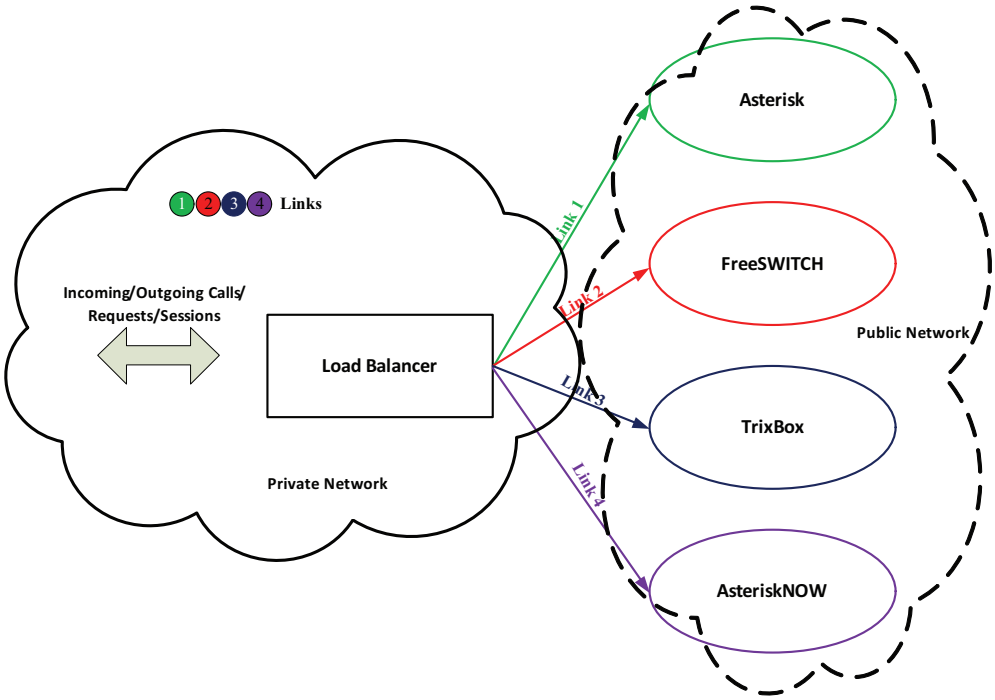

Figure 4.2: Load Balancer Clustering Scenario

modate is already known) and the service quality (calculated from the CDR dumps) respectively.

4.1.1 Weighted Sum Method (WSM)

The weighted sum model (WSM) is probably the simplest and the most commonly used approach while handling single dimensional problems. The basic principle behind this technique is the additive utility assumption. That is, if the performance of each alternative in terms of each criterion in the decision problem (i.e., the values) is measurable and is of the same unit where higher is better, then the alternative with the largest cumulative value is the best [112] satisfying the following expression.

$$A^*_{WSM-score} = \max_i \sum_{j=1}^{n} a_{ij} w_j, \quad \text{for } i = 1, 2, ..., m. \tag{4.1}$$

where: $A^*_{WSM-score}$ is the WSM score of the best alternative, n is the number of decision criteria, a_{ij} is the actual value of the $i-th$ alternative in terms of the $j-th$ criterion, and w_j is the weight of importance of the $j-th$ criterion.
The assumption that governs this model is the additive utility assumption. That is, the total value of each alternative is equal to the sum of the products given as (4.1). In

single-dimensional cases, where all the units are the same (e.g., dollars, feet, seconds), the WSM can be used without difficulty. Difficulty with this method emerges when it is applied to multi-dimensional MCDM problems. Then, in combining different dimensions, and consequently different units, the additive utility assumption is violated and the result is equivalent to "adding apples and oranges".
Suppose that an MCDM problem involves four criteria, which are expressed in exactly the same unit, and three alternatives. The relative weights of the four criteria were determined to be: $w_1 = 0.20$, $w_2 = 0.15$, $w_3 = 0.40$, and $w_4 = 0.25$. Also, the performance values of the four alternatives in terms of the four decision criteria are assumed to be as follows:

$$A = \begin{bmatrix} 25 & 20 & 15 & 30 \\ 10 & 30 & 20 & 30 \\ 15 & 20 & 30 & 15 \\ 30 & 10 & 30 & 10 \end{bmatrix} \begin{matrix} L_1 \\ L_2 \\ L_3 \\ L_4 \end{matrix} \tag{4.2}$$

The corresponding column vectors represent the individual criteria (Number of ongoing calls, Cost, number of dropped calls (within total capacity of 1000 calls for each link) and service quality respectively) for the four alternative links each having the corresponding weight values (representing the relative importance of the attributes/parameters for the alternative link). The data for the underlying MCDM problem is illustrated in the decision matrix as follows:

Criteria	C_1	C_2	C_3	C_4	
Weights	0.20	0.15	0.40	0.25	
A_1	25	20	15	30	L_1
A_2	10	30	20	30	L_2
A_3	15	20	30	15	L_3
A_4	30	10	30	10	L_4

When equation (4.1) is applied on the decision matrix, the scores of the four alternatives are:

$$\begin{aligned} A_{1,WSM-score} &= 25 \times 0.20 + 20 \times 0.15 + 15 \times 0.40 + 30 \times 0.25 \\ &= 21.50 \end{aligned}$$

Similarly, for A_2:

$$A_{2,WSM-score} = 22.00$$

For A_3

$$A_{3,WSM-score} = 21.75$$

and finally

$$A_{4,WSM-score} = 20.00$$

Therefore, the best alternative in the maximization case is alternative A2 (because it has the highest WSM score; 22.00). Moreover, the following ranking is derived: $A_2 > A_3 > A_1 > A_4$ (where the symbol " $>$ " stands for "better than").

4.1.2 Weighted Product Method (WPM)

The Weighted Product Model (WPM) is very similar to the WSM. The main difference is that instead of addition in the model there is multiplication. The application of WPM is accomplished by using the same criteria having same weight values used in the previous use-case. The only difference lies in that; three alternatives are considered for simplicity. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In general, in order to compare two alternatives A_K and A_L the following product (Bridgman [113] and Miller and Starr [114] has to be calculated:

$$R\left(A_K/A_L\right) = \prod_{j=1}^{n} \left(a_{Kj}/a_{Lj}\right)^{w_j}, \tag{4.3}$$

where n is the number of criteria, a_{ij} is the actual value of the $i-th$ alternative in terms of the $j-th$ criterion, and w_j is the weight of importance of the $j-th$ criterion. If the term $R\left(A_K/A_L\right)$ is greater than or equal to one, then it indicates that alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to all other alternatives.
The WPM is sometimes called dimensionless analysis because its structure eliminates any units of measure. Thus, the WPM can be used in single and multi-dimensional MCDM. An advantage of the method is that instead of the actual values it can use relative ones. This is true because:

$$\frac{a_{Kj}}{a_{Lj}} = \frac{a_{Kj}/\sum_{i=1}^{n} a_{Ki}}{a_{Lj}/\sum_{i=1}^{n} a_{Li}} = \frac{a/_{Kj}}{a/_{Lj}} \tag{4.4}$$

A relative value $a/_{Kj}$ is calculated using the formula: $a/_{Kj} = a_{Kj}/\sum_{i=1}^{n} a_{Ki}$ where the a_Kj's are the actual values. Consider the problem presented in the previous WSM use-case while the omitting the alternative A_3 for simplification. However, now the restriction to express all criteria in terms of the same unit is not needed. When the WPM is applied, then the following values are derived:

$$\begin{aligned} R\left(A_1/A_2\right) &= (25/10)^{0.20} \times (20/30)^{0.15} \times (15/20)^{0.40} \times (30/30)^{0.25} \\ &= 1.007 > 1. \end{aligned}$$

Similarly, we also get:

$$R\left(A_1/A_3\right) = 1.067 > 1,$$

and $R\left(A_2/A_3\right) = 1.059 > 1$. Therefore, the best alternative is A_1, since it is superior to all the other alternatives. Moreover, the ranking of these alternatives is as follows: $A_1 > A_2 > A_3$. An alternative approach with the WPM method is for the decision maker to use only products without ratios. That is, to use the following variant of formula (4.3):

$$P(A_K) = \prod_{j=1}^{n} \left(a_{Kj}\right)^{w_j}, \tag{4.5}$$

In the previous expression the term $P(A_k)$ denotes the performance value (not a relative one) of alternative A_k when all the criteria are considered under the WPM model. Then, when the previous data are used, exactly the same ranking is derived.
The proposed load balancing schemes that in turn are called link selection mechanisms outperforms the various load balancing algorithms (Weighted Round Robin Scheduling, Weighted Least Connection Scheduling, Random Selection, Hash Over Called/ From URI/ To URI/ Request URI) offering more control and flexibility. But Companym@ges framework requires some refined and tuned mechanism due to the dynamic variations, diverse services groundwork, varied access network bindings and compound infrastructure while offering unified communication. Moreover the WSM method does not accommodate more than one dimensions and WPM method while handling multi-dimensional data does not accommodate fluent variations and dynamicity over the proposed architecture.

4.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS, developed by Yoon and Hwang [115] is used for decision computation to accommodate dynamicity, fluent variability and fluctuations over the platform. It is an alternative to ELECTRE [116] and is considered to be one of its variants. TOPSIS is known as a double standard method that evaluates alternatives through two basic criteria. First, the chosen alternative should have the shortest distance from the positive ideal solution and secondly it must be farthest from the negative-ideal solution for the posed MCDM problem. The perceived positive and negative ideal solutions are based on the range of attribute values available for the alternatives. The distances are measured in Euclidean terms. The Euclidean distance approach is proposed to evaluate the relative closeness of the alternatives to the ideal solution. The reason for choosing TOPSIS is that it will rank/grade the available alternatives (links) whenever applied by taking into account all the variations/dynamics and static configurations of the platform

4.2.1 Problem Formulation and Application of TOPSIS

The process of decision-making involves choosing the best alternative, given a set of alternatives (available external links and a set of criteria (context of the request and predefined configurations/settings over the proposed platform). These alternatives can also be ranked on the basis of multiple criteria using some specific MCDM method. MCDM methods have been used to help solve a wide variety of problems in many different applications such as telecommunications, manufacturing, transportation and software engineering [117–120]. Experiences show that there is not a single MCDM technique to deal with all multi-criteria problems. Indeed each situation requires a specific MCDM technique. The choice of the technique and its impact on the decision-making is not within the scope of this work and the reader is referred to [121] for an overview of this particular domain. The targeted objectives in the multi-criteria decision-making problems might sometimes be conflicting and/or overlapping. There are various approaches to deal with such sort of problems, each having its pros and cons but this issue is not within the scope of present work.
Each MCDM problem is associated with multiple attributes. These attributes are linked to the goals and are referred to as decision criteria. Since different criteria represent different dimensions of alternatives, they may conflict with each other (e.g., cumulative bandwidth may be confused with total bandwidth, traffic measurements, granularity (call/connection/session level) mania, cost, etc.). The underlying criteria are assigned different weights accordingly.
Conventional algorithms used for link selection at private-public network border with multi-homing support are either service-centric or diverged from congestion or the or converged towards SLA compliance or focalize for efficient resource utilization over the platform and/or they are rationalize towards application optimization for desired QoS and QoE. However, to cope with all these multi-criteria goals and objectives, MCDM theory is required.

4.2.1.1 TOPSIS MCDM Method Application Steps

For brevity and to avoid the complexity of stringent mathematics, 6 attributes are chosen for the application of MCDM methods on 4 alternative links (architecture shown on left hand side of Fig. 4.1) for routing the multimedia sessions (voice and video communication is emphasized here due to resource and QoS requirements). Fig. 4.3 illustrates the hierarchy of the desired goal, the criteria and the available alternative links. As mentioned earlier that SIP based multimedia communication is focused, so let us have the QoS requirements for these services as follows: Video Call: It requires a higher bandwidth than voice so the available bandwidth, the transport cost and current utilization are important factors. Its ability to buffer a longer duration data before playback makes it less vulnerable to delay and jitter than voice.
Voice Call: It is very sensitive to delay and jitter, requiring low bandwidth but this

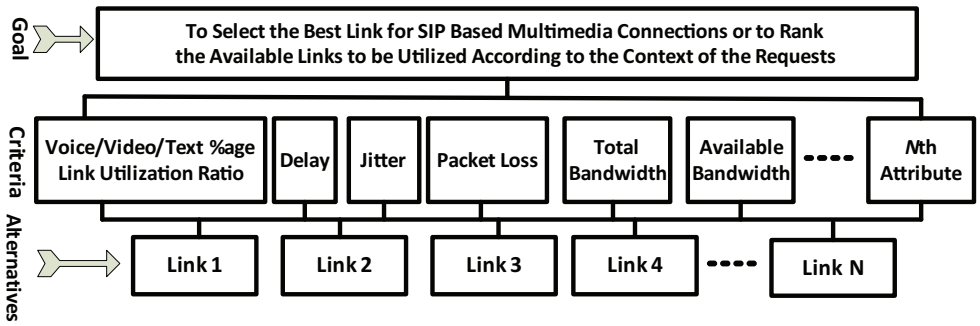

Figure 4.3: Candidate Links (Alternatives), Attributes (Criteria) and Objectives(Goals) Hierarchy

service is susceptible to packet losses to some extent. Because of its low bandwidth usage, the transport cost factor is considered negligible. Total bandwidth and available bandwidth are not significant factors due to low bandwidth requirements. Since there is some correlation of utilization with jitter and delay, it is preferred to have a low utilization for the selected network.
There are four links L_1, L_2, L_3 and L_4 and 6 attributes: Utilization Ratio UR, Delay (D), Jitter (J) Packet Loss (PL), Total Bandwidth (TB) and Available Bandwidth (AB) respectively are considered for the application of TOPSIS over the platform. The row vector attributes representing the corresponding alternatives (links) as follows:

$$L_i = \left[\begin{array}{cccccc} UR & D & J & PL & TB & AB \end{array} \right] \tag{4.6}$$

These row vectors shown in equation 4.6 corresponding to alternative links constitutes the Decision Matrix (DM) as follows:

$$DM = \left[\begin{array}{cccccc} UR_1 & D_1 & J_1 & PL_1 & TB_1 & AB_1 \\ UR_2 & D_2 & J_2 & PL_2 & TB_2 & AB_2 \\ UR_3 & D_3 & J_3 & PL_3 & TB_3 & AB_3 \\ UR_4 & D_4 & J_4 & PL_4 & TB_4 & AB_4 \end{array} \right] \begin{array}{l} < -L_1 \\ < -L_2 \\ < -L_3 \\ < -L_4 \end{array} \tag{4.7}$$

The corresponding column vectors shown in equation 4.7 represent the corresponding criteria and different weights are assigned in accordance to the context and platform's pre-defined rules and settings. The numerical values of these attributes are extracted/computed from the SNMP traps, Service Level Agreements (SLAs) related to the corresponding links over the platform and pre-defined business objectives and rules over the converged infrastructure. TOPSIS application steps are applied on the DM as follows:

1. Normalize the Decision Matrix containing the link attributes: the process is to transform different scales and units among various criteria into common measur-

able units in order to allow comparisons across the criteria. As the parameters involved in the DM come from different sources, the units representing the values are different. Normalization of these parameters is required in order to make them unit-less. The attributes having bigger values (e.g., TB is in Mega) are divided by the largest value in the corresponding column vector while the smaller range attribute (e.g., D, which is in milliseconds) is divided by the smallest value in the corresponding column vector. The normalized Decision Matrix is given by

$$\widetilde{DM} = \begin{bmatrix} \widetilde{UR}_1 & \widetilde{D}_1 & \widetilde{J}_1 & \widetilde{PL}_1 & T\widetilde{B}_1 & A\widetilde{B}_1 \\ \widetilde{UR}_2 & \widetilde{D}_2 & \widetilde{J}_2 & \widetilde{PL}_2 & T\widetilde{B}_2 & A\widetilde{B}_2 \\ \widetilde{UR}_3 & \widetilde{D}_3 & \widetilde{J}_2 & \widetilde{PL}_3 & T\widetilde{B}_3 & A\widetilde{B}_3 \\ \widetilde{UR}_4 & \widetilde{D}_4 & \widetilde{J}_4 & \widetilde{PL}_4 & T\widetilde{B}_4 & A\widetilde{B}_4 \end{bmatrix} \begin{matrix} L_1 \\ L_2 \\ L_3 \\ L_4 \end{matrix} \tag{4.8}$$

2. The next step is to construct the weighted normalized DM: it cannot be assumed that each evaluation criterion is of equal importance because the evaluation criteria have various meanings. As we are emphasizing over voice communication (an outbound call in the presented use-case), the Delay and Jitter are given more importance to meet QoS requirements and hence, the weights corresponding to each attribute in the DM are chosen according to the context. The available bandwidth is coupled with the user profile loaded from the profile base (in the case of a gold profile, it is highly desirable to choose the link with good available bandwidth so AB and U will also be given appropriate weight values). Business objectives of the platform and the preconfigured configurations over the architecture are pivotal indicators for suitable weight values. These assigned weights illustrate the relative importance of each attribute in the DM such that:

$$W = W_{UR} + W_D + W_J + W_{PL} + W_{TB} + W_{AB} = 1 \tag{4.9}$$

The corresponding weighted normalized entities in the DM are represented by subscript wn (e.g. for UR will be UR_{wn}). Now positive and negative ideal solutions for each attribute are computed: the positive ideal solution indicates the most preferable alternative and the negative ideal solution indicates the least preferable alternative as follows (e.g. voice/video link Utilization Ratio, UR):

$$UR^+ = (Max\,(UR_{wn})_i) \parallel (Min\,(UR_{wn})_i)\,, i = 1, 2, 3, 4 \tag{4.10}$$

and

$$UR^- = (Min\,(UR_{wn})_i) \parallel (Max\,(UR_{wn})_i)\,, i = 1, 2, 3, 4 \tag{4.11}$$

3. The Euclidean distance method is applied to measure the separation from the

positive and negative ideal for each alternative

$$S_i^+ = \sqrt{\begin{array}{c}((UR_{wn})_i - UR^+)^2 + ((D_{wn})_i - D^+)^2 + ((J_{wn})_i - J^+)^2 + \\ ((PL_{wn})_i - PL^+)^2 + ((TB_{wn})_i - TB^+)^2 + ((AB_{wn})_i - AB^+)^2\end{array}} \tag{4.12}$$

and

$$S_i^- = \sqrt{\begin{array}{c}((UR_{wn})_i - UR^-)^2 + ((D_{wn})_i - D^-)^2 + ((J_{wn})_i - J^-)^2 + \\ ((PL_{wn})_i - PL^-)^2 + ((TB_{wn})_i - TB^-)^2 + ((AB_{wn})_i - AB^-)^2\end{array}} \tag{4.13}$$

4. Finally, the candidate links are ranked by measuring the relative closeness of an alternative (candidate links L_1, L_2, L_3 and L_4 under consideration represented by a row vector in the Decision Matrix) to the ideal solution S^+ as follows:

$$R_i = \frac{S_i^+}{S_i^+ + S_i^-} \tag{4.14}$$

The links L_1, L_2, L_3 and L_4 characterized by attributes voice/video Utilization Ratio UR, Delay (D), Jitter (J) Packet Loss (PL), Total Bandwidth (TB) and Available Bandwidth (AB) respectively are represented by the values shown in Table 4.1. SIP-based voice communication is considered here so D, J and PL are given higher weights (outgoing voice call) while keeping in view the required bandwidth judged from the codec negotiated during the call setup. The alternative links with parametric

	UR	**D**	**J**	**PL**	**TB**	**AB**
	%age	**Milliseconds (ms)**	**ms**	**%age**	**Megabits per second (Mbps)**	**Mbps**
$\mathbf{L_1}$	66.65	300	50	35	100	65
$\mathbf{L_2}$	53.84	200	25	25	100	71
$\mathbf{L_3}$	81.81	100	15	10	100	81
$\mathbf{L_4}$	25.00	150	30	30	100	46

Table 4.1: Links With Corresponding Parametric Values

numerical values represented by the row vector with corresponding criteria indicated by column vectors are ranked after the application of TOPSIS. The ranking against the R-values of the alternative links are shown in table 4.2 TOPSIS is applied on the Companm@ges proposed architecture in order to accommodate the multiple criteria and diversified data sets while capturing the dynamic variations offering multi-dimensional support. Occasionally, the column vectors inside the decision matrix repressing the

	$\mathbf{L_1}$	$\mathbf{L_2}$	$\mathbf{L_3}$	$\mathbf{L_4}$
R Value	0.0788	0.6852	0.7805	0.7186
Rank	4	3	1	2

Table 4.2: R Values and the Corresponding Grading of Alternative Links

corresponding criteria (e.g. jitter) might not have exact and accurate numerical values. Decision engine inside the PS require frequent and fast interactions with different planes and domains over the platform to gather the required data to calculate the corresponding attributes that in turn are utilized for decision commutation. Moreover, the proposed platform is binding the access technology from diverse carriers, it converge different services being offered by another group of providers over the same architecture, the cost might be handled by a third party enterprise and the applications are outsourced to a different company. The underlying scenario sparks an issue of level of access and poses the question on authenticity and accuracy of gathered information extracted from different data sets owned by different vendors. Hence TOPSIS is extended to provide the solution for such use-cases by defining upper and lower bounds representing the criteria for the application of an extended TOPSIS.

4.3 Extended TOPSIS

Due to convergence of diverse networking technologies, services and application, there might be situations in which information required to construct the decision matrix (which ultimately is processed to compute the decisions) is incomplete or imprecise or level of access is subjected to the reciprocal SLA or the lingua franca of the data sharing encourages probabilistic approach. To address the aforementioned issues, TOPSIS is extended by introducing the upper and lower bounds as the precise determination of exact values of the corresponding attributes are difficult.
Suppose $A_1, A_2, ..., A_m$ are m possible alternatives and $C_1, C_2, ..., C_n$ are the n criteria, x_{ij} is the measurement of the corresponding attribute correlated to alternative A_i and criterion C_j and it is not known exactly and the system only knows $x_{ij} \in \left[x_{ij}^L, x_{ij}^U\right]$. A MCDM problem with interval data can be concisely expressed in matrix format as follows:

$$DM = \begin{array}{c|cccc} & C_1 & C_2 & ... & C_n \\ \hline A_1 & \left[x_{11}^L, x_{11}^U\right] & \left[x_{12}^L, x_{12}^U\right] & ... & \left[x_{1n}^L, x_{1n}^U\right] \\ A_2 & \left[x_{21}^L, x_{21}^U\right] & \left[x_{22}^L, x_{21}^U\right] & ... & \left[2n, x_{2n}^U\right] \\ A_m & \left[x_{m1}^L, x_{m1}^U\right] & \left[x_{m2}^L, x_{m2}^U\right] & ... & \left[x_{mn}^L, x_{mn}^U\right] \end{array} \tag{4.15}$$

w's are the corresponding weights of the criteria representing the relative importance

$$W = [w_1, w_2, ..., w_n]$$

where w_j is the weight of criterion C_j. A systematic approach to extend the TOPSIS with interval data by considering the m alternative links while taking n attributes (criteria) into account includes establishing system evaluation criteria that connect the system capabilities to goals, developing the alternatives systems for achieving the goals, evaluating the alternatives in terms of criteria (construction of the utility functions) and identifying the weights for the corresponding criteria. The Extended TOPSIS application steps are as follows:
First we calculate the normalized decision matrix as follows:
The normalized values $\overline{n}_{ij}^L$ and $\overline{n}_{ij}^U$ are calculated as

$$\overline{n}_{ij}^L = x_{ij}^L / \sqrt{\sum_{j=1}^{m} \left(x_{ij}^L\right)^2 + \left(x_{ij}^U\right)^2}, \quad j = 1, 2, ..., m, \; i = 1, 2, ..., n. \tag{4.16}$$

$$\overline{n}_{ij}^U = x_{ij}^U / \sqrt{\sum_{j=1}^{m} \left(x_{ij}^L\right)^2 + \left(x_{ij}^U\right)^2}, \quad j = 1, 2, ..., m, \; i = 1, 2, ..., n. \tag{4.17}$$

Now interval $\left[\overline{n}_{ij}^L, \overline{n}_{ij}^U\right]$ is normalization of the interval $\left[x_{ij}^L, x_{ij}^U\right]$. The ranges of normalized interval numbers belong to $[0, 1]$. The next step is to construct the weighted normalized DM as it cannot be assumed that each evaluation criterion is of equal importance because the evaluation criteria have various meanings. As we are emphasizing voice communication (an outbound call in the presented use-case), and to meet QoS requirements of voice, (Delay and Jitter are given more weight values), we choose the weights corresponding to each attribute in the DM. The available bandwidth is coupled with the user profile loaded from the profile base (in the case of a gold profile, it is highly desirable to choose the link with good available bandwidth so AB and U will also be given appropriate weight values). Business objectives of the platform and the preconfigured configurations over the architecture are pivotal indicators for suitable weight values. These assigned weights illustrate the relative importance of each attribute in the DM such that:

$$\overline{v}_{ij}^L = w_i \overline{n}_{ij}^L, \quad j = 1, 2, ..., m, \; i = 1, 2, ..., n, \tag{4.18}$$

$$\overline{v}_{ij}^U = w_i \overline{n}_{ij}^U, \quad j = 1, 2, ..., m, \; i = 1, 2, ..., n, \tag{4.19}$$

where w_i is the weight of the ith attribute or criterion, and $\sum_{i=1}^{n} w_i = 1$. Next steps to identify positive ideal solution and negative ideal solution as follows:

$$\overline{A}^{+} = \left\{\overline{v}_1^{+}, ..., \overline{v}_n^{+}\right\} = \left\{\left(\max_j \overline{v}_{ij}^{U} \mid i \in I\right), \left(\min_j \overline{v}_{ij}^{L} \mid i \in J\right)\right\}, \quad (4.20)$$

$$\overline{A}^{-} = \left\{\overline{v}_1^{-}, ..., \overline{v}_n^{-}\right\} = \left\{\left(\min_j \overline{v}_{ij}^{L} \mid i \in I\right), \left(\max_j \overline{v}_{ij}^{U} \mid i \in J\right)\right\}, \quad (4.21)$$

where I is associated with benefit criteria, and J is associated with cost criteria. The separation of each alternative from the positive ideal solution, using the $n-$dimensional Euclidean distance, is calculated as

$$\overline{d}_j^{+} = \sqrt{\sum_{i \in I} \left(\overline{v}_{ij}^{L} - \overline{v}_i^{+}\right)^2 + \sum_{i \in J} \left(\overline{v}_{ij}^{U} - \overline{v}_i^{+}\right)^2}, \quad j = 1, 2, ..., m. \quad (4.22)$$

Similarly, the separation from the negative ideal solution is calculated as

$$\overline{d}_j^{-} = \sqrt{\sum_{i \in I} \left(\overline{v}_{ij}^{U} - \overline{v}_i^{-}\right)^2 + \sum_{i \in J} \left(\overline{v}_{ij}^{L} - \overline{v}_i^{-}\right)^2}, \quad j = 1, 2, ..., m. \quad (4.23)$$

A closeness coefficient is defined to determine the ranking order of all alternatives, once the $\overline{d}_j^{+}$ and $\overline{d}_j^{-}$ of each alternative A_j is calculated. The relative closeness of the alternative A_j with respect to $\overline{A}^{+}$ is defined as

$$\overline{R}_j = \overline{d}_j^{-} / \left(\overline{d}_j^{+} + \overline{d}_j^{-}\right), \quad j = 1, 2, ..., m. \quad (4.24)$$

Obviously, the alternative A_j is closer to the $\overline{A}^{+}$ and farther from $\overline{A}$ as $\overline{R}_j$ approaches to 1. Therefore, according to the closeness coefficient, system can determine the ranking order of all alternatives and select the link accordingly.

Extended TOPSIS resolved the issues of dynamicity and variability by capturing the inappropriate data sets knowledge that is not suitable for the appellation of simple TOPSIS and its extension (introduction of lower and upper bounds throughout its appellation steps) led the system to handle inaccurate and imprecise information. Moreover network management and control involves certain technology specific and technology independent attributes that require Min/Max, and/or lower/upper-threshold values (e.g. cost, bandwidth). Extended TOPSIS overcomes this issue by its application on interval data (i.e. lower and upper values of an attribute) over the proposed architecture.

TOPSIS and Extended TOPSIS are able to capture the dynamic behavior and fluent variations taking place over different control, network and access technology planes via different tweaked interfaces and modified protocols. But the context of the re-

quest/call/session is not being taken into account on the basis of fine granularity. Macro contexts information regarding the service, application, control, network/transport and access technology planes are taken into account while deploying TOPSIS and extended TOPSIS as well. But micro contexts information while considering the individual requests/calls/sessions that might contain technology specific and technology independent context-aware data at lower granularity (e.g. codec used during a voice call which reflect the bandwidth requirement, user type indicating the level of access and QoS profile etc.) has not been taken into account. To accommodate the context information at fine granularity along with the aforementioned dynamic information domains, another MCDM method is introduced.

4.4 Grey Relational Analysis (GRA)

GRA is a decision-making technique that is based on grey system theory. Originally developed by Deng [122], Grey theory is widely applied in fields such as systems analysis, data processing, modeling and prediction, as well as control and decision-making. It is an effective mathematical means to deal with systems characterized by conflicting and partial information. Grey relation refers to the uncertain relations among things, among elements of systems, or among elements and behaviors. Due of its ability to use reference attribute vector, it is being applied in the proposed decision-making system. Moreover, the platform's latest conditions and the context of the request are taken into account while constructing the reference vector.
GRA application is presented on similar grounds by considering 6 attributes representing the corresponding criteria on 4 alternatives (links) over the multi-homed platform. SIP-based voice call will be routed to one of the 4 alternative links by using the proposed decision engine. L_1, L_2, L_3 and L_4 are the four links and UR, D, J, PL, TB and AB are 6 attributes representing the voice/video Utilization Ratio, Delay, Jitter, Packet Loss, Total Bandwidth and Available Bandwidth respectively. The information from the context of the request is bundled with the link latest information to construct the reference vector as follows:

$$Ref\,(L) = \left[\begin{array}{cccccc} UR & D & J & PL & TB & AB \end{array}\right] \tag{4.25}$$

The candidate link attributes constituting the Decision Matrix (DM) is given as follows:

$$DM = \begin{array}{c} \left[\begin{array}{cccccc} UR_1 & D_1 & J_1 & PL_1 & TB_1 & AB_1 \\ UR_2 & D_2 & J_2 & PL_2 & TB_2 & AB_2 \\ UR_3 & D_3 & J_3 & PL_3 & TB_3 & AB_3 \\ UR_4 & D_4 & J_4 & PL_4 & TB_4 & AB_4 \end{array}\right] \end{array} \begin{array}{c} L_1 \\ L_2 \\ L_3 \\ L_4 \end{array} \tag{4.26}$$

The values of these attributes are obtained from the SNMP traps and the Service Level Agreements (SLAs) of the corresponding links over the platform. As the parameters

involved in the DM come from different sources, the units representing the values are different. We need to normalize these parameters in order to make them unit-less. The attributes having bigger values (e.g., TB is in Mega) are divided by the largest value in the corresponding column vector, while the smaller range attribute (e.g., D is in milliseconds) is divided by the smallest value in the corresponding column vector. The normalized Decision Matrix is given by

$$\widetilde{DM} = \begin{array}{c} \left[\begin{array}{cccccc} \widetilde{UR}_1 & \widetilde{D}_1 & \widetilde{J}_1 & \widetilde{PL}_1 & \widetilde{TB}_1 & \widetilde{AB}_1 \\ \widetilde{UR}_2 & \widetilde{D}_2 & \widetilde{J}_2 & \widetilde{PL}_2 & \widetilde{TB}_2 & \widetilde{AB}_2 \\ \widetilde{UR}_3 & \widetilde{D}_3 & \widetilde{J}_2 & \widetilde{PL}_3 & \widetilde{TB}_3 & \widetilde{AB}_3 \\ \widetilde{UR}_4 & \widetilde{D}_4 & \widetilde{J}_4 & \widetilde{PL}_4 & \widetilde{TB}_4 & \widetilde{AB}_4 \end{array} \right] \end{array} \begin{array}{c} L_1 \\ L_2 \\ L_3 \\ L_4 \end{array} \tag{4.27}$$

The normalized reference vector is given by

$$Ref\left(\widetilde{L}\right) = \left[\begin{array}{cccccc} \widetilde{UR} & \widetilde{D} & \widetilde{J} & \widetilde{PL} & \widetilde{TB} & \widetilde{AB} \end{array} \right] \tag{4.28}$$

Now the distance between the corresponding normalized reference vector entities and the normalized Decision Matrix entities is calculated as follows:

$$\Delta_{UR_i} = \left| \widetilde{UR} - \widetilde{UR}_i \right|, i = 1, 2, 3, 4 \tag{4.29}$$

The Δ Decision Matrix is obtained by applying Eq. 4.29 to the corresponding entities in the normalized Decision Matrix and the normalized reference vector:

$$\Delta_{DM} = \begin{array}{c} \left[\begin{array}{cccccc} \Delta_{UR_1} & \Delta_{D_1} & \Delta_{J_1} & \Delta_{PL_1} & \Delta_{TB_1} & \Delta_{AB_1} \\ \Delta_{UR_2} & \Delta_{D_2} & \Delta_{J_2} & \Delta_{PL_2} & \Delta_{TB_2} & \Delta_{AB_2} \\ \Delta_{UR_3} & \Delta_{D_3} & \Delta_{J_3} & \Delta_{PL_3} & \Delta_{TB_3} & \Delta_{AB_3} \\ \Delta_{UR_4} & \Delta_{D_4} & \Delta_{J_4} & \Delta_{PL_4} & \Delta_{TB_4} & \Delta_{AB_4} \end{array} \right] \end{array} \begin{array}{c} L_1 \\ L_2 \\ L_3 \\ L_4 \end{array} \tag{4.30}$$

Grey Relation Coefficients (GRCs) representing the measurement of similarity of an attribute to its reference are calculated (e.g. for voice/video Utilization Ratio of a link UR) as follows:

$$GRC_{UR_i} = \frac{\Delta_{\min} + \alpha\Delta_{\max}}{\Delta_{UR_i} + \alpha\Delta_{\max}}, i = 1, 2, 3, 4 \tag{4.31}$$

where $\alpha \in [0, 1]$; $\Delta_{\min}$ and $\Delta_{\max}$ are calculated as follows:

$$\Delta_{\max} = \max_i \left(\Delta_{UR_i} + \Delta_{D_i} + \Delta_{J_i} + \Delta_{PL_i} + \Delta_{TB_i} + \Delta_{AB_i}\right) \tag{4.32}$$

$$\Delta_{\min} = \min_i \left(\Delta_{UR_i} + \Delta_{D_i} + \Delta_{J_i} + \Delta_{PL_i} + \Delta_{TB_i} + \Delta_{AB_i}\right) \tag{4.33}$$

As we are emphasizing on voice communication (outbound calls) and to meet the QoS requirements of voice, (Delay and Jitter are given more weight), we choose the weights

corresponding to each attribute in the Decision Matrix. The available bandwidth is coupled with user profile loaded from the profile base (in case of gold profile, it is highly desirable to choose the link with good available bandwidth so AB and U will also be given suitable weight values). These assigned weights illustrate the relative importance of each attribute in Decision Matrix such that:

$$W = W_{UR} + W_D + W_J + W_{PL} + W_{TB} + W_{AB} = 1 \tag{4.34}$$

The weighted GRC coefficient representing an attribute column is given by:

$$GRC_{wUR_i} = W_{UR} * GRC_{UR_i}, i = 1, 2, 3, 4 \tag{4.35}$$

The resulting weighted GRC matrix is given by equation 4.36.

$$GRC_{wDM} = \begin{array}{c} \left[\begin{array}{cccccc} GRC_{wUR_1} & GRC_{wD_1} & GRC_{wJ_1} & GRC_{wPL_1} & GRC_{wTB_1} & GRC_{wAB_1} \\ GRC_{wUR_2} & GRC_{wD_2} & GRC_{wJ_2} & GRC_{wPL_2} & GRC_{wTB_2} & GRC_{wAB_2} \\ GRC_{wUR_3} & GRC_{wD_3} & GRC_{wJ_3} & GRC_{wPL_3} & GRC_{wTB_3} & GRC_{wAB_3} \\ GRC_{wUR_4} & GRC_{wD_4} & GRC_{wJ_4} & GRC_{wPL_4} & GRC_{wTB_4} & GRC_{wAB_4} \end{array} \right] \end{array} \begin{array}{c} L_1 \\ L_2 \\ L_3 \\ L_4 \end{array} \tag{4.36}$$

The GRC value for individual link is calculated as follows:

$$\begin{aligned} Coef\,(GRC)_i = GRC_{wUR_i} + GRC_{wD_i} + GRC_{wJ_i} + GRC_{wPL_i} \\ + GRC_{wTB_i} + GRC_{wABi}, i = 1, 2, 3, 4. \end{aligned} \tag{4.37}$$

The Candidate Link with the highest GRC coefficient value is the final decision, i.e., the best link for the request. The links L_1, L_2, L_3 and L_4 characterized by attributes UR, D, J, PL, TB and AB are represented by the values shown in Table 4.3. D, J and PL are given higher weights due to voice call (outgoing) while keeping in view the required bandwidth judged from the codec negotiated during the call setup. For the application of GRA on the links represented by the corresponding row vectors in Table 4.3, all the steps are gone through in the order stated above in this section. The links are ranked with GRC values as mentioned in Table 4.4. The Candidate Link

	UR	**D**	**J**	**PL**	**TB**	**AB**
	%age	**Milliseconds (ms)**	**ms**	**%age**	**Megabits per second (Mbps)**	**Mbps**
$\mathbf{L_1}$	49.65	145	21	22	100	80
$\mathbf{L_2}$	31.84	150	24	26	100	79
$\mathbf{L_3}$	20.81	110	18	13	100	88
$\mathbf{L_4}$	25.00	155	32	28	100	74

Table 4.3: Links With Corresponding Parametric Values

	L_1	L_2	L_3	L_4
GRC Value	0.4624	0.4107	0.8101	0.3981
Rank	2	3	1	4

Table 4.4: GRC Values and the Corresponding Grading of Alternatives (Links).

with the highest GRC coefficient value shown in 4.4 is ranked as best and the alternative with the 2nd highest GRC value is graded as number 2 and so and so forth. There are two possibilities for calculating/declaring the reference attribute vector: the first is to compute the reference attribute vector before the request arrives and the second is to calculate it on the fly (on-line). The susceptible QoS sets of parameters are well defined and known for multimedia communication (voice and video). The range of required bandwidth for different codecs (used by the end points during the multimedia communication) is also well documented. The attribute, available bandwidth is calculated by keeping the track of number of ongoing calls/requests on a particular link (i.e., Available Bandwidth=Total Bandwidth - Used Bandwidth). It is important to mention that the presented GRA includes the simplest possible case. Embedding the reference vector beforehand can be tedious and complex as the number of links and attributes increases. The business objectives of an enterprise might change (e.g., voice might be given priority over video, the silver profile might use gold profile service during night (free hours), etc.), the user profile priorities/authentication/authorization parameter (QoS profile corresponding to a user profile) may go through modification, or the link resources might go through up-gradation/downgrading. The underlying complexity can be handled though, but it requires extensive administrative efforts. The objective however, is to minimize these efforts at minimal while taking into account the dynamicity that the conventional and manual systems are not able to accommodate.

4.5 Summary

This chapter formulates the multi-dimensional planer representation of technology specific and technology independent data sets over the hybrid framework from different domains by framing the multifaceted orientation of access technology convergence for the application of MCDM. A basic use-case for the application of MCDM (WSM) pertaining to Companyma@ges simplest scenario is initially presented for routing the calls to different links at private-public network border. WSM outperforms the conventional load balancing algorithms. However, it can only handle single dimensional problem. WPM addresses the dimensionality issue by supporting multi-criteria attributes. These subsequent methods (WSM and WPM) are not able to tackle the dynamicity and fluent variations over the unified infrastructure with multi-homing support. TOPSIS is then introduced to capture the dynamic variations and frequent fluctu-

ations over the unified platform. TOPSIS elaborates candidate links (alternatives), attributes (criteria) and objectives (goals) by connecting them in a hierarchy. The underlying TOPSIS method is then extended to handle incomplete/inappropriate/imprecise data sets by introducing the upper and lower bounds. Finally GRA is used to overcome the shortcomings of ignoring the context information of the call/session/request.

5

Policy Engine in Companym@ges Framework

RULE based management and control is a familiar technique used for effective and efficient administration of heterogeneous networks. It brings flexibility to the platform while accommodating the frequent variation by change management. The ultimate goal is to adapt the behavior dynamically without resetting/restarting/stopping the system by inheriting the corresponding intrinsic and extrinsic knowledge base from different domains over the hybrid platform. This knowledge base along with business objectives of the platform and administrative configurations are exploited for policy (decision) computation. These decisions are meant to govern the behavior of the communication infrastructure by enforcing these decisions at different granularity over the platform.

Policy/decision framework requires information model, semantics variations/behavioral fluctuations capturing mechanism/tools, information sharing/dissemination and intercommunication procedure, protocols especially the signaling protocols for control and management data sharing at micro and macro level and the language over the infrastructure to represent the platform's rules, business objectives and administrative and/or configurational instructions in a standardized and understandable fashion over the converged infrastructure. This chapter presents the decision engine's (constituting an important and key component of PS) modular framework, the flow and sequence of information among various modules and components within the decision engine. The information model representing the knowledge base over the platform is discussed in consent with the underlying decision engine. Three information models are analyzed and discussed keeping in view the platform's requirements and the expertise and it is proposed to adapt an existing information model. Language should be deeply rooted within the framework in order to avoid the conflicts, enforcement issues along with the behavioral, communicational and functional representation difficulties. Three languages are analyzed and compared keeping in view the Companym@ges framework for the same use case used for the analysis and application of MCDM. None of the languages fulfills the requirements even for the simple use case of call routing at

private-public network border. So a language is developed but its simple version for the same use case is presented. After presenting all the ingredients of the rule based management and control framework, a test bed for validating the decision computation and its enforcement is illustrated using the same use case previously used for MCDM methods application and comparisons. Observations for the corresponding metrics (throughput, Call Dropping Probability (CDP), and delay) that are important and sensitive regarding the multimedia communication are performed/captured and compared for the subsequently adapted 5 MCDM methods. Decision system supports online and offline decision computation. Decision enforcement in the provisioning and outsourcing mode is discussed keeping in view the online and offline decision computation. Two metrics of the system (CDP and delay) are observed and plotted for the underlying decision computation in coordination with decision enforcement.
It is emphasized throughout the document that the framework supports technology and service convergence with heterogeneous infrastructure while supporting the multi-homed network. But the tests and observations are conducted by considering the routing problem at private-public network however it is important to note that out interest is the fist hop so the solution is not intended to cater the end to end route computation/calculation problem. To validate the convergence and heterogeneity, an environment is built by tweaking the all-open source solutions. The decision engine over this unified framework has the capability of handing the dynamic routing the converged border in addition to its ability to handle the horizontal handover decisions without resetting/restating the system. Stress testing of the unified platform accommodating the routing decisions and horizontal handover in consent with the multi criteria decision making targeting multiple objectives is accomplished using the same test bed but with certain adaptations and modifications. Observations are made for different parameters and are then plotted for dissuasion and comparisons.
MCDM theory is used for decision computation/calculation and the adapted methods are exploited according to the scenario and decision computation mode while keeping in view the corresponding enforcement mode. Weight computation within those MCDM methods is crucial as it identifies the relative importance of the underlying criteria. Weight computation of the corresponding criteria is applied and a scale is revised according to the requirement over the platform. Finally ontology is integrated with the adapted MCDM methods in order to capture the semantics variation over the platform. Simple use case used before for validation of the concepts is emulated for the proof of the concept of ontology and MCDM integration and the results are discussed and compared.

5.1 Decision Engine Modular Framework

Decision Engine is the core and central unit within the PS. It takes all the technology specific and technology independent static/dynamic information into account

over the heterogeneous infrastructure. Decision Engine's functionality regarding the MCDM theory is illustrated in Fig. 5.1. All the planer and domain specific information is fetched and adapted for the construction of goal, criteria/sub-criteria and alternatives hierarchy. Global and local priorities are taken into account keeping in view the corre-

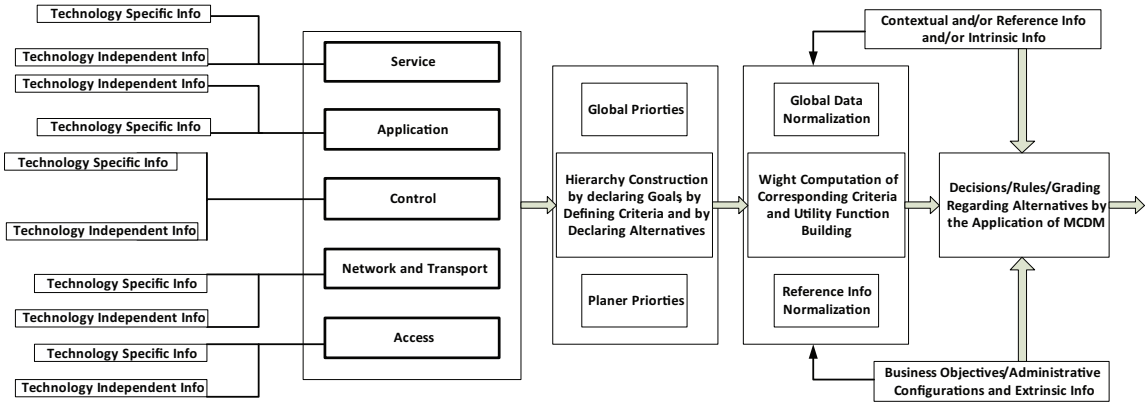

Figure 5.1: MCDM in the Context of Decision Engine.

sponding services and QoS profiles. Normalization helps in accommodating the multi dimensional data sets. The intrinsic and extrinsic information reflecting the dynamicity and variations is taken into account. The chosen MCDM method is applied for decision/rule computation. These decisions are enforced keeping in view the context of the request, business objectives of the platform, latest state of the network and/or administrative configurations over the infrastructure. An illusion of the diverse information domains/planes and their corresponding mapping of the distinctive attributes and/or parameters is presented in Fig. 5.2. The G's, C's and A's with the specific subscripts are the relevant goals, criteria and alternatives over these distinct layers presenting the corresponding information domains or planes. The underlying mapping helps in hierarchy construction by declaring the goals, fixing the criteria and the alternatives while describing the resources over the converged platform, reflecting the business objectives of the platform and ultimately presenting the service/application logic for dynamic decision making.

Block diagram shown in Fig. 5.3, illustrates the modular framework of Decision Engine that partly constitutes the PS. All the units are connected via the adaptive control/trigger bus. Resource manager in the unified communication environment keeps all the business, system, network and service level resource information. Context manager detects any sort of changes in the application/service plane, network/transport plane and business objectives of the platform and triggers a new set of rules for control and adaptation. The inference engine via the semantics fusion/normalization unit drives the parser for ontology inheritance and overloading in addition to the reasoning and learning performed under the dictation of embedded axioms. Knowledge base

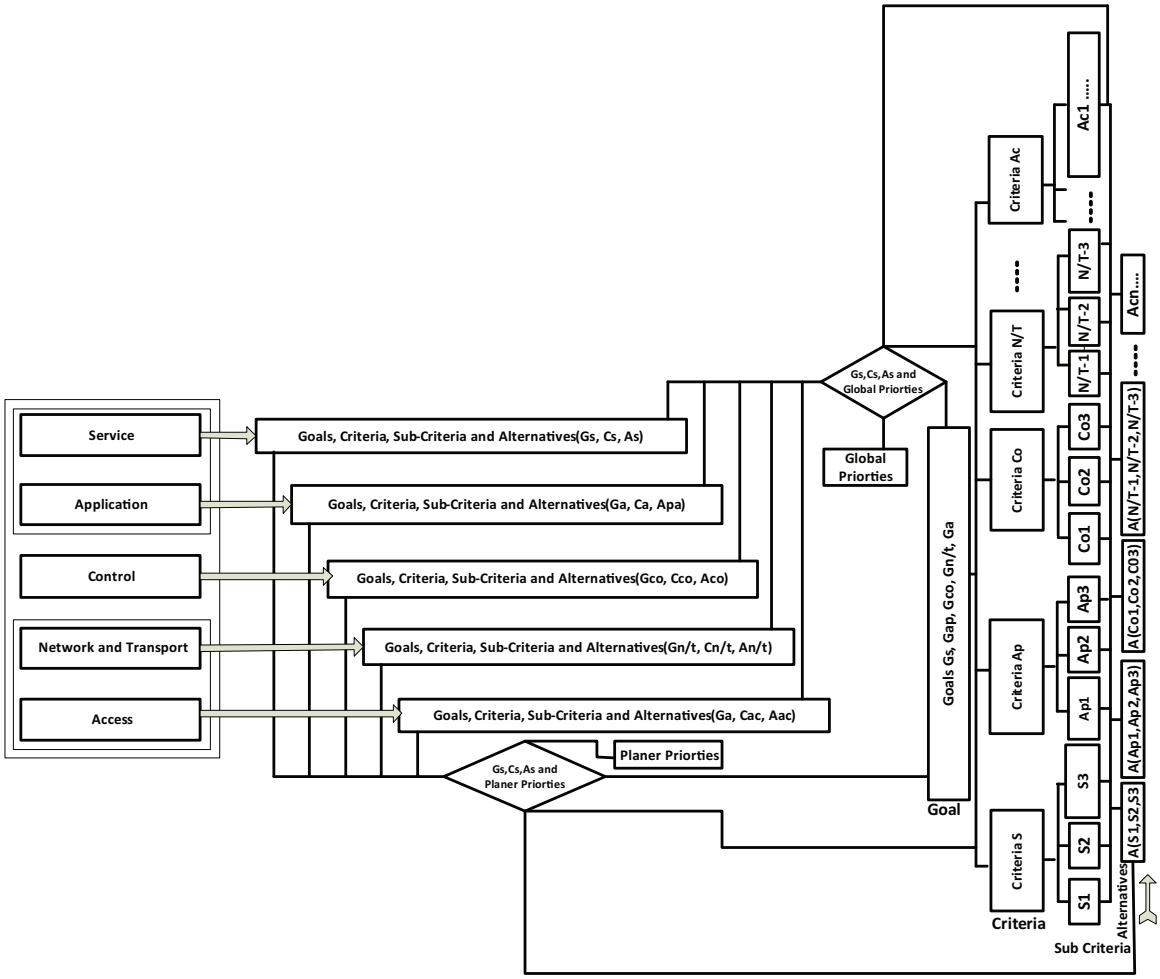

Figure 5.2: Platform's Layered and Planer Representation and Their Corresponding Mapping to Goals, Criteria and Alternatives Hierarchy

unit contains all the technology specific and technology independent service, profile and network data sets. Rule manager contains the predefined set of rules added by the administrator of the platform reflecting the targeted goals. Decision engine is analyzing, adapting and handling the multi-criteria and multidimensional information coming from different sources with multiple objectives. The underlying system precisely illustrates different components and their interactions. Decision Engine use ontology in coordination with MCDM over the unified platform for capturing the semantic variations alongside multiple criteria and versatile objectives.

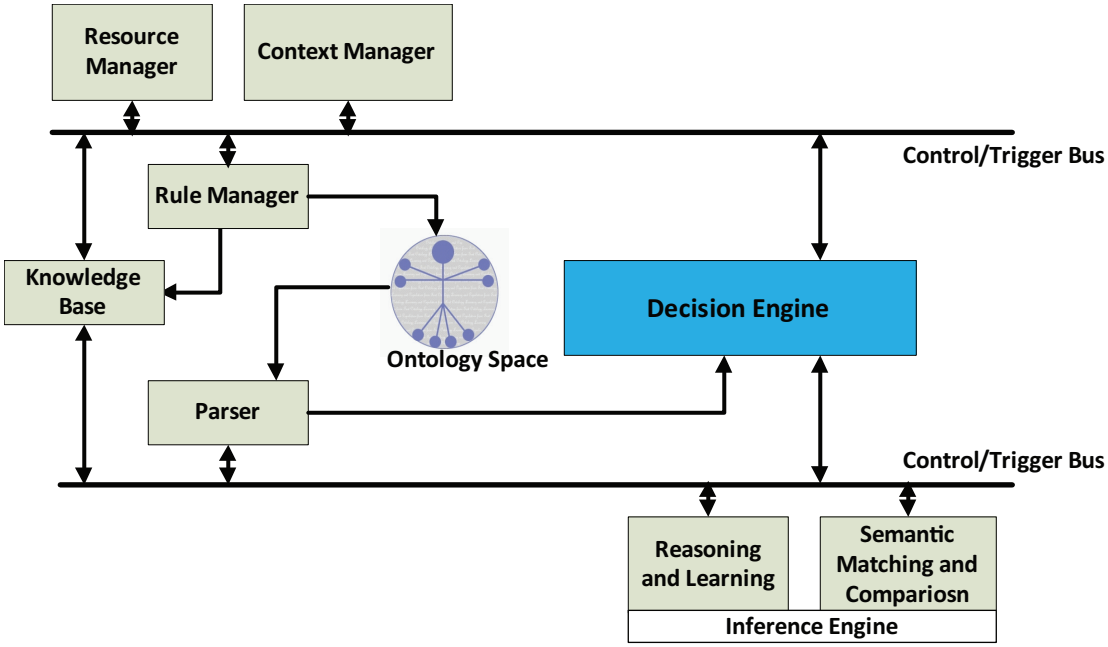

Figure 5.3: Modular Framework of the Decision Engine.

5.2 Information Models for PBNM and Extracted Model for the Platform

An information model is a representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse (or plane e.g. service plane, control plane etc.) . It provides sharable, stable and organized structure of information requirements for the domain/plane context. The real objects over the system are abstracted by the information model. It provides formalism to the description of those specific domains/planes without constraining how that description is mapped to an actual implementation. Thus, different mappings can be derived from the same information model.

Information models are a mean to represent the characteristic and behavior of system entities. Three models discussed previously in the introductory chapter (CIM, SID and DEN-ng) are analyzed to choose the one accordingly. The features are listed and compared in Table 5.1.

CIM does not provide specifications for important network concepts such as separation of physical and logical device interfaces, templates for network entities (routers, bridges, gateways etc.). Moreover it does not support QoS models that contribute a lot towards network requirement, management and control. SID is left out due to the following reasons; first SID is inflexible compared to DEN-ng, secondly, the business-to-network translation and vice-versa can not be realized in any tangible form, thirdly,

Feature	**DEN-ng**	**SID**	**CIM**
Classification Theory Patterns	Strictly used	Not consistently used	Not used at all
Views	Life-chain, not life-cycle	Business only	One view
Policy Model	DEN-ng v6.6.4	DEN-ng v3.5 O	IETF model
Policy Application Model	66DEN-ng v6.6.4	NONE	NONE
Policy Negotiation Model	DEN-ng v6.6.4	NONE	NONE
State Machine Model	DEN-ng v6.6.4	NONE	NONE
Ontology Compatibility	STRONG	NONE	NONE
Capability Model	DEN-ng v6.6.4	NONE	Simplified
Context Model	DEN-ng v6.6.4	NONE	NONE
Metadata Model	DEN-ng v6.6.4	NONE	NONE
Supports ECA model	YES	YES	NO
Supports Goal Policies	YES	NO	NO
Supports Utility Functions	YES	NO	NO
Separates Policy Representation from Content	YES	NO	NO
Supports Policy Contract Definitions	Yes	If built	NO
Supports Policy Subjects and Targets	YES	NO	NO
Separate Metadata for Policy Rules vs. Component	YES	NO	NO
Separate Metadata for different Policy Rule types	YES	NO	NO
Context-Aware Policy Definition	YES	NO	NO
Supports External Application Integration	YES	NO	NO
Supports Extensible Application Definition	YES	NO	NO

Table 5.1: Comparison of DEN-ng, SID and CIM

it can not accommodate context and finally it does not provide artifact for the design of entities behavior such as state machine. Dynamic PBNM requires an information model that is able to describe different entities over the infrastructure with change management. Moreover the model should reflect the technology neutrality in order to accommodate the different concepts and mechanisms to represent, measure, and manage information over distinct planes/domains. DEN-ng, an object-oriented information model provides the aforementioned features. It uses software patterns to describe complex architectures efficiently and make the model more understandable and extensible. A pattern defines a generic, reusable solution to a commonly occurring problem by improving the model's readability and reusability. The development team involved in the Companym@ges project extracted/extended the DEN-ng by tagging the base model for the platform accordingly.

5.3 Rule Specification Languages and the Followed Approach

PBNM allows organizations to apply rules and regulations on their infrastructure where policies are often applied to automate network administration tasks. Dynamic PBNM accommodates the change management and business processes by following the business logic of the company. Multiple approaches for policy specification have been proposed that range from formal policy languages that can be directly processed by a computer, to rule-based policy notations, and to representation of policies as entries in a table consisting of multiple attributes. Three languages, ponder, KAoS and Rei [123–125] are evaluated in the context of our framework and the corresponding requirements. Lets consider the simple use case mentioned before in chapter 4, comprising of 4 alternative links and the six attributes that are extracted from the underlying platform having different planes (service, application, control network and transport, access technology etc.), It is assumed that the cost over the platform is calculated in terms of total number of calls to avoid complexity. The platform offers the provision of adding new services from different providers. The business logic of the company may go through changes/modifications. Those 6 attributes chosen for the application of MCDM for decision making are abstracted and are linked to the criteria representing the generalized attributes as shown in Fig. 5.4. These policy languages have their own syntax and semantics and are connected to different building blocks providing a policy framework enriched strongly with policy specifications and management mechanism. The architecture (Fig. 4.1 is used in the context of rule specifications, management, analysis and the enforcement of decisions by considering the simple use case. These three languages are evaluated regarding the formal semantics representation of the inter/intra-domain and/or inter-intra/planer knowledge and the extensibility/scalability keeping in view the service/application extension and/or

access technology addition/modification. Moreover they should support provision of distributed decision enforcement (e.g. the decisions are computed at PS and disseminated to SBC where a Local PDP (LPDP) picks the corresponding decision accordingly and enforce it). These languages should accommodate platform's configurational and administrative rules (e.g. constraints and priorities etc.) that in turn are termed as rules about rules (meta rules). The business objectives of the company may go through the change so they (specification languages) should support business goal representation with dynamicity. Lets discuss these languages keeping in view the requirements for the use case over the platform.

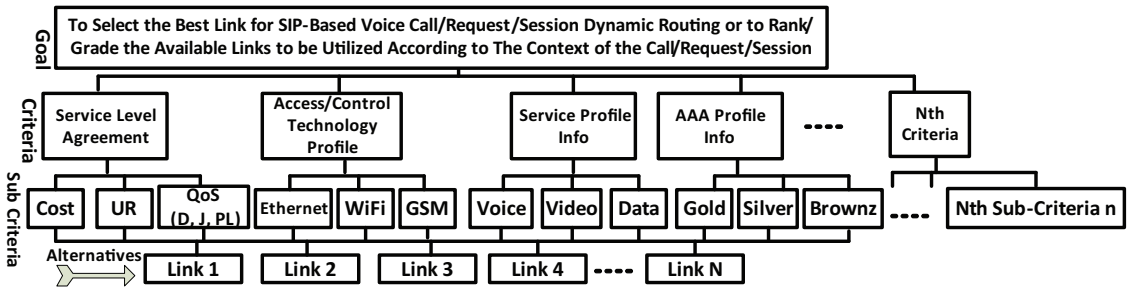

Figure 5.4: Goal, Criteria, Sub-Criteria and Candidate Links Hierarchy.

5.3.1 Ponder

Ponder is a declarative and object-oriented language for specifying security and management policies for distributed systems. Besides, policy specification, Ponder can group policies into roles and relationships; and then define configurations of roles and relationships as management structures. Ponder implementation is not platform specific; rather it can map to and co-exist with one or more underlying platforms. Ponder supports an extensible range of policy types such as: authorization policies; obligation policies; refrain policies; delegation policies; composite policies; constraints; meta-policies etc. Domain, a grouping of managed objects that share the same, object type, responsibility, geographical boundaries and authority is supported in ponder.
Regarding the use case mentioned over the proposed architecture if the arrival of the request/call is considered as an event and platform's conditional parameters and contextual attributes are converted to conditions and the routing of the call to one of the alternative links is taken action. Then the underlying scenario is modeled by ponder obligation policy (representing an event-condition(s)-action tuple policy). Corresponding attributes over the domain/plane (belonging to service, control and network plane) representing the managed objects (regarding ponder) can be changed dynamically with addition or removal of managed entities. A managed object can belong to multiple domains in ponder so the overlapping and conflict can be handled by using the ponder

meta policy. The problem with ponder lies in dynamicity accommodation, whenever a change occurs, the enforcement points needs to be reconfigured (ponder policies are compiled by the ponder compiler into policy java classes and are represented at runtime as policy java objects). The dynamic support lagging does not coincide with the requirements as the enforcement point (SBC) might be handing ongoing calls/requests. Hence its reset is not a good idea to accommodate the changes over the platform. Additionally ponder partially supports business oriented policy specification. Ponder therefore is left out due the unavailability of change management as required over the platform regarding the presented simple use case, resulting in an evaluation of another language.

5.3.2 KAoS

KAoS is a collection of services and tools that allow for the specification, management, conflict resolution and enforcement of policies. It uses ontology concepts encoded in Ontology Web Language (OWL) [126] to build policies. Its OWL ontologies make the system easily expandable and adaptable to different domains. The applicability of the policy is defined by a set of conditions or situations whose definition can contain components specifying required history, state and currently undertaken action. In the case of the obligation policy the obligated action can be annotated with different constraints restricting possibilities of its fulfillment. Rules can be defined to accommodate minimum and maximum cardinality for the entities as well as universal quantifiers over the objects instantiated from the concepts and classes. The dynamicity regarding the runtime role/entity assignment using OWL however is not supported natively.
KAoS uses ontologies to represent policies, domains objects, business and organizational concepts. The proposed architecture also use ontology to capture inter/intra domain/planer semantics and dynamics over the proposed unified infrastructure (shown in Fig. 4.1). The simple use case presented in the previous section can be handled by defining obligation policies (event-condition-action tuple) by extracting the corresponding attributes from conditional, administrative configurations over different planes/domains and business objectives of the platform. KAoS support the representation of business rules via ontology. Moreover it accommodates the dynamicity and the enforcement points do not require the hot reset/ rather they can be updated at runtime. The simple use case fulfills the requirements using KAoS as there are only 4 alternative links and 6 attributes involved. KAoS representation in OWL is supported by description logic. The policy refinement therefore becomes description logic inference. This leads to performance issues when inference needs to be done on a large scale accommodating the large sets of concepts and relationships. KAoS is also left out of the batch of three languages and lets move to evaluation of third choice.

5.3.3 Rei

Rei is a policy framework that integrates support for policy specification, analysis and reasoning. It allows users to express and represent the concepts of rights, prohibitions, obligations, and dispensations. In addition, It permits users to specify policies that are defined as rules associating an entity of a managed domain with its set of rights, prohibitions, obligations, and dispensations in pervasive environment. Rei does not use ontology to represent the domain/planer knowledge. The syntax is represented in the form of Resource Description Framework (RDF), the semantics follow the rule-based language conventions. The major draw set back of using Rei is that it down not support rule enforcement. The proposed platform requires the policy enforcement support and even in case it is handled externally outside the policy framework, then there should be problems when enforcement feedback and monitoring is required. Moreover Rei does not support policy disclosure and conflict resolution as there are no capabilities for ontological reasoning.
Policy/Rule language must be deeply rooted into the PBNM framework. Network entities are inherently complicated and dynamic (e.g. to model a router, one would have to model its static properties (e.g., an interface) as well as its dynamic properties (e.g., instantiating a VPN requires use of shared resources) and behavior (e.g., modeling of particular bugs and side effects)). The language should accommodate a number of dialects while supporting the PBNM information model. The model should be capable of capturing semantics and syntactic relationship and concepts. Each policy language has its own semantics and syntax that is usually correlated and grounded in a particular logic description. It is therefore suitable to derive the policy language from the proposed framework rather than picking one of the subsequently mentioned languages offering limitations and restrictions.

5.4 Decision Computation and Management

Decision making is the process of selecting a possible course of action from a set of alternatives. In almost all problems, the multiplicity of criteria for judging an alternative prevails. That is, for many problems, the decision system is targeted to attain more than one goal in selecting the course of action while satisfying the constraints dictated by environment processes and resources. Decision computation and its management is thus crucial for systems accommodating the dynmicity. Chapter 4 elaborates the MCDM methods in the context of our proposed framework and maps those methods to a platform specific simple example. The explained MCDM methods are then executed by considering a simple use case consisting of 4 alternative links and 6 attributes (extracted from the planes/domains over the unified infrastructure). The same set of MCDM methods (WSM, WPM, TOPSIS, Extended TOPSIS and GRA) are evaluated on the real time architecture shown in the Fig. 5.5. It is important to mention here that SIP-based multimedia communication is tested over the real time architec-

ture [127] while applying the underlying 5 MCDM methods one by one. SIPp [128]

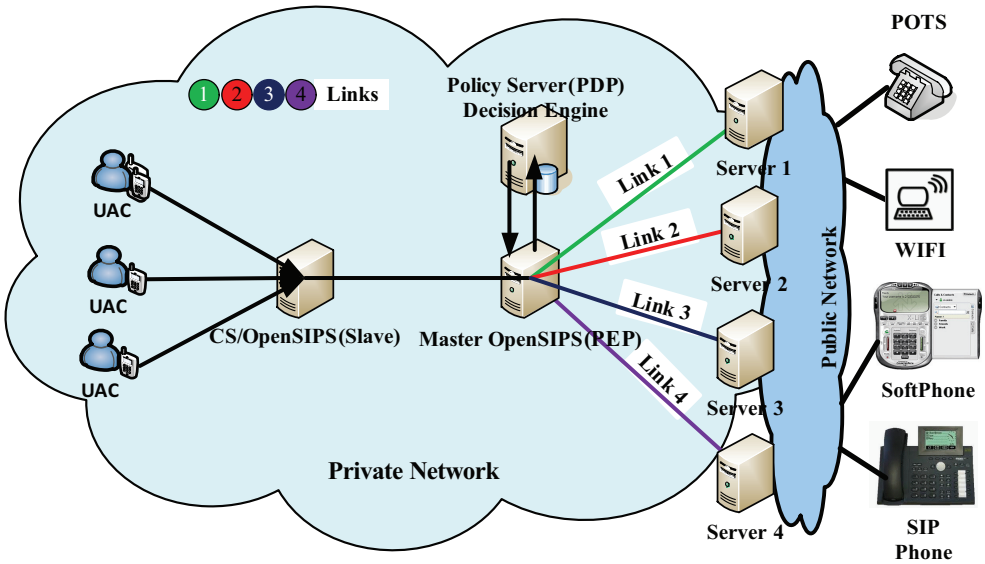

Figure 5.5: Real Time Architecture for Corresponding MCDM Methods Evaluation.

is used to generate extensive SIP requests (INVITE messages). It is a configurable traffic generator and is extensible via a simple XML configuration language. OpenSIPS [129], an open source SIP server is tweaked to act as Back-2-Back User Agent (B2BUA) and Session Border Controller (SBC) for Slave/Master deployment respectively. Moreover, the Master OpenSIPS is extended to act as Policy Enforcement Point (PEP) for enforcing the decisions. It is built around the core that is responsible for the basic processing and handling of SIP messages. The modules developed around its core are responsible for the majority of OpenSIPS functionalities. Its scalability and modular design provides a number of functionalities (registrar, router/proxy (LCR, dynamic routing, dial-plan features), redirect server, B2BUA etc).
Call model with User Agent Client (UAC) at slave OpenSIPS sends an INVITE to SIP server (same machine) that adds the resource priority tag and forwards the request to Master OpenSIPS (tweaked to act as SBC). Master OpenSIPS analyzes the request to judge its communication type and pairs it with the resource priority tag sent by the slave OpenSIPS. Resource priority type and communication type tuple is mapped to an appropriate user profile from central profile base at PS. Table 5.2 presents the "Resource Priority Type, Communication Type" tuple and their corresponding mappings to appropriate profiles. This table can be computed a-priori as the user groups and the communication types are known by SBC/PS respectively so the corresponding entries are populated with the passage of time and learning process. It is important to mention here that a random number is generated to send the codec information along with the

Communication Type	ProfileType
(Resource Priority Type XYZ, Communication Type-A)	Profile AXYZ
(Resource Priority Type YZX, Communication Type-C)	Profile CYZX
(Resource Priority Type ZYX, Communication Type-D)	Profile DZYX
(Resource Priority Type ZXY, Communication Type-B)	Profile BZXY

Table 5.2: Resource Priority Type and Communication Type Mappings to Corresponding Profiles

SIP message. The bandwidth requirement of the call is judged from the codec information and the request is forwarded to an appropriate link by enforcing the decision computed by deploying one of the MCDM methods. Network Address Translation (NAT) is enabled at master OpenSIPS (SBC) and the decision is enforced during NAT implementation. The Remote SIP server responds with 100 TRYING, 180 RINGING and 200 OK. UAC then sends an ACK and the call is established. The UAC closes the communication after a pause of variable duration by sending a BYE that is acknowledged by the SIP server with 200 OK. Wireshark [130] is used to capture the traffic at different interfaces (links). OriginLab [131] is used for data analysis from the captured file. Throughput of each link is measured by applying the underlying MCDM methods; WSM, WPM , TOPSIS, Extended TOPSIS and GRA accommodating the multiple criteria, multi-criteria with multiple dimensionality, multi criteria with dynamicity and multi criteria with context/dynamicity respectively. The throughput of each link is plotted by applying the mentioned MCDM methods one by one as shown in Fig. 5.6. It is observed that there is a significant improvement in the throughput for each link with decision engine while performing SIP-based call routing.

WSM and WPM methods are showing almost the same throughput with little raise while using the WPM. Minor rise in the throughput is due to the fact that WPM can accommodate multi dimensional data. TOPSIS and Extended TOPSIS shows throughput improvement on similar grounds respectively i-e Extended TOPSIS attains higher throughput than the simple TOPSIS due to accommodation of upper and lower bounds as in some cases when the exact value of an attribute (e.g. bandwidth) is not known then these bounds can be used rather than using/guessing imprecise and/or imperfect information. TOPSIS and Extended TOPSIS resolved the problem of dynamicity accommodation but they did not take context of the on going request/session/call into account while computing the decision. GRA, however is targeting both the dynamicity and context at the same time so attains the highest throughput over the test bed used for the presented simple use case.

The retransmission mechanism within SIPp is turned off when INVITE messages are sent in order to know that a call has been dropped. The aggregated call dropping probability (for the 4 links shown in Fig. 5.5) is calculated by using the corresponding

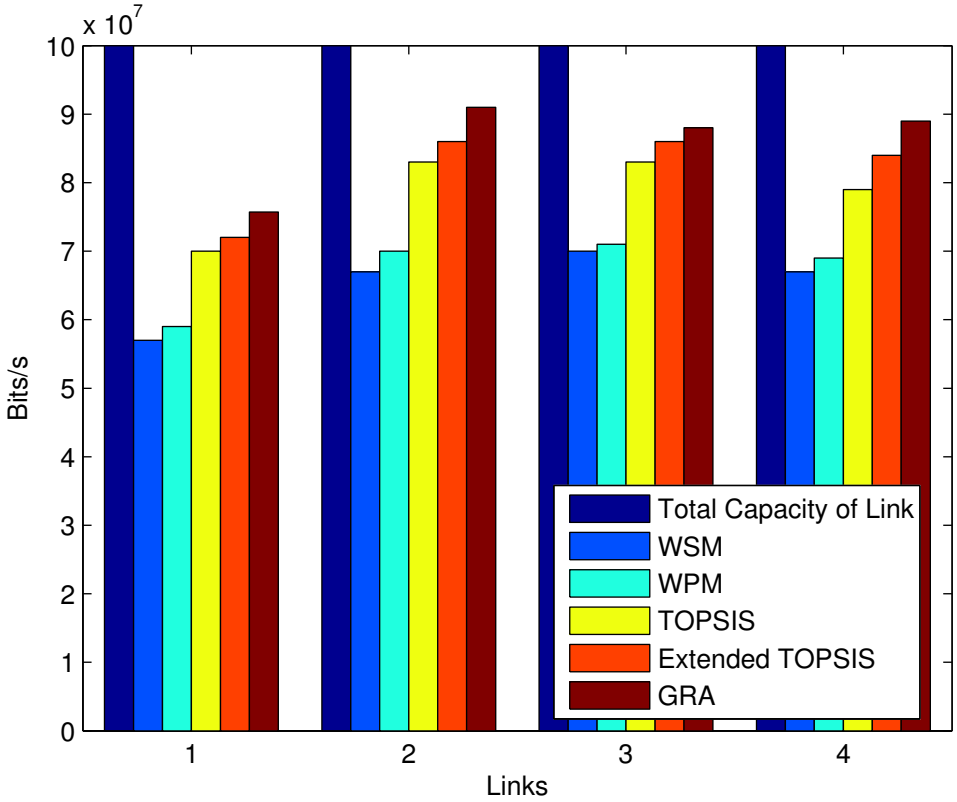

Figure 5.6: Throughput of Each Link With the Corresponding MCDM Methods.

MCDM methods one by one and is shown in Fig. 5.7. Number of call drop while using WSM and WPM is higher than the other methods and it started earlier as compared to the rest of the used methods (Call Dropping started when the system is accommodating 20 calls/s). The main reason behind the higher and earlier call dropping is that these two methods are not taking the latest dynamics of the platform into account so there is higher probability of mismatching between the computed decisions and the infrastructure state and conditions. There must be clear distinction between TOPSIS and Extended TOPSIS in terms of number of dropped calls as Extended TOPSIS is supposed to accommodate the dynamics over the platform in addition to capturing uncertain and indefinite behavior of an attribute. But the curves for these two methods show almost identical behavior while overlapping at some points. The similar and alike conduct of these two methods is due to the fact that the platform chosen reflects the simple use case involving few attributes facing little dynamicity. It is thus foreseen and apprehended that addition of more links and attributes may draw a clear line between

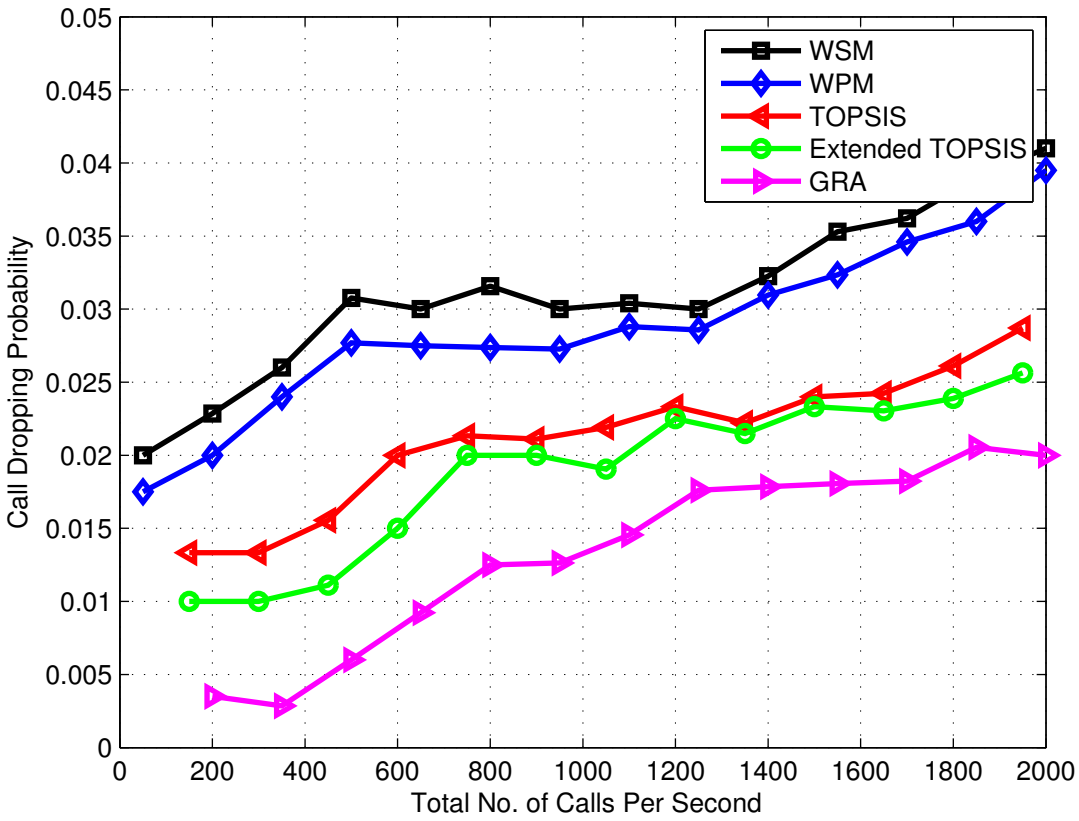

Figure 5.7: Aggregated Call Dropping Probability of the Links With Different MCDM Methods.

these two methods in terms of call dropping probability.

The delay introduced by the system while deploying theses MCDM methods is also plotted as shown in Fig. 5.8. TOPSIS and Extended TOPSIS interchange their positions as opposed to the previous measurements (Throughput and Call Dropping Probability). More computational power is required to fix the interval data involving upper and lower bounds (Extended TOPSIS) than the exact valued calculation during the simple TOPSIS application. The system delay increase almost linearly as the number of calls rises while during the application of WSM, WPM, TOPSIS, Extended TOPSIS and GRA (in the same order) MCDM methods respectively has more dynamics are involved requiring more information processing during these methods. The delay however has a little impact, as the decisions are being executed and enforced during call/connection setup time. The delay offered by the system is thus measured to avoid annoying QoE and to put some upper limit regarding the global unified infrastructure offering highly delay sensitive multimedia services

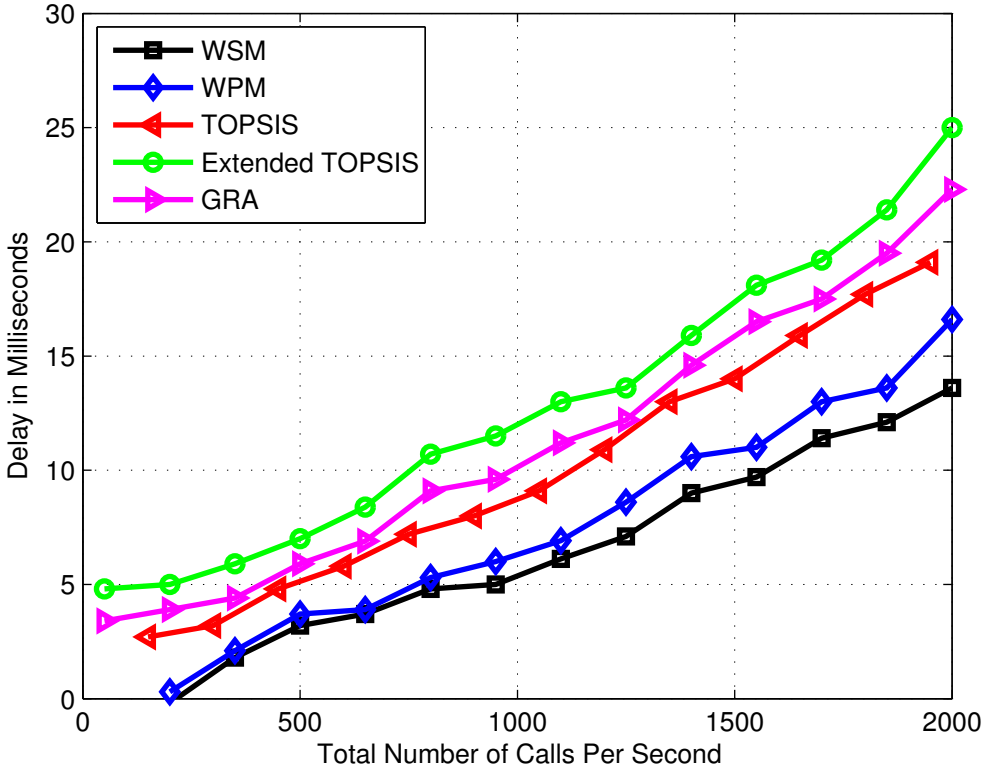

Figure 5.8: Delay (Milliseconds) Introduced by the System by Deploying the 5 MCDM Methods.

5.5 Online and Off-Line Policy/Decision Computation

Decision computation and its enforcement are coupled over the multi-homed architecture that binds diverse access technology links offering a variety of services. The decision system supports two policy enforcement modes; outsourcing mode and provisioning mode, offering online and offline decision computation in the former enforcement mode while later mode can work with offline decision computation. In order the experiments these two modes over the platform It is assumed that by default the system is configured to work in provisioning mode. Whenever a request arrives, the SIP/SDP analyzer extracts the required information and sends this information to LPDP, which

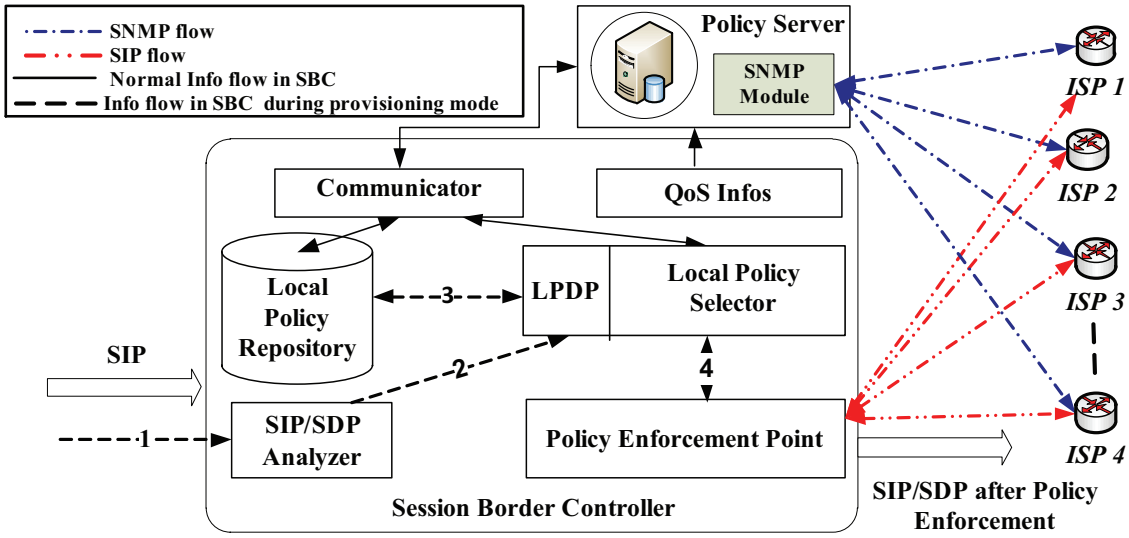

Figure 5.9: Information Flow in Provisioning Mode

then maps an appropriate decision/policy from the rule base, the process resumes otherwise on mapping failure and the information is sent to the communicator at SBC. The decision/policy enforcement irrespective of the two modes is ultimately done at SBC (PEP). In provisioning mode the pre-computed decisions/policies are available in the decision/policy repository at SBC. In outsourcing mode the extracted information from the pending request is fetched to the PDP at PS via communicators. PS, in outsourcing mode is delegated to compute/use online/off-line policy/decision based on the request and the system conditions. Pre-computed decision/policies in the provisioning mode are fetched at SBC, a-priori irrespective of online or off-line computation. The two enforcement mechanisms are in contrast with each other but they are not mutually exclusive. The unified platform is capable of handling both data and multimedia services. However we are explaining the two policy enforcement modes while considering SIP based multimedia communication. The initial inter-communication of different modules and the information flows in the provisioning and outsourcing modes shown in Figs. 5.9 and 5.10 respectively are identical till step '3' and it is given in the following.

1. This will be a SIP INVITE from CS with resource priority header information as CS is managing registration, user profile management and service control with the underlying profile based CAC mechanism.

2. The SIP/SDP analyzer will then examine the request/session and will send the extracted information to the LPDP, e.g. the communication type can be identified by SBC after analyzing the SDP payload while the user type is computed from

proprietary SIP header fields (sent by CS) mentioned earlier. This information is bundled into a pair and the corresponding profile is mapped using the table 5.2.

3. The LPDP will play with this information and sends a request to local decision/policy repository at SBC inquiring an appropriate decision/policy.

In provisioning mode, upon decision/policy mapping the response is sent back to LPDP otherwise on failure, the system resumes further processing and the system triggered to outsourcing mode now.

5.5.1 Provisioning Mode

Pre computed decisions/policies in provisioning mode are already available at local repository at SBC before the request/session arrives. LPDP will select an appropriate decision/policy from local decision/policy-base and its enforcement takes place at PEP. The information flow and the inter-communication between different modules is illustrated in Fig. 5.9. The tagged information flow till the step 3 (which is common to both modes) is mentioned above and the final step during the provisioning mode is given in the following

4. LPDP disseminates the decision/policy for its enforcement to the enforcement point (PEP).

5.5.2 Outsourcing Mode

Unlike provisioning mode, the policy/decision is fetched from PS upon the arrival of request/session/call in outsourcing mode. When a request arrives at the SBC and it finds no decision/policy for the current request/session/call. It resumes further processing in outsourcing mode by marking the request as pending and sending the appropriate information to the PS Via Gq interface using the diameter protocol e.g. the communication type, user profile along with required QoS Info may be transmitted. The information flow is given in Fig. 5.10. Sequenced and tagged information except the 3 common steps in the two modes is explained below.

4a. LPDP asks the communicator at SBC to send request for post decisions/policies computation according to the context of the request/session.

4b. While LPDP is sending request to PS for decision/policy computation, it marks the current request at PEP as pending.

5. The two communicators at SBC and PS interact via Gq using Diameter protocol and the required information is transferred to PS

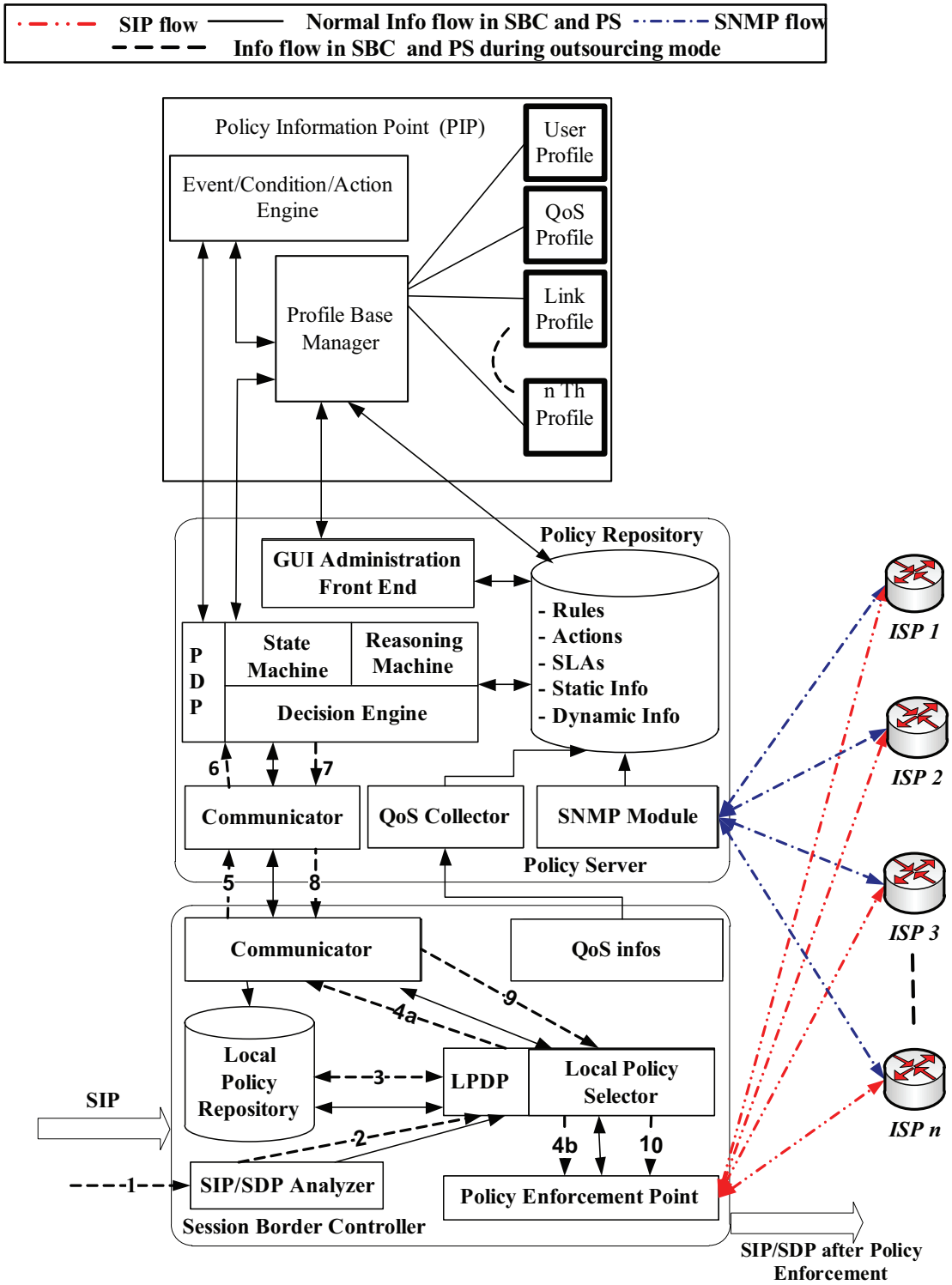

Figure 5.10: Information Flow in Outsourcing Mode

6. The PS server communicator sends this information to the PDP at policy server which compute/use online/offline policy/decision based on the request and the system configurations/conditions.
7. The PDP at PS then transfers the decision(s)/policy(s) to local communicator.
8. The PS communicator then transfers the decision(s)/policy(s) to the SBC communicator via Gq.
9. The communicator at SBC communicates the computed decision(s)/policy(s) to the LDPD.
10. LPDP transfer the decision(s)/policy(s) to PEP for enforcement onto the pending request/session.

5.6 Outsourcing and Provisioning Mode Comparison

The underlying enforcement modes (outsourcing and provisioning) are analyzed and/or evaluated by applying the GRA on the platform shown in Fig. 5.5. GRA is chosen due to fact that it supports dyanmicity while accommodating the context. There are two possibilities for calculating/declaring the reference attribute vector (used for the application of GRA): the first is to compute/declare the reference attribute vector before the request arrives (might be used for a-priori decision calculation in provisioning mode and offline outsourcing mode) and the second is to calculate it on the fly (used to the decisions in online outsourcing mode). The susceptible QoS sets of parameters are well defined and known for voice and video. The range of required bandwidth for different codecs (used by the end points during the multimedia communication) is also well documented. The attribute, Available Bandwidth (one of the attribute among the set of 6 attributes used for GRA application) is calculated by keeping the track of number of ongoing calls/requests on a particular link (i.e., Available Bandwidth=Total Bandwidth - Used Bandwidth). It is important to mention that the presented GRA includes the simplest possible case. Embedding the reference vector beforehand can be tedious and complex as the number of links and attributes increases. The business objectives of an enterprise might change (e.g., voice might be given priority over video, the silver profile might use gold profile service during night (free hours), etc.), the user profile priorities/authentication/authorization parameter (QoS profile corresponding to a user profile) may go through modification, or the link resources might go through up-gradation/downgrading. The underlying complexity can be handled though but it requires extensive administrative efforts. The objective however, is to analyze and compare the two enforcement modes.

The system performance is analyzed by calculating the delay and call dropping proba-

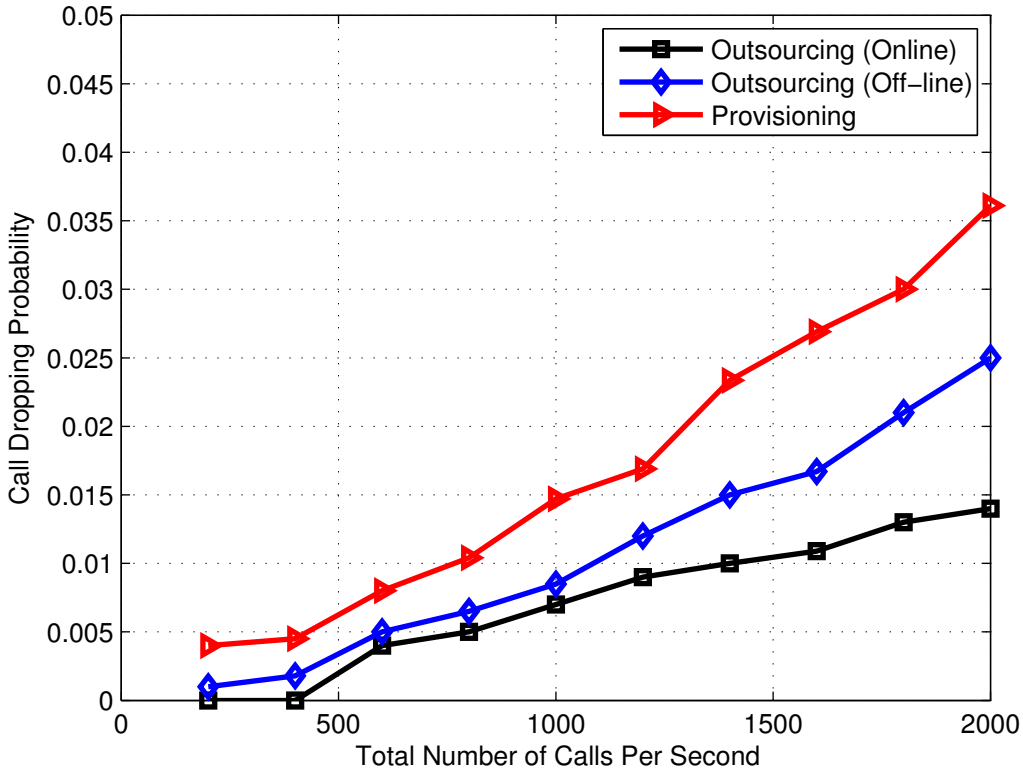

Figure 5.11: Call Dropping Probability Introduced by the System in Outsourcing (Online and Off-line) and Provisioning Mode Respectively.

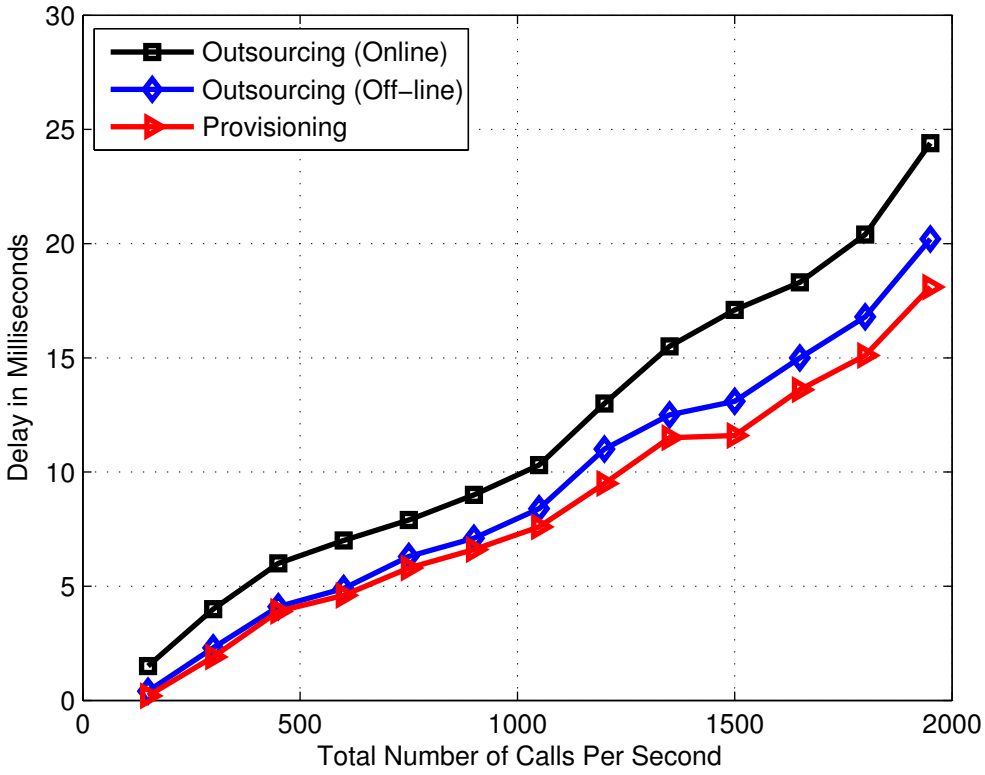

Figure 5.12: Delay (Milliseconds) Introduced by the System in Outsourcing (Online and Off-line) and Provisioning Mode Respectively.

bility and then these metrics are compared in these enforcement modes. As mentioned subsequently that multimedia traffic is focused over the converged hybrid architecture with multi-homing support. Moreover there is signaling protocol (SIP) involved for connection/session/call setup before the actual data starts flowing. The supported outsourcing and provisioning enforcement modes are strongly correlated with signaling phase of multimedia communication. Moreover the decisions/rules are enforced during the signaling procedure. Additionally the choice of the decision computation (on-line or off-line) is dependent upon the pre-defined rules entered by the administrator of the platform. Data services (Web, FTP, Mail) are not considered here as they are more immune to delay and connection dropping as compared to real time multimedia traffic which are more sensitive to delay, jitter and connection/session/call dropping while requiring good QoS. Delay introduced by the decision engine and the call dropping probability in outsourcing (online and off-line) and provisioning enforcement modes are shown in Figs. 5.11 and 5.12 respectively.
More resources are required in outsourcing mode than provisioning mode due to dynamics and variations involved during the former mode that has to be captured requiring intensive computation. Outsourcing mode (especially the online-outsourcing enforcement) take in to account the latest platform's conditional and environmental parameters, newest pre-configured rules and network information (external links latest state) introducing more delay. In provisioning mode, the policies may have conflict with the platform conditions and/or resource info due to the frequent dynamics onto the platform, which might not be captured for decision making hence call dropping probability is higher in this particular mode as compared to online/offline outsourcing modes (as the outsourcing mode supports both online and off-line decision computation while pre-computed decision is selected from local repository in provisioning mode). The reader is refereed to [132] for the application of more MCDM methods in these enforcements modes along with their comparison and analysis.

5.7 Application of Decision Engine for Heterogeneous and Converged Environment

Decision Engine over the proposed architecture has been discussed and experimented along with it analysis and evaluation so far keeping in view service, application, control and network convergence. The access technology convergence analysis and evaluation in the context of proposed decision engine has not been discussed yet as the simple use cases presented previously over the former platform can be a trend setters in order to merge the access technology convergence. This convergence brought about new dimension involving more variations, add-on technology independent and technology specific attributes from diverse planes. The same Decision Engine is able to handle the handover (vertical) decision computation in addition to private-public network border routing decisions.

Enterprises nowadays are approaching towards an all IP paradigm by subscribing to different access technology links from several service providers for reliability and redundancy while providing good Quality of Service (QoS). Global System for Mobile Communications (GSM) to Voice over IP (GSM-2-VoIP) convergence and vice-versa is a step forward towards this unification goal. It requires dynamic routing between IP, digital, analog and GSM networks. A decision-making framework is presented that can handle both the dynamic routing decision computation at private-public network border for inbound/outbound calls (GSM-2-VoIP) and the horizontal handover decision-making among various GSM cells [133].
This unification enables operators to lower their overall operational and management costs while offering innovative advanced services with improved Quality of Service (QoS) to the end users. Each level of the value chain is benefitting directly or indirectly: fixed operators have the benefit of a reduced infrastructure and maintenance expenditure; mobile operators can accelerate fixed-mobile substitution by offering services previously available only for fixed lines. Access technology convergence, lowering the infrastructure and service cost from the provider and customer view point and a unified network control and management module for the platform are some of the main objectives targeted in this section
Least Cost Routing (LCR) and Call Admission Control (CAC) are the mechanisms traditionally used to control, manage and route the private-public network border traffic. However, the decision-making mechanisms involved in these methods are usually static and/or semi-dynamic. Moreover the access technology convergence and traffic unification over the converged platform introduce new criteria and attributes with different dimensions while computing the decision at the network border. Choice of the Link (Internet Service Provider), taking multiple criteria into account for decision calculation and Service Level Agreement (SLA) compliance over this unified communication platform are some of the issues for the traffic (calls) traversing from GSM to multi-homed VoIP network. Handover decision computation, Load Balancing (LB) and mobility management are to be taken into account for requests in the opposite direction (VoIP to GSM). The decision computations in these two scenarios (decisions for routing and handover) have different sets of parameters with different dimensions and contexts. The goals and alternatives have different set of quantitative and qualitative representation and requirements with distinct objectives. The proposed decision framework accommodates the decision-making in two distinct dimensions with diverse knowledge and objectives over the multi-homed, converged and unified platform enabling the support for services in a cost-effective and scalable way.

The QoS-centered architecture shown in Fig. 5.13 provides an all IP cost effective solution offering versatile access technology convergence while highlighting network traffic unification. The multi-homed infrastructure offering multimedia and data services is developed to support both routing and handover mechanisms for SIP-based voice/video calls by considering all the dynamics over the platform. On-the-fly load

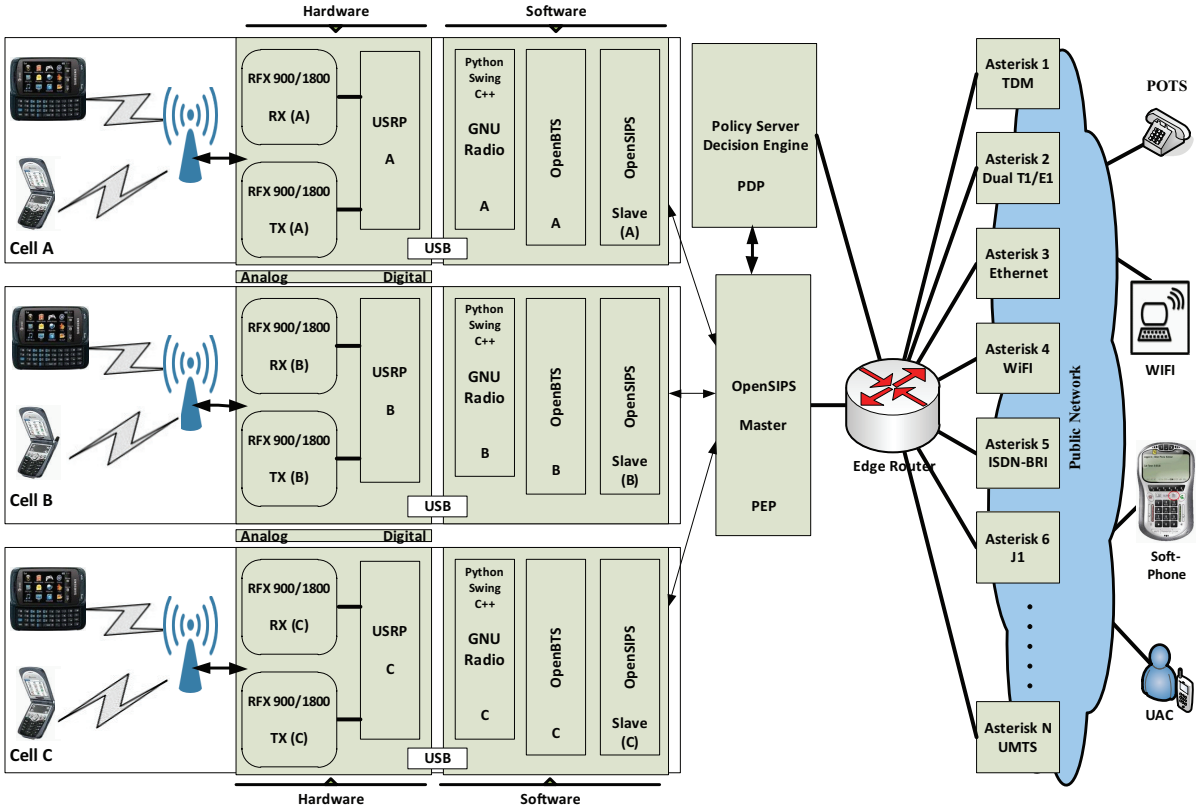

Figure 5.13: Architecture for Unified Communication with Convergence.

balancing at the private-public network border and seamless handover mechanism within the fixed-mobile converged infrastructure are targeted using a single standalone decision engine. The underlying solution stems from competitivity cluster for handling traffic management issues at the network border in either direction (inbound and outbound traffic). Convergence of the ubiquitous GSM air interface with VoIP backhaul forms the basis of a new type of network that is deployed and operated at substantially lower cost (one tenth) than existing technologies, as the radical two-tier pricing would be disruptive for existing carriers.

The Universal Software Radio Peripheral (USRP) is designed as a general-purpose hardware subsystem for Software Defined Radio (SDR) having open source schematics and layouts [134]. It supports the simultaneous transmission and reception of four real or two complex channels in real-time. For reception, it utilizes four 12-bit Analog-to-Digital Converters (ADCs) operating at 64 MHz, and four Digital-Down Converters (DDCs) with programmable decimation rates. The transmit side of the USRP incorporates four 14-bit Digital-to-Analog Converters (DACs) that operate at 128MHz, and two Digital-Up-Converters (DUCs) with programmable interpolation rates. The

on-board Altera Cyclone Field Programmable Gate Array (FPGA) is responsible for channelization, down-conversion and up-conversion. Data is transferred between the host computer and the USRP via a USB 2.0 interface, hence limiting the sustainable data rate to 32 MBps half-duplex. USRP here is used to present a GSM air interface "Um" to a conventional GSM handset.
Different frequencies require different antennas and sometimes different signal processing, like amplifiers or filtering, to receive or transmit correctly. The USRP motherboard by itself does not provide direct Radio Frequency (RF) access; rather it utilizes an assortment of daughterboards to perform the RF-to-Intermediate Frequency (IF) translation. These daughterboards are plugged directly into the USRP motherboard. Some daughterboards are receive-only, some are transmit-only and some are transceiver devices that provide both receive and transmit functionality. RFX-1800 daughterboards (transceivers) are used in the proposed architecture.
GNU Radio [135] is an open source SDR. It is a software toolkit that provides a library of signal processing blocks that run on a host-processing platform. Algorithms implemented using GNU radio send/receive baseband data directly to/from the USRP, which is the hardware that provides RF access. The GNU library contains lots of standard signal processing functions. These functions, usually called blocks, are often divided into three categories: source blocks (USRP drivers, but also file readers and tone generators), sink blocks (USRP drivers, graphical sinks like an oscilloscope and sound-card drivers) and processing blocks (like filters, FFT and (de)modulators). The processing blocks are written in C++, and made callable from Python via SWIG (Simplified Wrapper and Interface Generator). Standard practice is to create a Python flow-graph by connecting the appropriate signal processing blocks. If a custom signal processing block is desired, it can be created in C++ and integrated into the GNU Radio development environment via SWIG.
A universal SDR structure with the specific software (GNU Radio) and hardware

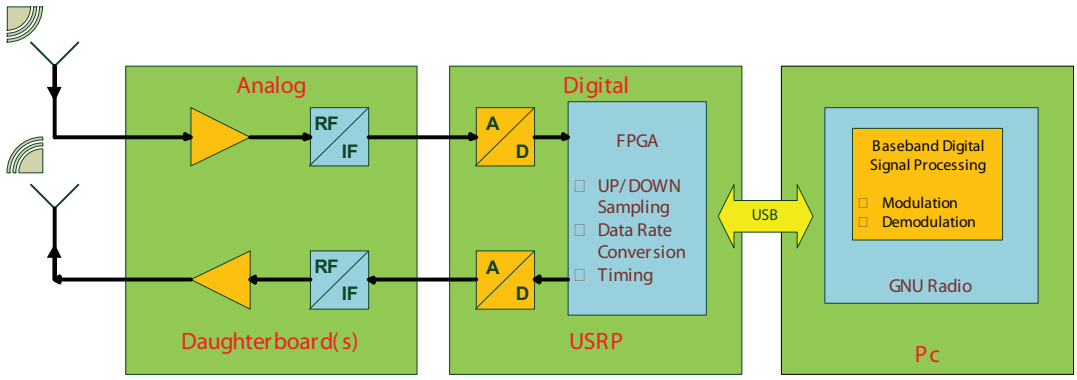

Figure 5.14: Software Defined Radio Block Diagram.

(USRP) is shown in Fig. 5.14. The left hand side forming the RF front-end of the hardware serves as an interface to the analog RF domain. In the middle block, the intelligence of the hardware part is implemented, forming the interface between the digital and the analog world. The whole signal processing is done in the right hand side block in Fig. 5.14. Digital Signal Processing (DSP) chips are very expensive and are flexible to certain limits for customization while targeting a particular application. The combination of GNU Radio and USRP along with daughterboards offers flexibility with efficient customization for signal processing applications. This fully open source and cost effective solution is being used/developed by a large and diverse community (research, academia and industry). The stumbling bottleneck in moving towards SDR is the availability of high speed analog to digital and vice-versa (ADC/DAC) Convertors. SDRs invariably require parallel and sequential partitioning of algorithms to get the required processing power so yet another issue is the computational power of the host machine. The motivation behind using USRP with GNU radio is the performance of ADC/DAC modules over USRP kit and the flexible/modular approach adopted in GNU radio (C++ is used for core and the modules are glued using python). The idea here is to perform most of the DSP specific hardware based processing using conventional computation (PC). Another objective is to transfer the complexity of the radio system, design from hardware to software while moving the software as close as possible to the antenna.

OpenBTS [136] is an open source linux-based application that uses USRP to present GSM air interface (Um) to standard GSM handsets (mobile phones). OpenBTS makes it possible to create a GSM network without using the networks of the various service providers. Its architecture completely differs from the conventional GSM hierarchical architecture. OpenBTS replaces the traditional GSM operator network switching subsystem infrastructure, from the Base Transceiver Station (BTS) upwards. Instead of forwarding call to an operator's Mobile Switching Centre (MSC), the calls are terminated on the same box by forwarding the data onto the Asterisk using SIP.

OpenSIPS [129], is acting as Back-2-Back User Agent (B2BUA) and Session Border Controller (SBC) for Slave/Master deployment respectively. Master OpenSIPS is tweaked to act as Policy Enforcement Point (PEP) for decisions enforcement. OpenBTS emulates the mobile handsets as the SIP endpoint and these handsets are treated as SIP extensions while registering to Slave OpenSIPS. After the initial registration and authentication, SIP request is then forwarded to Master OpenSIPS for routing the call/text messages to the appropriate link (Asterisk Server) in consent with the decision calculated on the basis of platform's conditional parameters, link state, business objectives of the company and context of the request. Moreover, the Slave and Master OpenSIPS servers share and exchange relevant information for the special scenario of Horizontal Handover (HH) decision-making during an ongoing call.

Policy Server (PS) is the main controller over the platform shown in Fig. 5.13. It acts as a Policy Decision Point (PDP). It computes all the decisions by taking into account

the static configurations and dynamics taking place over the platform, in addition to the policy enforcement supervision. The proposed dynamic Decision Engine partly constitutes the core of PS. Multi Criteria Decision Making (MCDM) theory is used to compute the decision on the basis of multiple criteria for call routing/handover at the private-public network border/(within the GSM-cells).

Asterisk [137] Cluster within the proposed architecture emulates the multi-homed links, providing an interface to the public network via different access technologies as shown in Fig. 5.13. Asterisk, an open source Internet Protocol (IP) based Private Branch eXchange (PBX) system, supports various VoIP protocols such as, SIP, H.323, MGCP, SCCP. It can be connected with IP network and conventional telephone networks via analog/digital interfaces. Inter Asterisk communication is accomplished via proprietary Inter-Asterisk eXchange (IAX2) protocol providing, efficient trunking of calls among Asterisk PBXes. Asterisk has flexible and extensible architecture designed by following the modular approach. Asterisk flexibility permits it to be deployed as PBX, VoIP, Interactive Voice Response (IVR), softswitch, codec translator and Call Conferencing as well as Voice Mail system.

All these open-source modules are integrated over a single platform to perform inbound and outbound dynamic call/request routing at the private-public network border and HH decision-making. The Decision Engine takes into account multiple criteria (Service Level Agreement (SLA), service profile, reliability information of the links, user profile, time of the day, static configuration over the platform, mobility within the GSM cells, dynamic variations over the platform) and uses MCDM theory for decision computation. Diameter Protocol is used for inter-communication between PDP and PEP. SNMP-based information over the underlying architecture is exploited to gauge the QoS parameters of access links (router interfaces). Private-public border traffic management issues for request routing decisions are handled at the application layer (OSI). The mobility management and cell load issues within the GSM cells are resolved by handover mechanism. It supports dynamicity by using MCDM theory. The calculated decisions are enforced in outsourcing (on-the-fly) and provisioning (offline) modes (more details about these enforcement modes are available in [17]) by using existing standards and mechanisms, without introducing overheads in the protocol stack. It is worthwhile to mention here that outbound dynamic call routing is emphasized here due to the following factors: cost (International and Long Distance Routing of Mobile through VoIP), access technology convergence providing unified communication at the private-public network border, multiple criteria including large number of attributes involved in the outbound routing decision-making, and finally this scenario represents an ongoing and existing business model experienced by different companies. A simple HH scenario has been considered due to native functionality of OpenBTS and its integration with OpenSIPS.

The system is capable of accommodating a large number of alternatives with an enormous set of attributes associated with those alternatives (links/GSM-cells). These at-

tributes are obtained from the SNMP traps, business objectives of the company, context of the request, LB info, mobility management scenario and service/user profiles, depending on the decision computation and its enforcement mode. However, for brevity and to avoid the complexity of stringent mathematics, 6 attributes are chosen for the application of MCDM methods on 4 alternative links (decision computation for link selection regarding the dynamic routing of calls is presented first as it is most likely and frequently use case). Fig. 5.4 illustrates the hierarchy of the desired goal, the criteria, sub-criteria and the available alternative links. Two users Alice (local to GSM network) and Bob (remote), are supposed to communicate (outgoing SIP communication) with each other by using the available resources on the platform as shown in Fig.5.13. Alice initiates the communication and dials the destination address from her handset. The request traverses the hardware kit (RF front end and USRP). The data is sampled by the FPGA and is then sent to the host PC via USB (USB 2.0 (32 MB/s half duplex)). Then data is processed (modulated/demodulated) using GNU Radio and GSM stack at the host machine (OpenBTS emulates the mobile handsets as SIP extensions). An INVITE is then sent by SIP stack to the Slave OpenSIPS which is configured to act as B2BUA. Slave OpenSIPS routes the request with additional resource priority tag carrying user profile info to the Master OpenSIPS. The Master OpenSIPS acting as SBC extracts the information from the context of the request while the user and communication types (more details are available in [17]) must at least be known. This information is sent to the PS and the corresponding user, application and QoS profiles are loaded from the profile base at PS. This information is bundled with the alternatives (links) latest information gathered by SNMP traps alongside other relevant information to compute the decision for request routing.
The four links L_1, L_2, L_3 and L_4 and the 6 attributes: Delay (D), Jitter (J), Packet Loss (PL), Utilization Ratio of a link (UR), Total Bandwidth (TB) and Available Bandwidth (AB) are considered respectively for the application of TOPSIS over the unified infrastructure. The alternative links with corresponding row vector consisting of the aforementioned attributes with their numerical values are represented in Table 5.3. For the application of TOPSIS on the links represented by the corresponding row vectors in Table 5.3, all the steps mentioned subsequently (section 4.2.1.1) are gone through in order. The links are ranked with R values as mentioned in Table 5.4.

5.8 Test Bed for the Evaluation of Converged Architecture With Unified Communication

Dynamic call routing decision-making at private-public network border under the control of Decision Engine is investigated first. The system offers the provision of on-the-fly and off-line decision computation depending on the chosen enforcement mode. But online decision computation in outsourcing mode is used due to more dynamics and variation involved in this configuration and hence providing real time stress

	D	J	PL	UR	TB	AB
	Milliseconds (ms)	ms	%age)	%age	Megabits per second (Mbps)	Mbps
L_1	190	15	21	55.73	100	75
L_2	175	20	20	49.17	100	66
L_3	100	14	13	35.5	100	80
L_4	150	20	30	28.9	100	47

Table 5.3: Links With Corresponding Parametric Values.

	L_1	L_2	L_3	L_4
R Value	0.3790	0.3725	0.8003	0.3692
Rank	2	3	1	4

Table 5.4: R Values and the Corresponding Grading of Links.

testing scenario. Test bed used for validating the concept is shown in Fig. 5.15. GSM calls from mobile handsets (coming through Daughterboard-USRP-GNU Radio) are emulated as SIP calls by OpenBTS in combination with native OpenSIPS (Slave) at the host machine. SIPp [128] is used to generate extensive SIP requests (INVITE). User Agent Client (UAC) sends an INVITE to OpenSIPS (Slave), which adds the re-

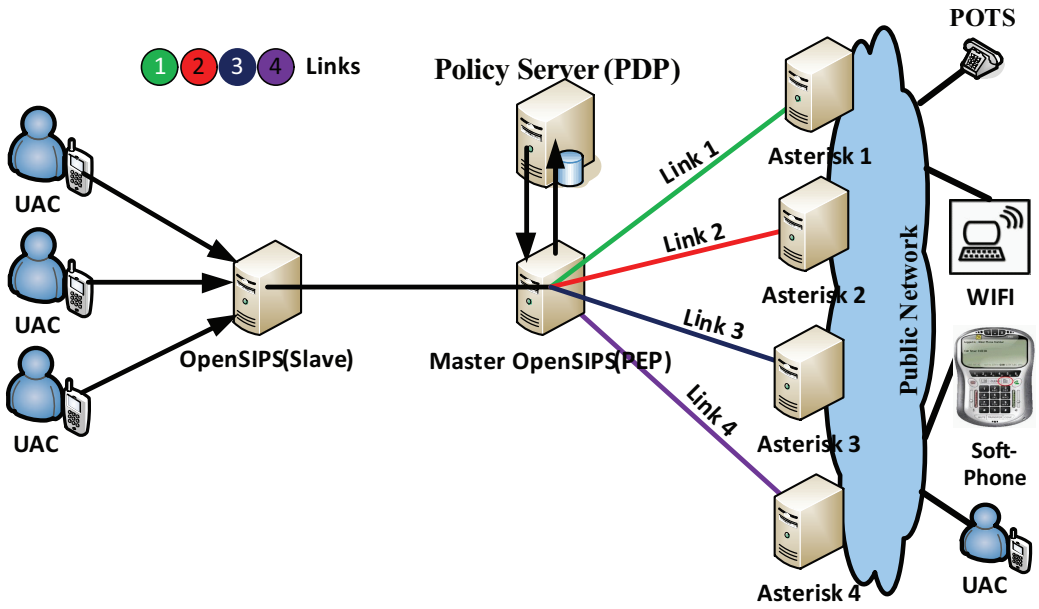

Figure 5.15: Test Bed With 4 Links.

source priority tag and forwards the request to Master OpenSIPS. Master OpenSIPS analyzes the request to judge its communication type by guessing the codec negotiated between end points and/or from the preferred list of codecs. It is important to mention here that the random number(s) is/are generated to send the codec(s) information along with the SIP message. The bandwidth requirement of the call is judged from the codec information. The tuple containing the User Type and Communication Type is disseminated to the PS as the system is functioning in outsourcing mode. An appropriate profile type is mapped from the profile base at PS by looking the User Type and Communication Type tuple. It is crucial to comment here that the underlying call is in its signaling phase so it can bear a reasonable delay. A random delay is thus added to each call in order to emulate its wireless leg i-e GSM. The decision is computed by following the TOPSIS application steps (section 4.2.1.1) and the decision is enforced at Master OpenSIPS and the call is forwarded to the chosen link (remote Asterisk server). Network Address Translation (NAT) is enabled at Master OpenSIPS and the decision is enforced during NAT implementation. The remote Asterisk server responds with 100 TRYING, 180 RINGING and 200 OK. UAC then sends an ACK and the call is established. The UAC closes the communication after a pause of random and variable duration by sending a BYE that is acknowledged by the SIP server with 200 OK. Wireshark is used to capture the traffic at different interfaces (links). OriginLab [131]

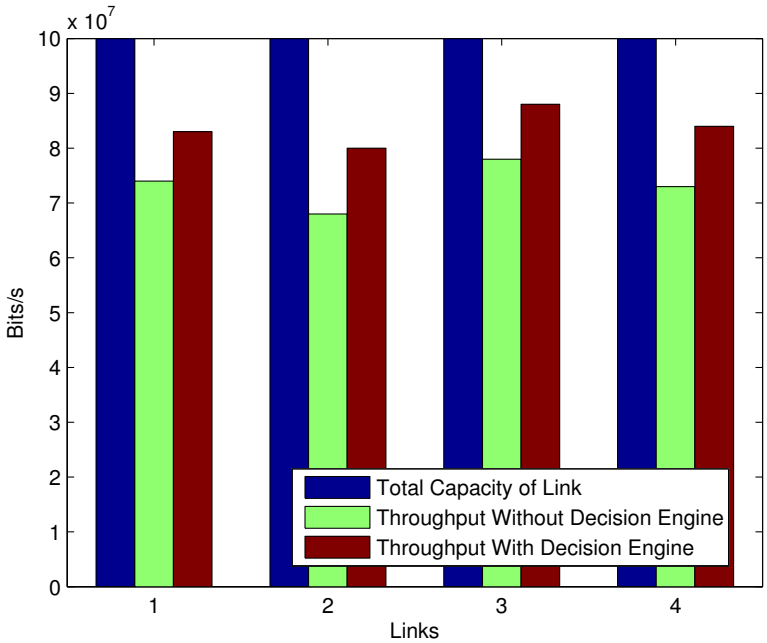

Figure 5.16: Throughput of Each Link With and Without Decision Engine.

is used for data analysis from the captured file. OpenSIPS provides its built in decision engine for load balancing the calls to different links. The proposed Decision Engine is compared with the OpenSIPS built in decision engine. Throughput of each link is plotted with and without Decision Engine (i.e. using built-in Load Balancer (LB) in OpenSIPS) as shown in Fig. 5.16. It is observed that there is significant improvement in the throughput for each link with proposed Decision Engine while performing SIP call routing. The retransmission mechanism within SIPp is turned off when INVITE messages are sent in order to know that a call has been dropped. The aggregated call dropping probability (for the 4 links shown in Fig. 5.15) with the proposed Decision Engine has lower value than the ordinary Opensips's LB as shown in Fig 5.17. The

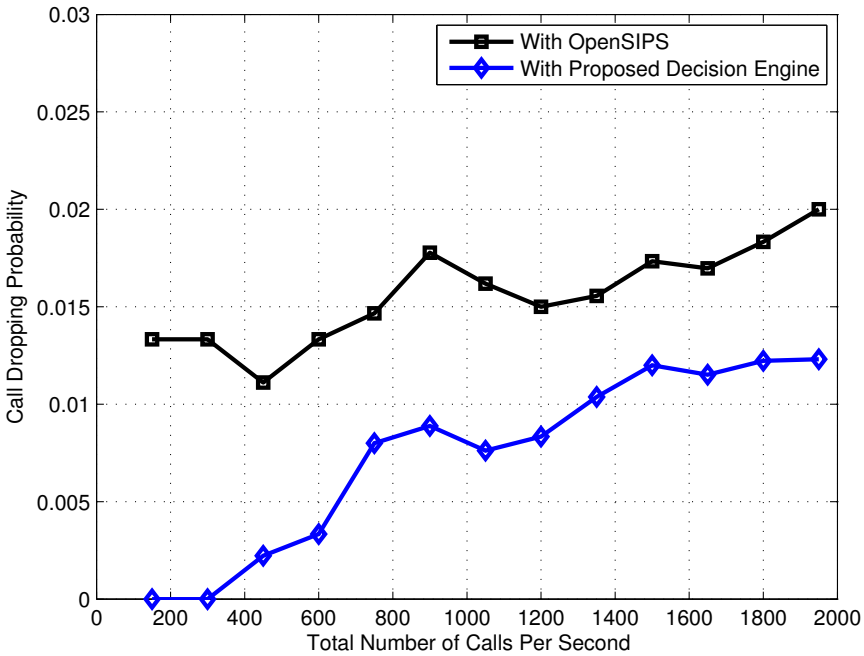

Figure 5.17: Call Dropping Probability With OpenSIPS and With Decision Engine.

delay introduced by the system with and without Decision Engine is also calculated over the same test bed. The graph shown in Fig. 5.18 indicates that addition of Decision Engine in the system introduces a minor overhead (delay). This calculation is performed in outsourcing enforcement mode due to more dynamics involved in that particular mode (for detailed functionality, information sharing and communication between different devices over the presented architecture in outsourcing and provisioning modes respectively, the reader is referred to [17]). The delay increases almost linearly as the number of calls/requests increases and is small enough having very little

impact on services. It is due to the fact that the decisions are being executed and enforced during call/connection setup time so delay has nothing to do with the ongoing calls/communication.

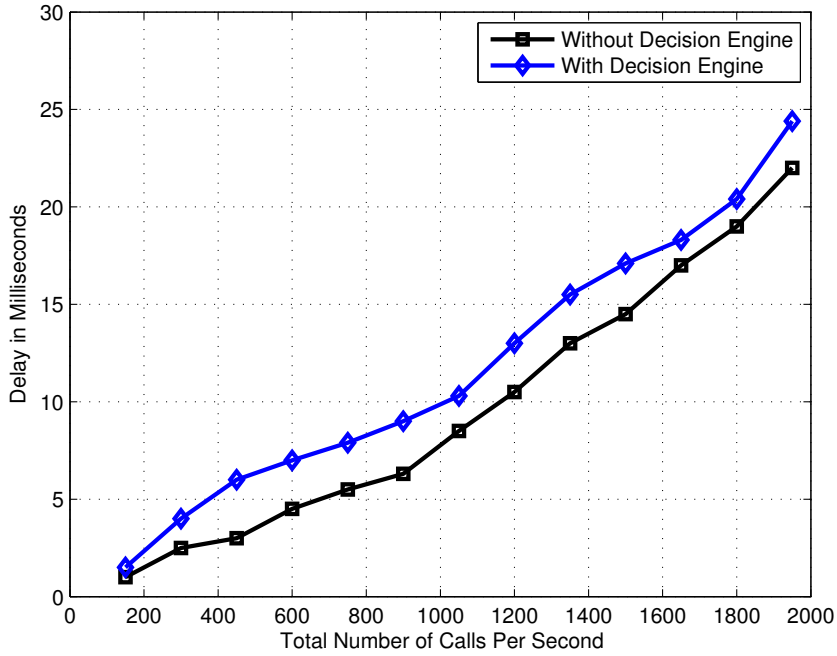

Figure 5.18: Delay (Milliseconds) Introduced by the System With and without Decision Engine.

5.8.1 Horizontal Handover Decision Computation Using Same Decision Engine

The arrival of a new call triggers the decision system to compute the routing decision at private-public unified platform. Attributes involved in the decision-making for link selection (dynamic routing) are extracted from the context of the call and platform's conditional set of parameters along with the pre-configured business rules. Motivating factors and the sources involved during the initiation of HH decision-making across the presented platform are different from the routing problem. HH is a Peer-to-Peer (P2P) mechanism involving the BTS boxes regarding the decision enforcement. However, the handover decision is computed at the master OpenSIPS as all the decision logic is embedded there. Being a single point of contact to all OpenSIPS slaves, master has the latest information regarding resources. Moreover, the handover employs some SIP signaling (REFER or re-INVITE) for call transfer, which is totally different

from conventional GSM. All the GSM handsets (Mobile Phones acting as SIP end points) are registered using their International Mobile Subscriber Identity (IMSI) to the corresponding slave OpenSIPS. The registrations are mirrored to the master OpenSIPS server. During an ongoing call, if a duplicated registration with similar IMSI is found at master OpenSIPS, handover decision computation is triggered. Master OpenSIPS takes the snapshot of the environmental and conditional parameters of the corresponding OpenSIPS slaves (cells) and pre-configured business. The HH decision is computed and enforced at the corresponding OpenSIPS slaves. An illustration of a handover scenario is depicted in Fig. 5.19.

The aim is to avoid involving the user in the handover process and to conduct it

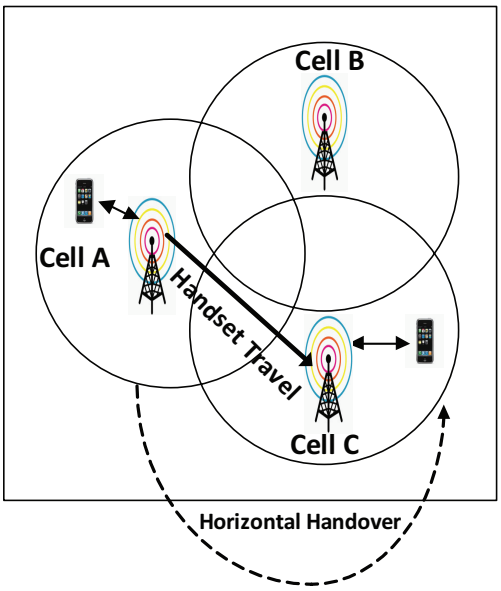

Figure 5.19: Horizontal Handover Scenario.

without the user's awareness (i.e., seamless handoff). Additionally, its a soft handover as the hard handover involves "break before you make", so it is easier to realize the seamless handover in soft rather than the hard handover. HH decision computation mechanism remains the same (TOPSIS in coordination with AHP) except that the criteria involving the attributes and alternatives repressing the candidate cells are changed. The objective here is to rank the corresponding cells for possible HH decision-making. Fig. 5.20 illustrates the hierarchy of the desired goal, the criteria (set of attributes involved in the HH) and the available alternative (GSM-cells). The alternatives (links) over the test bed are supposed to behave as GSM-cells at times for testing purposes. It has been mentioned previously that the mobile handsets are emulated as SIP extensions (endpoints) using the triplet (USRP, OpenBTS and OpenSIPS) over the real time unified platform. SIP infrastructure is highly open and flexible, offering facilities

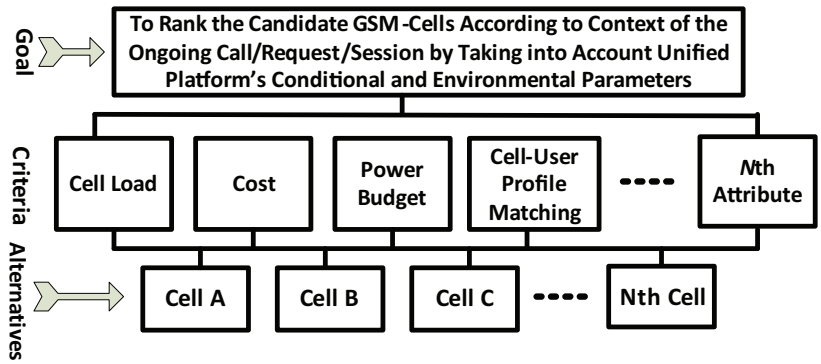

Figure 5.20: Candidate GSM-cells, Attributes and Goals Hierarchy for Horizontal Handover Decision-Making.

to services. SIP allows the creation, modification and termination of service sessions independently of the underlying data-link layer technologies and transport protocols. Asterisk servers over the platform are configured to accept the SIP methods/request blindly for testing the HH decision-making and its enforcement. The XML source file for generating the extensive SIP requests is modified to send a random re-INVITE after variable amount of time during the ongoing calls. The HH decisions (pre-ranked links supposed to behave as GSM-cells) are enforced during the launch of re-INVITE by changing the interface pointing towards another link (e.g.; if the link 1 is used for an ongoing call before re-INVITE, decision enforcement allocate another link e.g. link 4). The ongoing calls with re-INVITE/(200 OK and BYE after variable time interval) are recorded and the calls with re-INVITE but without 200 OK/BYE are also counted. The call dropping probability shown in Fig. 5.21 is plotted against the total number of calls with re-INVITE which are considered as the functional mobile handsets looking for HH. The proposed decision engine yields lower call dropping probability than the random selection scheme. Conventional algorithms used for dynamic routing/horizontal-handover at higher layers in multi-homing setups with access technology convergence are either application oriented or service dependent. Performance optimization is the ultimate goal in some cases while the others are technology specific. To address all these multi-facet goals in addition to dynamics and fluctuations handling over the platform, MCDM methodology is applied. A dynamic Decision Engine for call-routing/horizontal-handover is presented. The system is capable of accommodating the fluent dynamics while handling a large set of attributes representing the underlying criteria in MCDM. The same system is handling the private-public network border routing decision-making along with horizontal handover decision computation.

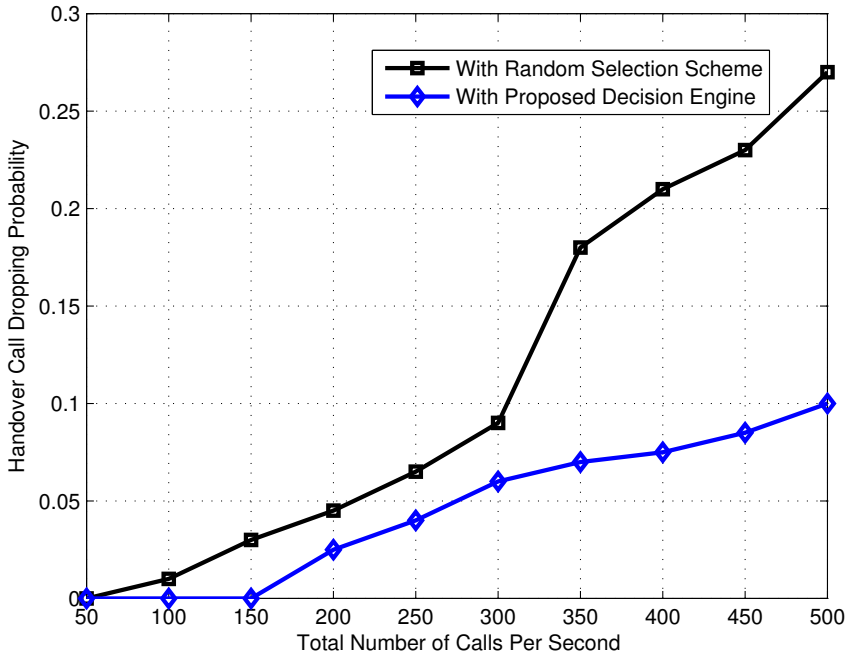

Figure 5.21: Handover Call Dropping Probability With and Without the Decision System.

5.9 Weight Computation for Corresponding Criteria in MCDM

MCDM problem formulation regarding the proposed architecture includes the declaration of goals (routing and/or handover decisions), criteria (set of attributes e.g. SLA, Link Profile, User Profile etc.) sub-criteria, alternatives links (ISPs, Candidate Link where calls/requests are routed, GSM cells for horizontal handover etc.). Hierarchy construction involves the placement of goals, decision factors (criteria and sub-criteria) and the alternatives positions with the corresponding levels and links. There is another important mechanism of weight conversion/calculation and its assignment to the criteria and/or sub-criteria describing the relative importance of the attributes constituting the criteria and/or sub-criteria. All the MCDM methods used so far contain static and/or manual weights conversion/calculation. These weight values are devised from the business objectives of the platform, services/user/link profiles, context of the ongoing request/call and administrative variables over the platform. For instance in case of decision computation for an outgoing voice call (outbound call); the QoS requirements of voice requires that the attributes delay and jitter should be given more weight values, the available bandwidth is coupled with user profile loaded from the

profile base (in case of gold profile, it is highly desirable to choose the link with good available bandwidth) so the available bandwidth and attributes representing user profile will also be given suitable weight values. These assigned weights illustrate the relative importance of each attribute.
The weight deduction and computation used so far is based on subjective approach in addition to the static scale used for weight assignment. Linguistics is mapped to the numbers using this approach (e.g. voice is more important than video, gold profile has the highest priority, number of calls on a link are as important as the reliability etc.). The former approach includes embedding the scale for subjective and objective weight assignment to corresponding criteria/sub-criteria beforehand and declaring the predefine methodology to extract weights from the business objectives of the company. It can be tedious and complex as the number of links and criteria/sub-criteria increases. The business objectives of the company may change; e.g., video might be given priority over video, the silver profile might use gold profile service during night (free hours), etc.), the user profile priorities/authentication/authorization parameter (QoS profile corresponding to a user profile) may go through modification, or the link resources might go through up-gradation/downgrading. Though this complexity can be handled, but it requires extensive administrative efforts. The objective however, is to minimize these efforts at minimal while taking into account the dynamicity that the manual system is not able to accommodate. So the weight deduction and computation mechanism should also be automated to handle dynamicity with least administrative and manual efforts over the hybrid platform.
Analytical Hierarchy Process (AHP) [138] is used to calculate the weights (w_1, w_2, w_3, w_4, w_5 and w_6) of the corresponding column vector laying out the criteria, representing attributes for the alternative links as shown in equation 5.1 (same set of attributes and alternative links with same hierarchy are used in order to present AHP). AHP can fragment a problem into a hierarchy of simpler and manageable sub-problems. It is a MCDM methodology in itself. However, its ability to elicit accurate ratio scale measurements and combine them across multiple criteria has led us to use it.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	
Weights	w_1	w_2	w_3	w_4	w_5	w_6	
A_1	UR_1	D_1	J_1	PL_1	TB_1	AB_1	L_1
A_2	UR_2	D_2	J_2	PL_2	TB_2	AB_2	L_2
A_3	UR_3	D_3	J_3	PL_3	TB_3	AB_3	L_3
A_4	UR_4	D_4	J_4	PL_4	TB_4	AB_4	L_4

(5.1)

Where $C's$ are the criteria, $w's$ are the weights and $A's$ are the alternative links respectively. Pairwise comparison is used to determine the relative importance of each alternative in terms of each criterion. These pairwise comparison are qualified by using the Saaty's scale [138] shown in table 5.5. Two weighting classes have been

Relative Importance of Corresponding Elements in a Class	Saaty's Scale
Equally Important	1
Moderately Important	3
Strongly Important	5
Very Strongly Important	7
Extremely Important	9
Intermediate Values	$2, 4, 6, 8$
Reciprocal Values	$1/2, 1/3, ., 1/9$

Table 5.5: Relative Importance of the Attributes and Their Corresponding Values Used for Pairwise Comparison.

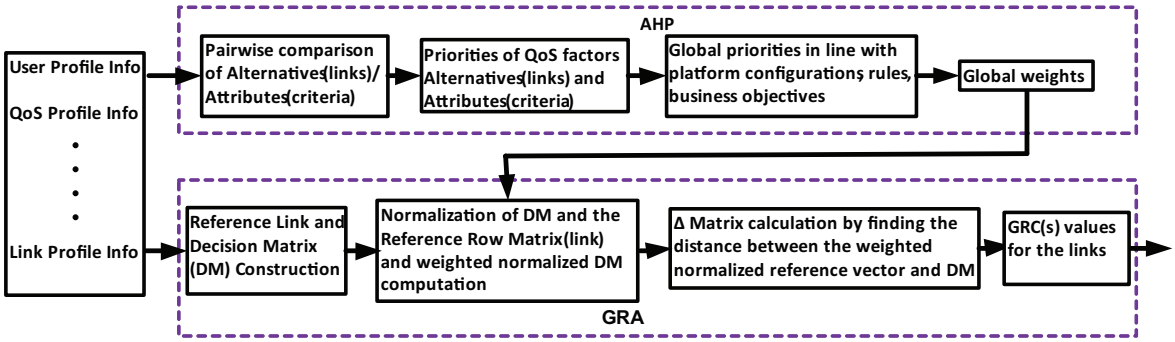

Figure 5.22: GRA and AHP Integration for Decision System.

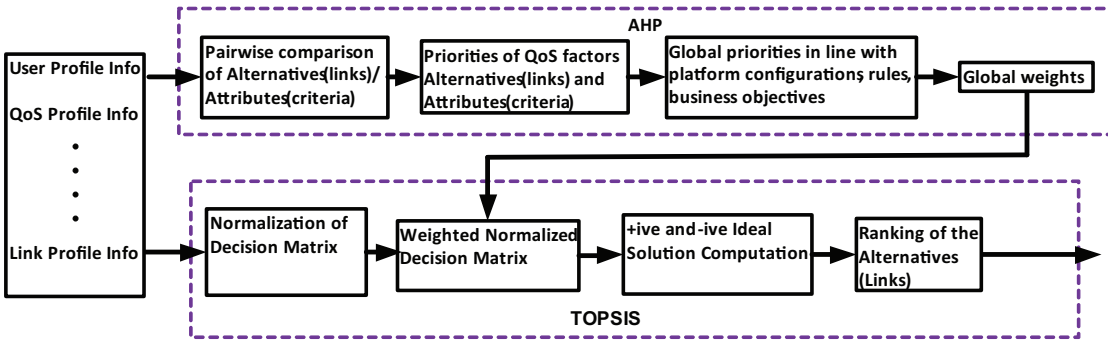

Figure 5.23: An Integration of TOPSIS and AHP for Decision System to Automate Weight Computation.

devised using Saaty's scale: the first class formulates the global priorities of the alternatives (links) illustrating the degree of importance of those candidate links and the second class is conceived by the pairwise comparison of the attributes involved in the

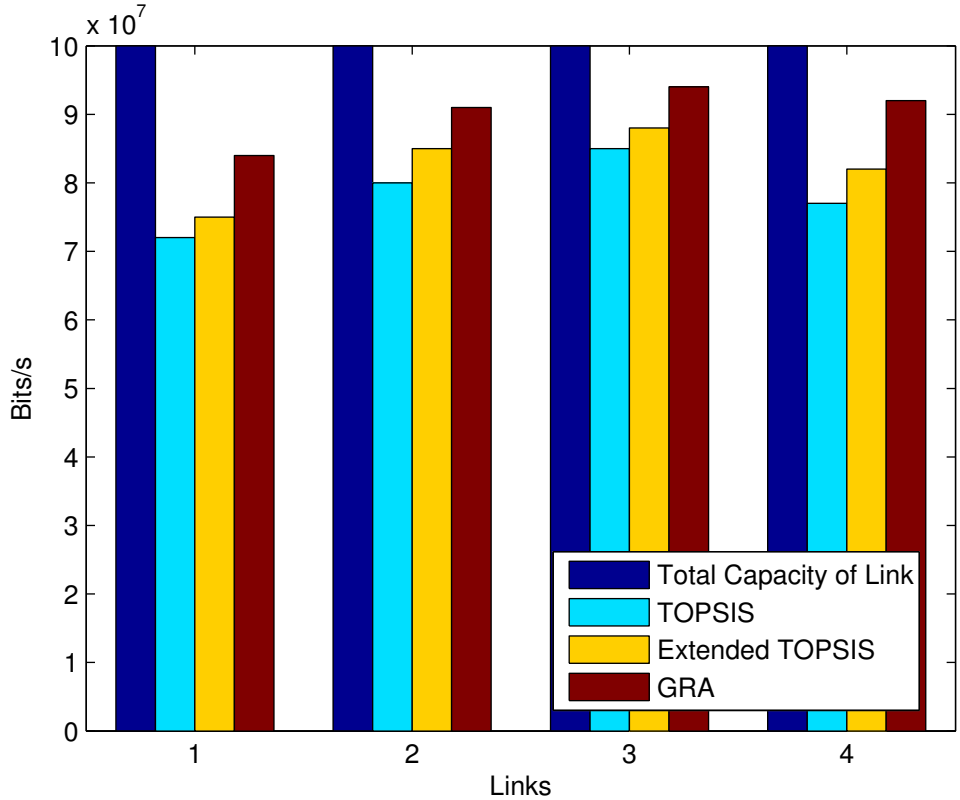

Figure 5.24: Throughput of Alternative Links by the Integration of TOPSIS, Extended TOPSIS and GRA with AHP.

decision matrix in equation 5.1 using the same scale as shown in Table 5.5. AHP application steps illustrated in [138] are performed in order to calculate the weights of the corresponding column vectors repressing the criteria. There exist other methods to calculate the corresponding weights and they might be exploited accordingly [139, 140]. However, AHP is used here as it facilitates the construction of criteria and alternatives classes in addition to subjective weight computation of the later and former classes. But manual weights can be assigned to the criteria while using the standalone MCDM methods keeping in view the susceptible static ranges and marginal dynamic behavioral trade-off along with the convenience of the underlying system.

MCDM methods TOPSIS, Extended TOPSIS and GRA are applied again on the simple use case of 6 attributes with 4 alternative links. But the weight computation is automated here as compared to previous manual or semi dynamic approach. Block diagrams of TOPSIS and GRA integration with AHP are shown in figures 5.22 and 5.23 respectively Modified MCDM methods (TOSIS, Extended TOPSIS and GRA integra-

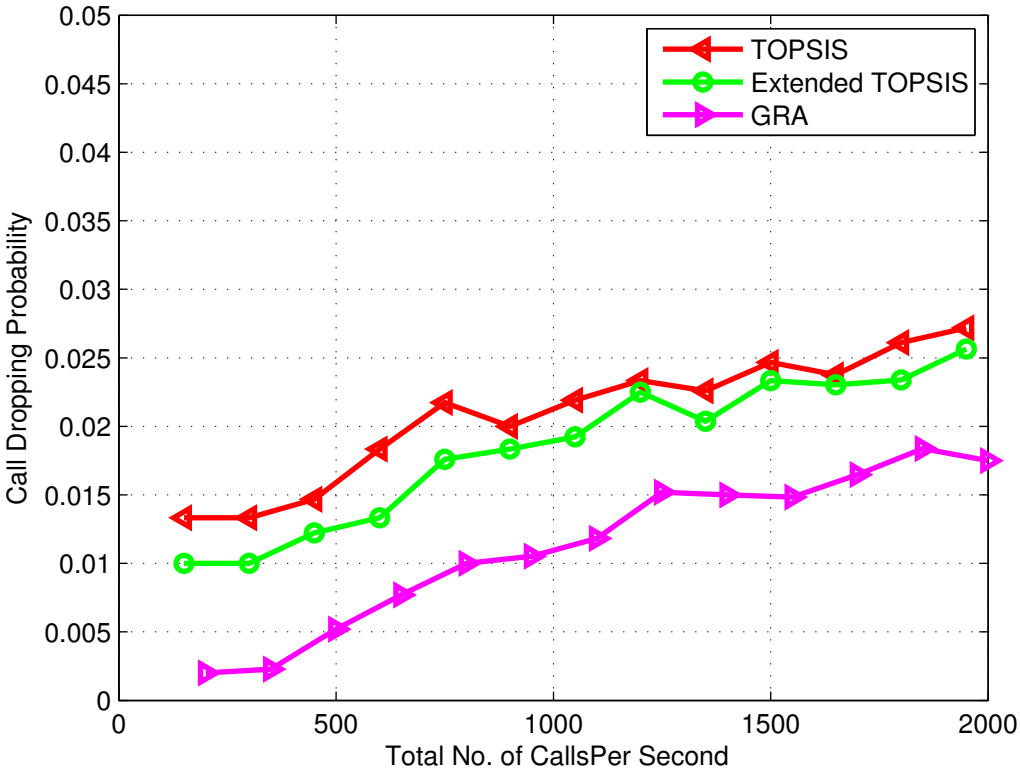

Figure 5.25: Aggregated Call Dropping Probability by the Integration of TOPSIS, Extended TOPSIS and GRA with AHP.

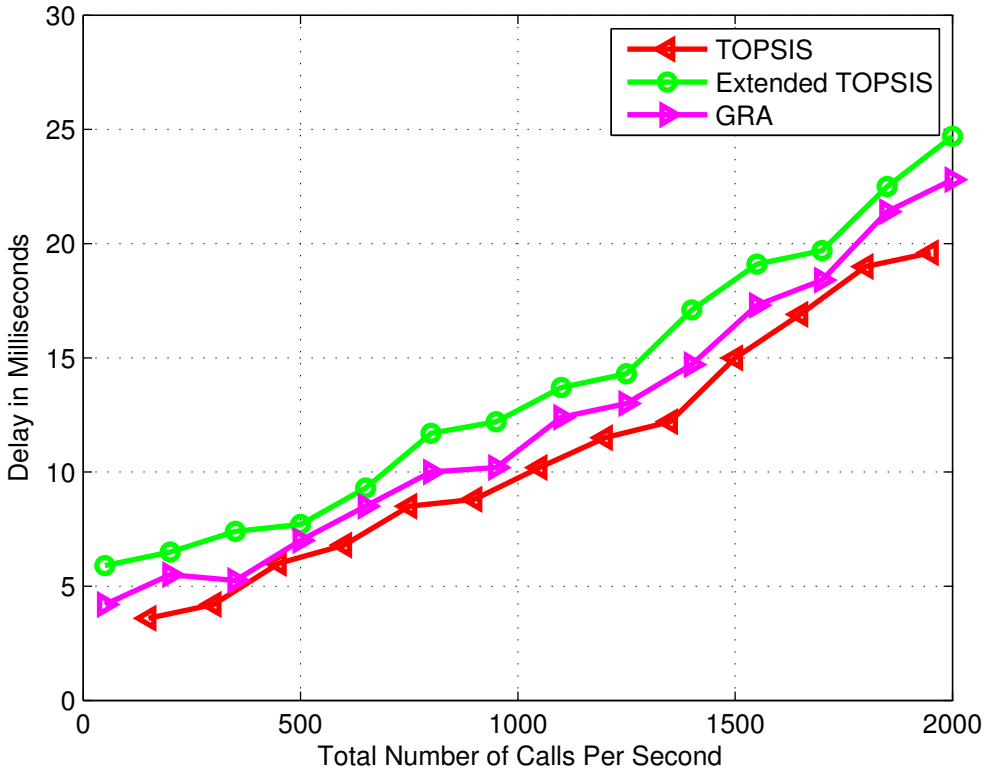

Figure 5.26: Delay Offered by the System By the Integration of TOPSIS, Extended TOPSIS and GRA with AHP.

tion with AHP) are applied again to the same use case of 6 criteria and 4 alternative links over the test bed used in section 5.4. Throughput, Call Dropping Probability and Delay are plotted using these integrated methods and are shown in figures 5.24, 5.25 and 5.26 respectively. It is observed that the throughput of the alternative links is improved. There is significant decrease in the call drop. The enhancement is due to the fact that the linguistic quantification of the business objectives and other administrative and configurational parameters by Saaty's scale helps in true numerical value conversions with their inter-dependence. The deployment of AHP steps for weight calculation takes all the local and global priorities by pairwise comparison. The cost of this improvement is an add-on delay system has to bear while computing the decisions.

5.10 MCDM and Ontology Integration

Rule based network management and control over the hybrid platform with service unification while offering multi-homing support requires intrinsic and extrinsic domain/planer knowledge to be specified and made understandable. The domains/planes acting as a source of knowledge base are complex and have enormous sub-domain/planes with frequent variations and dynamics. Moreover the relationships and semantics regarding the information base over these domains/planes are also critical for effective and efficient rule base management. Application, control and network information are to be shared within those distinct domains and across these planes for rule based network management. The attributes and parameters related to resources, profiles, services and dynamics taking place over those planes are disseminated and exchanged via different interfaces and protocols. The information sharing and exploitation process becomes more delicate when its control and management has to be performed under the dictation of certain set of pre-configured business objectives and administrative rules. Moreover, in heterogeneous unified communication systems, there are vendor-specific concepts and implementation dependencies with different means of information representation and processing.

The information sources representing different domains (e.g. service plane, control plane etc.) might be highly structured and synchronized locally (inter-domain/plane) but may have higher probability of asynchronous and un-structured information representation globally (intra-domains/planes). These highly dynamic, multidisciplinary and multivariate information domains (planes/layers) which are synchronized locally and asynchronous globally are behaving as GALS (Globally Asynchronous Locally Synchronous) system(s). Inter and intra domain/planer relationships between classes and/or instances within/over these GALS system(s) and the semantics among them are captured by using ontology. Moreover the variations and dynamics along with feedback over the system is handled by using a reasoner with certain set of axioms [50].

Ontology has its significance in the filed of philosophy for a number of decades. Ontology use has exploded within the realm of computing particularly in fields of Ar-

tificial Intelligence, Agent-Based computing and more specifically the semantic Web (WWW). The Semantic Web aims to revolutionize the Web by assigning explicit meaning to textual information to enable machines to automatically process and integrate information in a way not currently possible using plain text. Ontology can share vocabularies. It is defined as an explicit specification of a conceptualization [49]. It contains object types or concepts, properties and relationships. Ontology has some concepts in specific domain and its formal expression for their relationships. Generally, ontology has inference function aim at some properties of domain or to define the domain. In addition to ontology's native exploitation of inter and intra domain/plane knowledge representation while capturing the semantics while accommodating the variations and dynamic over the unified infrastructure. Ontology with inference engine configured with specific set of axioms is used for semantic matching between criteria for the application of MCDM theory.

Block diagram of the system shown in Fig. 5.27 is an improved form of the previ-

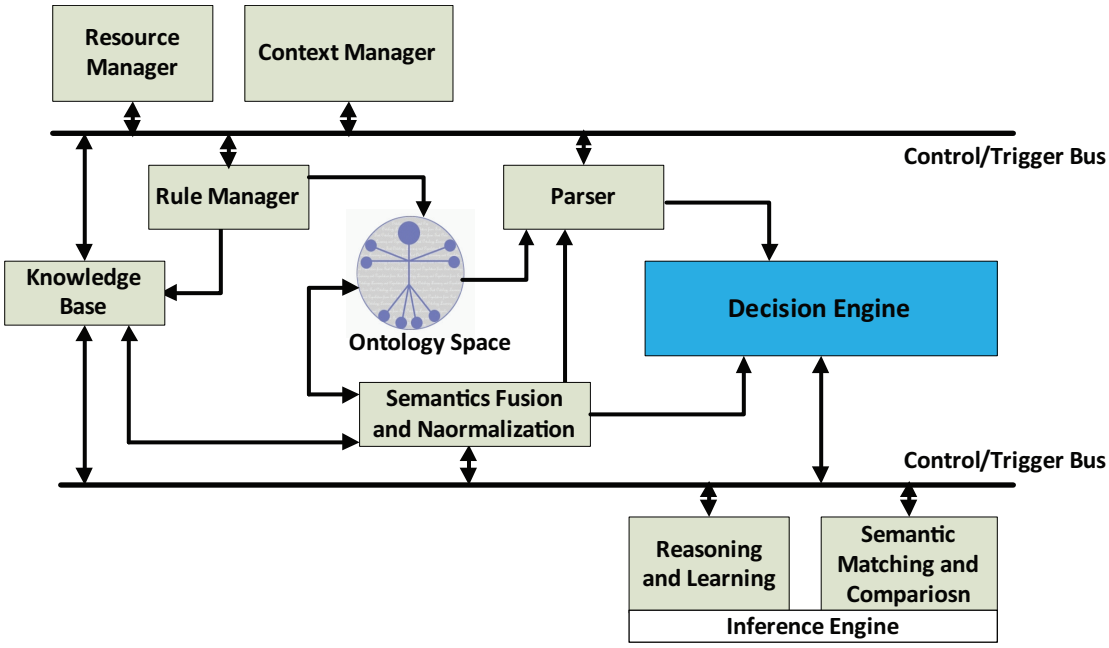

Figure 5.27: System Block Diagram With Modifications.

ous proposition shown in 5.3. Semantics fusion and normalization unit is introduced here in order to overcome the inter/intra-domain/plane knowledge representation complexity and to accommodate the semantics variation while supporting the feedback mechanism. All the units are connected via the adaptive control/trigger bus. Resource manager in the unified communication environment keeps all the business, system, network and service level resource information. Context manager detects any sort of

changes in the application/service plane, network/transport plane and business objectives of the platform and triggers a new set of rules for control and adaptation. The inference engine via the semantics fusion/normalization unit drives the parser for ontology inheritance and overloading in addition to the reasoning and learning performed under the dictation of embedded axioms. Knowledge base unit contains all the technology specific and technology independent service, profile and network data sets. Rule manager contains the predefined set of rules added by the administrator of the platform reflecting the targeted goals. Decision engine is analyzing, adapting and handling the multi-criteria and multidimensional information coming from different sources with multiple objectives. The underlying system precisely illustrates different components and their interactions. Ontology space obtains all the corresponding ontologies representing the global information and knowledge with semantics and classes/instances relations. Ontology space with reasoner via fusion unit helps for criteria matching and inheritance.

Diversity and dimensionality of the multifaceted service, control, transport and access

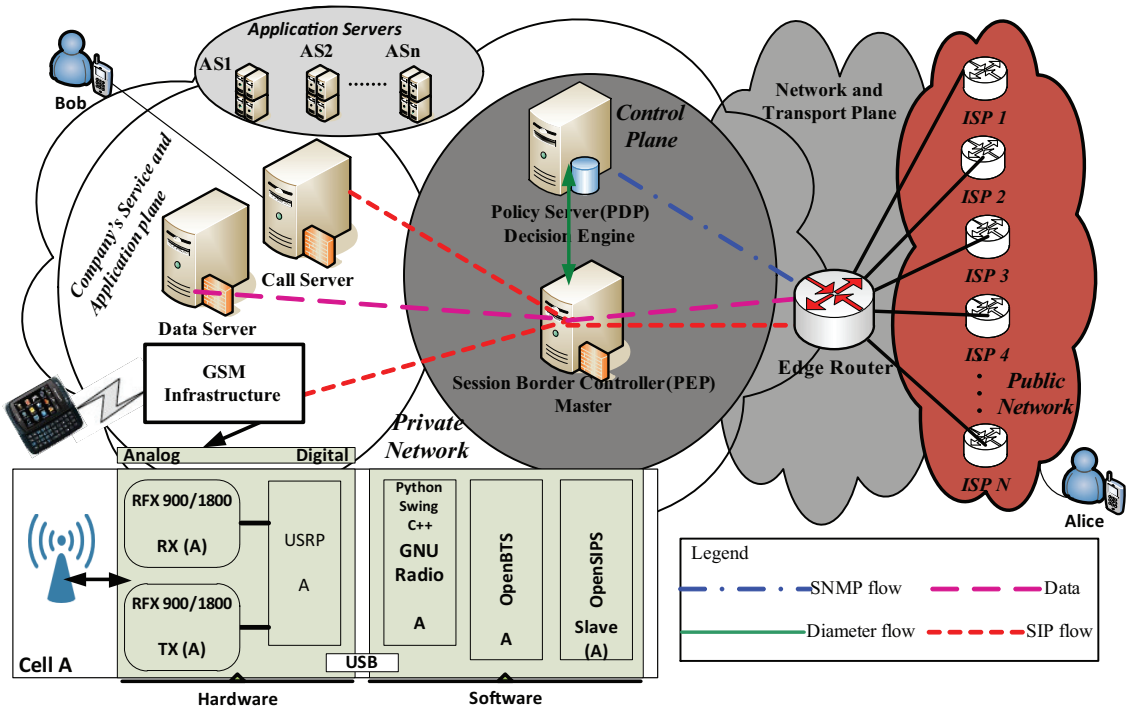

Figure 5.28: Architecture Used for MCDM and Ontology Integration Use Case.

planes along with multiple objectives in addition to the relational dynamics and semantics variations over the platform has led us to integrate MCDM and ontology. MCDM helps in achieving the multiple objectives on the basis of multi-disciplinary information domains. The ontology, on the other hand, overcomes the semantic matching

and reasoning issues using conventional object-oriented techniques with the help of inference engine. Though the ontology development is not within the scope of this document but a simple use case involving the same set of 6 attributes and 4 alternative links is presented for MCDM method and ontology integration. Multi-homing oriented architecture shown in Fig. 5.28 offers a cost effective unified communication platform providing versatile access technology convergence highlighting network traffic unification framework emphasizing private-public network border traffic management issues while targeting the multiple objectives capturing semantics variations and dynamics. Different modules over the platform are already explained before in the document except data server. Data server offers conventional web, FTP and mailing services (irrespective of access protocols and technology) over the normative unified architecture. SIP-based Multimedia services over the multi-homed unified platform are focused due their QoS requirements and control . Moreover, it is not possible to present an ontology on a piece of paper totally representing a particular domain. So a glimpse of service, QoS and SLA ontologies is shown in Fig. 5.29. Two user Bob (lo-

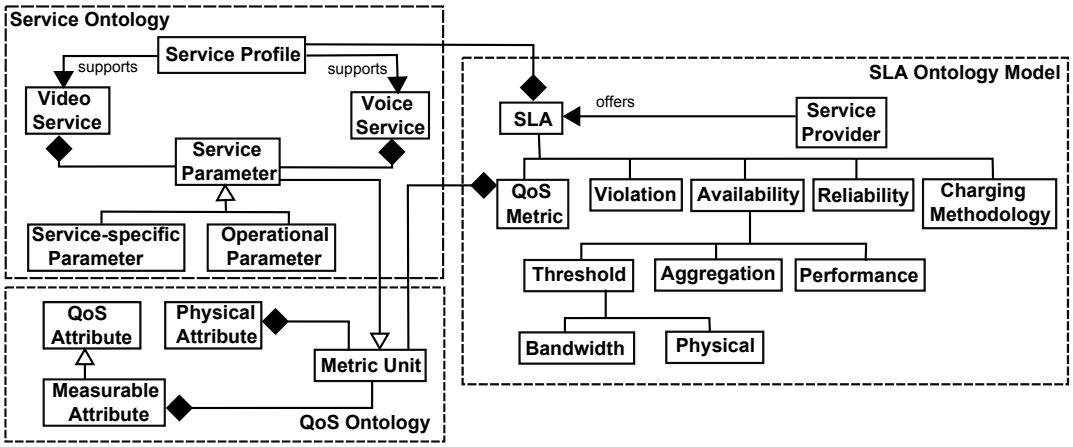

Figure 5.29: SLA Ontology Model and Service/QoS Ontologies.

cal) and Alice (remote) are supposed to communicate (outgoing SIP communication) with each other by using the available resources on the platform as shown in Fig 5.28. The hierarchy of the desired goal, the criteria, sub-criteria and the available alternatives is illustrated in Fig. 5.4. Bob initiates the communication and sends an initial INVITE to the CS. Resource priority tag indicating the user profile is added and the request is forwarded to the SBC. Communication type is evaluated at SBC and this information (resource priority tag, communication type) is sent to the PS. Decision engine within the PS maps the corresponding profiles from the central profile base and then generates a trigger and takes the snapshot of the platform's information for further processing. Particular context overrides the specific instance of the knowledge base (reliant on the semantics fusion/normalization unit which in turn is dependent on inference engine)

that embody the overloaded ontology space (containing concepts, classes relations and instances) for the ongoing context under the influence of embedded axioms and predefined set of rules. MCDM in coordination with ontology capture the knowledge relating to the service/control/transport planes, diverse network provider's capabilities, environmental constraints, business goals and dynamic variations over the underlying network infrastructure. Relevant goal, criteria and sub-criteria are adapted adequately and the utility function of the MCDM method is formed. Weights of the corresponding attributes (representing the criteria and sub-criteria) are computed by using pairwise comparison with AHP (the method is devised earlier in section 5.9) while keeping in view the context and the business rules in consent with the reasoner.
An integrated MCDM method (GRA with AHP) is applied (but TOPSIS with AHP is applied in another published work [133]). The application steps of the method are gone through in order illustrated in 4.4. SIP-based voice call is routed to one of the 4 alternative links by using the proposed decision engine. L_1, L_2, L_3 and L_4 are the four links and UR, D, J, PL, TB and AB are 6 attributes representing the voice/video Utilization Ratio, Delay, Jitter, Packet Loss, Total Bandwidth and Available Bandwidth respectively as shown in table 5.6. Integrated MCDM method application steps and more implementation details regarding the underlying use case over the platform are available in [50, 51]. The application of Integrated MCDM method in coordination with ontology over the alternative links represented by the row vectors having the corresponding criteria represented by the corresponding column vector produces the alternative rankings and the voice calls are forwarded to the ranked alternative links accordingly. The links are ranked with GRC values as mentioned in Table 5.7. Now extensive SIP traffic is generated using SIPp to validate the proposed solution on similar lines as explained in section 5.7. Throughput of each link is plotted with and without decision engine (i.e. using built-in LB in SBC) as shown in Fig. 5.30. It is observed that there is a significant improvement in the throughput for each link with decision engine while performing SIP-based call routing. The rise in the throughout is due to the fact that now the proposed decision system is taking in to account contextual dynamics and variation with multiple objectives by considering the inter/intra-domain and

	UR	**D**	**J**	**PL**	**TB**	**AB**
	%age	**Milliseconds (ms)**	**ms**	**%age**	**Megabits per second (Mbps)**	**Mbps**
$\mathbf{L_1}$	48.32	210	35	36	100	68
$\mathbf{L_2}$	30.84	200	25	25	100	71
$\mathbf{L_3}$	15.00	150	30	30	100	46
$\mathbf{L_4}$	20.25	100	15	10	100	81

Table 5.6: Links With Corresponding Parametric Values

	L_1	L_2	L_3	L_4
GRC Value	0.0698	0.4088	0.4846	0.8163
Rank	4	3	2	1

Table 5.7: GRC Values and the Corresponding Grading of Alternative Links

inter/intra-plane dependencies along with semantic and relational dynamics. Moreover the weight computation is also being done on similar lines by using AHP along with pairwise comparisons and Saaty's scale (section 5.9).

The retransmission mechanism within SIPp is turned off when INVITE messages

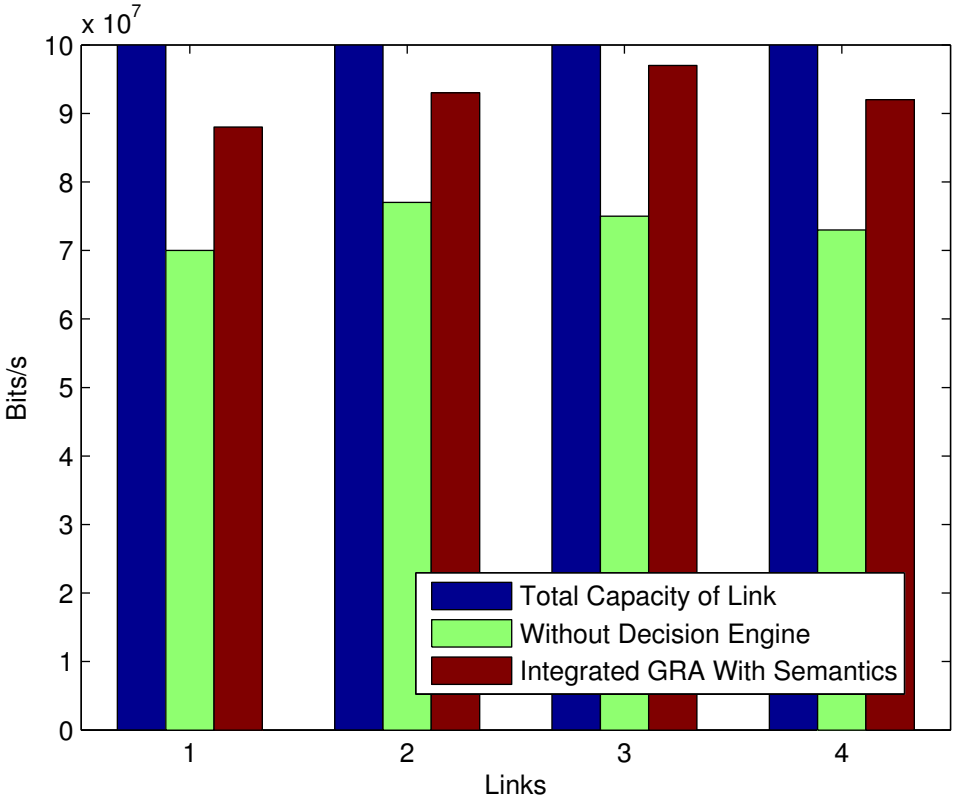

Figure 5.30: Throughput of Each Link With and Without Decision Engine.

are sent in order to know that a call has been dropped. The aggregated call dropping probability (for the 4 links shown in Fig. 5.28 with the proposed decision engine has lowest/lower value in the outsourcing mode (on-line/off-line) than the ordinary SBC's built-in LB as shown in Fig. 5.31. The decrease in number call drop is due the inherited matching of computed decisions with the platform's resources. Moreover the

dynamic and static conditional attributes and the administrative parameters and their inter-dependence with semantics play a crucial role in lowering the overall aggregated call drop. The delay introduced by the system with and without Decision Engine is

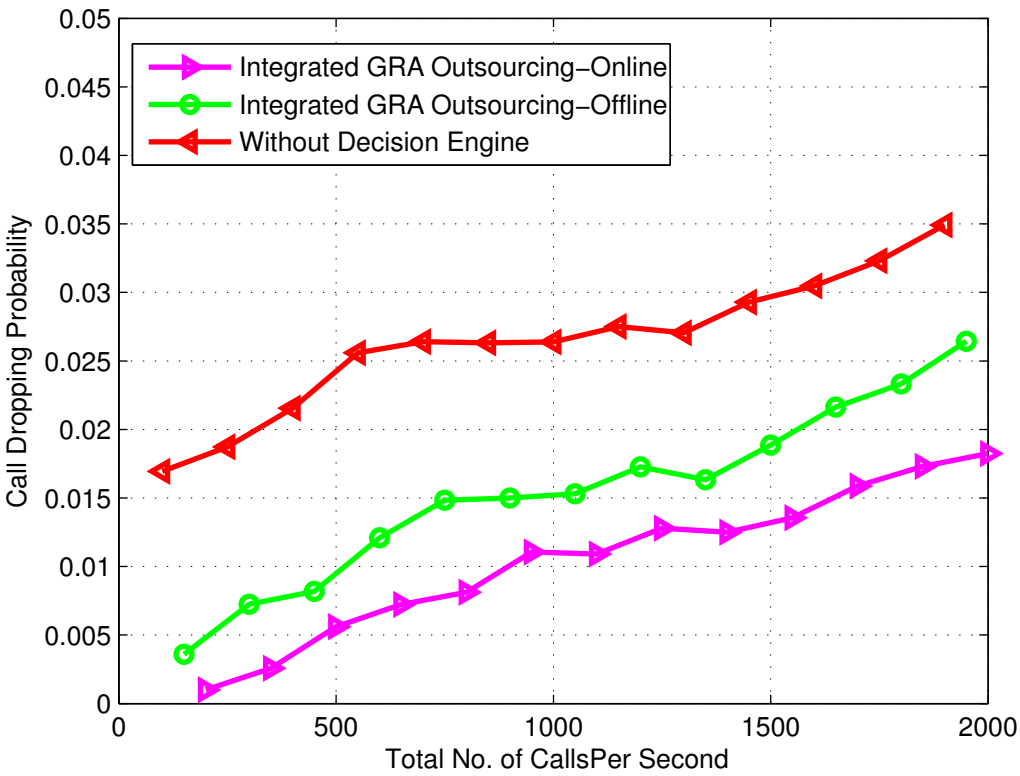

Figure 5.31: Call Dropping Probability Without and With Decision Engine (Outsourcing Mode (Online and Off-line)).

also calculated introducing the highest gap between the curves (i-e without the decision engine and the batch with decision engine representing online outsourcing mode and off-line outsourcing mode). The graph shown in Fig. 5.32 indicates that addition of decision engine in the system introduces overhead (delay). This calculation is performed in outsourcing enforcement mode (online and off-line) due to more dynamics involved in that particular mode (for detailed functionality, information sharing and communication between different devices over the presented architecture in outsourcing mode. The reasoning and inference with semantics dynamics and context of the ongoing request/call are the main causes of additional delay. Moreover the intra-domain/plane correlations and semantics dynamics also causes more delay. But the offered delay remains within the bounds without effecting the QoS and QoE. The delay increases

almost linearly as the number of calls/requests increases and is small enough having very little impact on services as the decision computation and calculation is being done during call/session/request setup time.

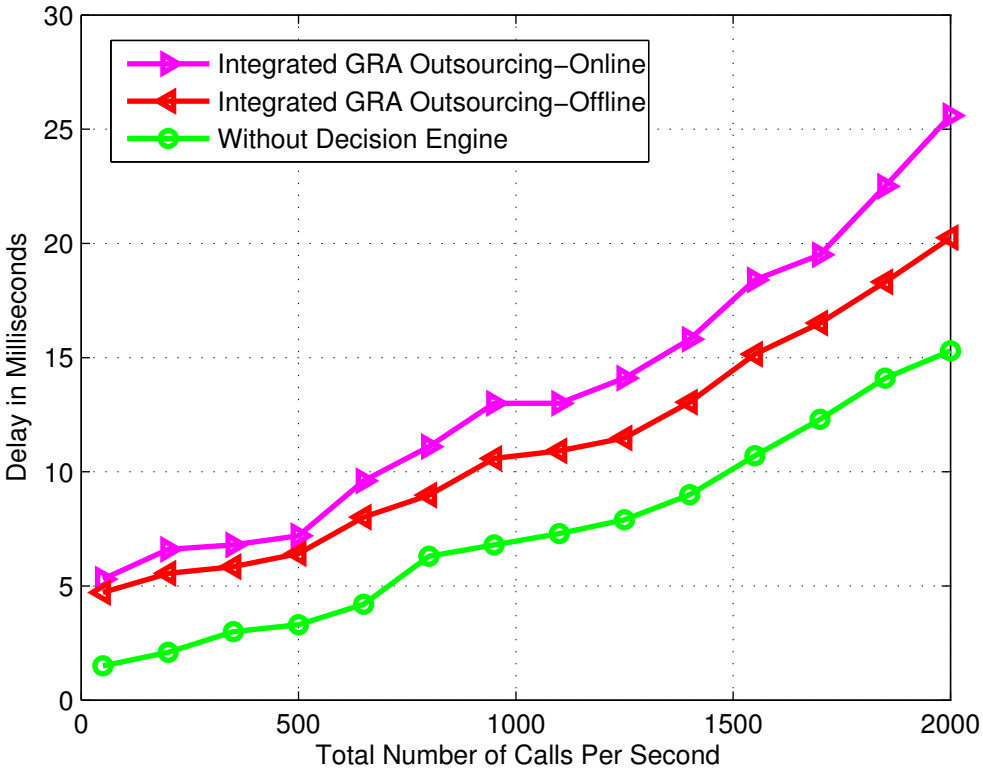

Figure 5.32: Delay (Milliseconds) Introduced by the System Without and With Decision Engine (Outsourcing Mode (Online and Off-line)).

5.11 Summary

This chapter includes all the ingredients required to built the rule/decision framework for multi-homed infrastructure with convergence and heterogeneity support for applications, services, and access and transport technologies respectively. These constituents incorporate from information model to semantics capturing, it embraces the representation of its communicational, behavioral and functional features and components, the control and management of the infrastructure is carried out by revamping the sole signaling protocols (e.g. SIP, diameter and SNMP) and finally the language over the platform gluing all the constructs and micro/macro rules/business ob-

jectives/administrative instructions over the platform as it is deeply rooted within the infrastructure. The modules/sub-modules and the components/sub-components, intercommunication, the behavior of the former and the later elements and the communication of the underlying elements along with the inheritance of the corresponding concepts regarding the decision engine is elaborated keeping in view decision computation and its enforcement. Layered approach is followed in order to exploit and map the planer and domain specific information regarding the MCDM theory. Decision engine's modular framework is presented by describing the technology specific and technology independent application service, control and network/transport planes data sets used by diverse modules/components within the decision engine. information model representing the concepts, relationships, constraints, rules, and operations to specify data semantics for the platform while describing the stable and organized structure of information requirements for the domains/planes over the infrastructure. The underlying information model complements the information capturing from diverse contexts regarding the requests and resources over the network. Three different information models are investigated and explored in the line of platform's obligations and stipulation. But after probing these three model it is recommended to tag and enhance an existing information model. (DEN-ng). Rule/policy management and its specifications have strong correlations as it accommodates the change management and business processes by following the business logic of the company. Policy specification approaches ranges from formal policy languages that can be directly processed by a computer, to rule-based policy notations/constructs, and to representation of policies as entries in a table consisting of multiple attributes. A simple use case (used for the application of MCDM) is adapted here in order to realize the nativity of the rule/policy representation languages. Three languages are examined and reviewed keeping in view the requirements of their deep roots within the platform. After the analysis and comparison it is observed that each policy language has its own semantics and syntax that is usually correlated and grounded in a particular logic description. It is therefore suitable to derive the policy language from the proposed framework rather than picking one of the subsequently mentioned languages offering limitations and restrictions. Decision computation and its management is discussed and presented from the MCDM theory point of view on the real time test bed. All the 5 MCDM methods are explained in the previous chapter in the context of the proposed framework and these methods are applied to a platform specific simple use case (consisting of 4 alternative links and 6 attributes (extracted from the planes/domains over the unified infrastructure)).
Throughput, CDP and Delay over the test bed are calculated for those 5 MCDM methods and these individual metrics are plotted for the analysis and comparison on the underlying 5 methods. It is found that GRA, extended TOPSIS, TOPSIS, WPM and WSM outperforms the OpenSIPS built-in load balancer and the gives higher throughput in order as mentioned (i-e GRA > extended TOPSIS > TOPSIS > WPM > WSM respectively).

The aggregated call dropping probability over the test bed is calculated by using the corresponding MCDM methods one by one and it is observed that number of call drop while using WSM and WPM is higher than the other methods and it started earlier as compared to the rest of the used methods (Call Dropping started when the system is accommodating 20 calls/s). The main reason behind the higher and earlier call dropping is that these two methods are not taking the latest dynamics of the platform into account so there is higher probability of mismatching between the competed decisions and the infrastructure state and conditions. There must be clear distinction between TOPSIS and Extended TOPSIS in terms of aggregated CDP as Extended TOPSIS is supposed to accommodate the dynamics over the platform in addition to capturing uncertain and indefinite behavior of an attribute. But the curves for these two methods show almost identical behavior while overlapping at some points. The similar and akin conduct of these two methods is due to the fact that the platform chosen reflects the simple use-case involving few attributes facing little dynamicity. It is thus foreseen and apprehended that addition of more links and attributes may draw a clear line between these two methods in terms of call dropping probability.
The cost of the improvement in terms of higher throughput and lower CDP is the add-on delay introduced by the decision engine. But the delay offered by the system is thus measured to avoid annoying QoE and to put some upper limit regarding the global unified infrastructure offering highly delay sensitive multimedia services. The system offered delay in oder as: WSM $<$ WPM $<$ TOPSIS $<$ extended TOPSIS $<$ GRA respectively.
Decision computation over the multi-homed converged platform is accomplished in online and offline mode and the decision computation mode is chosen depending upon the configurations of the platform and/or the context of the request. The system supports provisioning and outsourcing modes decision enforcement irrespective of the decision computation mode. Online and offline decision computation during these enforcement modes again depends on the administrative requirements and business rules over the platform. The tagged information flow and the sequence of steps involved during these modes are explained and the outsourcing and provisioning modes are compared keeping in view the online and offline decision computation. The plot indicted that the CDP is lowering in sequence as (Outsourcing-Online $<$ Outsourcing-Offline $<$ Provisioning enforcement-computation modes respectively). The price of getting lower CDP is the add-on delay but it has little impact as the decision computation and its enforcement is performed during the call/session/request set-up i-e the signaling phase.
So far the decision engine over the proposed architecture is investigated and experimented/tested along with the analysis and evaluations keeping in view the service, application, control and network/transport convergence with heterogeneous infrastructure while supporting the multi-homed infrastructure. But the tests and observations are then conducted by considering the routing problem at private-public network bor-

der; however it is important to note that our interest is the fist hop so the solution is not intended to cater the end-to-end route computation/calculation problem. To validate the application/service convergence and control/network/transport/access technology heterogeneity, an environment is built by tweaking the all-open source solutions. Decision engine over this underlying unified communication framework has the ability of handing the private-public converged network border dynamic routing. Moreover the solution has the capability of handling the horizontal handover decisions without resetting/restating the system. Stress testing of the unified platform that accommodates the routing decisions and horizontal handover decision making all together in consent with the multiple criteria while targeting the multiple goals/objectives is accomplished using the same test bed (used before for emulations and stress testing) but with certain adaptations and modifications. The unified solution is tested for the routing decision making at private-public network border emphasizing the access technology convergence and the same set of metrics (throughput, CDP and delay) are observed. The proposed decision engine is compared with the OpenSIPS (tweaked to act as SBC and PEP as well) built in decision engine. It is observed that there is significant improvement in the throughput for each link with proposed decision engine as compared to OpenSIPS load balancer while performing SIP-based call routing. Moreover the proposed decision engine has lower CDP than the ordinary OpenSIPS's LB with an add-on delay that has very little impact on the overall call/session/request setups. Horizontal handover usually suffers from call droppings so the CDP while emulating the horizontal handover is measured and compared with the built-in mechanism and it is observed that the proposed decision engine offers lower CDP regarding the seamless handovers. MCDM problem formulation regarding the proposed architecture includes the declaration of goals (routing and/or handover decisions), criteria (set of attributes e.g. SLA, Link Profile, User Profile etc.) sub-criteria, alternatives links (ISPs, Candidate Link where calls/requests are routed, GSM cells for horizontal handover etc.). Hierarchy construction involves the placement of goals, decision factors (criteria and sub-criteria) and the alternatives positions with the corresponding levels and links. There is another important mechanism of weight conversion/calculation and its assignment to the criteria and/or sub-criteria describing the relative importance of the attributes constituting the criteria and/or sub-criteria. All the experiments and tests performed so far includes static and/or manual weight calculation/assignment regarding the application of diverse MCDM methods. But stress tests and emulations performed in some scenarios shows few abnormalities and an in depth analysis and study reveal that the system shows abnormal behavior at some instances due to static/manual weight calculation/assignment. Moreover the inter-dependence of the underlying criteria has not been taken into account while computing the weight statically/manually. A scale is adapted according to the platform's requirements and a new MCDM method is used to calculate the weights of the criteria illustrating the relative importance by taking into account the inter-dependence of the criteria and it removes the abnormal behavior of

the system by showing improvements than the observations made before regarding the throughput and CDP with an add-on delay.
Network management and control over the hybrid platform with service unification while offering convergence with multi-homing support requires intrinsic and extrinsic domain/planer knowledge to be specified and made understandable alongside the semantics variations. The domains/planes acting as a source of knowledge base are complex and have enormous sub-domain/planes with frequent variations and dynamics. The relationships and semantics regarding the information base over these domains/planes are critical for effective and efficient rule base management. Application, control and network information are to be shared within those distinct domains and across these planes for rule based network management. The attributes and parameters related to resources, profiles, services and dynamics taking place over those planes are disseminated and exchanged via different interfaces and protocols. These highly dynamic, multidisciplinary and multivariate information domains (planes/layers) which are synchronized locally and asynchronous globally are behaving as GALS (Globally Asynchronous Locally Synchronous) system(s). Inter and intra domain/planer relationships between classes and/or instances within/over these GALS system(s) and the semantics among them are captured by using ontology. MCDM helps in achieving the multiple objectives on the basis of multi-disciplinary information domains. The ontology, on the other hand, overcomes the semantic matching and reasoning issues using conventional object-oriented techniques with the help of inference engine. Though the ontology development is not within the scope of this document but a simple use case involving the same set of 6 attributes and 4 alternative links is presented for MCDM method and ontology integration. Test bed regarding this simple use case is used for the validation of the proposed ontology and MCDM integration. The observations plotted for integrated GRA regarding the throughput and there is substantial increase in the throughput as now the proposed decision system is taking in to account contextual dynamics and variation with multiple objectives by considering the inter/intra-domain and inter/intra-plane dependencies along with semantic and relational dynamics. Moreover the weight computation is also being automated by using AHP that uses pairwise comparisons.
The aggregated CDP also decreases significantly by using the proposed decision engine and it has lowest/lower value in the outsourcing mode (on-line/off-line) than the ordinary SBC's built-in LB. The decrease in number call drops is due the inherited matching of computed decisions with the platform's resources. Moreover the dynamic and static conditional attributes and the administrative parameters and their inter-dependence with semantics play a crucial role in lowering the overall aggregated call drop. The price of the enhancement for throughput and decrease in CDP is an add-on delay and the system came across the maximum delay as compared to previous experiments/tests. It is due to fact that reasoning and inference with semantics dynamics and context of the ongoing request/call are being taken into account simul-

taneously. Moreover the intra-domain/plane correlations and semantics dynamics also causes more delay. But the offered delay remains within the bounds without effecting the QoS and QoE.

6

Conclusions

6.1 Conclusions

A dynamic decision-making framework implementing the multimedia traffic routing at private-public network border is developed. The ingredients required to built the framework are matured and produced in sequence and steps by following the bottom up approach starting from information model, to semantics capturing, to embracing the representation of its communicational, behavioral and functional features and components, to revamping the intercommunication signaling protocols and finally the proposed language evolving within the roots of the framework binding all the constructs and micro/macro rules/business objectives/administrative instructions over the platform. The service and/or application, operational and/or management/control and network/transport planes are dealt with distinctively in order to isolate the operational, business, technology dependent and technology independent procedures and processes. Layered approach is followed to handle the service, application, control, converged access network and transport issues while emphasizing the private-public network border traffic management issues.

QoS mechanisms and characteristics are key for the effective and efficient operation over the architecture. QoS mechanisms in combination with PBNM are devised keeping in view the variations and fluctuations in consent with certain set of metrics over the platform. The QoS requirements for data and multimedia differ a lot, so to use the resources over the platform effectively and efficiently, key indicators regarding the important parameters are presented and compared for voice, video and data communications. SIP modification for information sharing and dissemination at device level is described. Least Cost Routing is outlined, extended and generalized as a special case of QoS via SIP-based dynamic routing but taking into account delay, jitter, loss rate sensitive multimedia communication in addition business objectives along with its native attribute, the cost.

The isolation of the planes over the architecture represents multiple criteria and objectives over these distinctive planes while posing a multi criteria problem. The underlying architecture is then linked to the dynamic decision making framework by

describing the inter-intra communication between different modules over distinct domains. Hierarchical representation of the linkages among planes, relations between entities over diverse domains, their interaction, the corresponding functions and methods simplify the underlying decision making framework. The granularity of the decision making framework addresses the call/session/request level despite the fact that it is taking the lower layer informations into account while complementing the utilization of Multi Criteria Decision Making theory.
QoS profile of the links, user authentication/authorization profiles, business objectives of the company, reciprocal SLAs with providers, technology specific and technology independent information over converged infrastructure, fluent dynamics over the multi-homed platform and traffic management issues at private-public network border constitutes a multi-disciplinary and multi criteria problem reflecting multifaceted nature. MCDM theory is formulated and adapted in order to address the posed problem where the attributes are collated and traversed all around upwards from lower layers and the underlying metrics are exploited in addition to higher layers business objectives along with application and service requirements. Five different MCDM methods namely Weighted Sum Method (WSM), Weighted Product Method (WPM), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Extended TOPSIS and Grey Relation Analysis (GRA) in consent with platform are formulated and adapted in order to address multiple criterion attributes, dimensionality, dynamic variations and frequent fluctuations, incomplete/inappropriate/imprecise data sets and context (in addition to dynamism and dimensionality) respectively.
Tests for proof of the concept and validation are performed using the simple use case starting form basic MCDM method. It is observed that even the basic MCDM method outperforms the conventional solution working on similar lines (i-e performing the multimedia call routing at the edge for traffic load balancing). The strength of the proposed solution lies in its accommodation of all dynamic variations and fluctuations over the converged infrastructure by applying the QoS principles at the higher layer (traffic classification/policing/tagging data (e.g. time of the day, profiles, priorities, authentications, authorizations etc.)) in addition to the traffic engineering principles (regarding the external links that are linking the private world to public network) while sitting at the border of the platform despite the fact these two mechanisms are orthogonal. The system shows improvement regarding the better throughput and lower Call Dropping Probability (CDP) at the cost of bearable delay. Use of TOPSIS, extended TOPSIS, GRA offer better and improved throughput in order respectively. Moreover the CDP lowers down in reverse order by using the aforementioned MCDM methods respectively (GRA < extended TOPSIS < TOPSIS) with an add on delay.
Hierarchy construction involves the placement of goals, decision factors (criteria and sub-criteria) and the alternatives positions with the corresponding levels and links. There is another important mechanism of weight conversion/calculation and its assignment to the criteria and/or sub-criteria describing the relative importance of the

attributes constituting the criteria and/or sub-criteria. Weight computation within those MCDM methods is crucial as it identifies the relative importance of the underlying criteria. Weight computation of the corresponding criteria is applied and a scale is devised according to the requirement over the platform. Analytical Hierarchy Process (AHP) is used to calculate the weights of the corresponding column vector laying out the criteria, representing the attributes. The MCDM methods used subsequently are integrated in order to automate the weight computation with the underlying MCDM methods. This integration and automation removed the anomalies shown by the MCDM methods deployed over the platform for dynamic decision computation. The observations and calculations made by the deployment of integrated and automated solution shows higher throughput and lower CDP with an add-on delay than the MCDM methods used individually. The integrated MCDM methods take all the local and global priorities by pairwise comparison reflecting the better resource utilization and the computed decisions are in agreement with the platform's latest conditions. The cost of this improvement is an add-on delay system has to bear while computing the decisions.
It is hard to accommodate the semantics variation into account wit the simple information model. Moreover the relationships and semantics regarding the information base over these domains/planes are also critical for effective decision computation that in turn reflects efficient and dynamic rule-based management. Ontology is used to capture the semantics with the corresponding variations and fluctuations occurring frequently due to the heterogeneity, diversity, convergence of access technology and service unification in addition to multi-homing support over the underlying platform. MCDM methods help in achieving the multiple objectives on the basis of multi-disciplinary information domains. The ontology, on the other hand, overcomes the semantic matching and reasoning issues using conventional object-oriented techniques with the help of inference engine. Though the ontology development is not within the scope of this document but ontology space is emulated over the same test bed used for integrated MCDM methods for further observations and analysis. The observations plotted for integrated GRA regarding the throughput and there is substantial increase in the throughput as now the proposed decision system is taking in to account contextual dynamics and variation with multiple objectives by considering the inter/intra-domain and inter/intra-plane dependencies along with semantic and relational dynamics. The CDP also lowers down in comparison with the integrated MCDM method with an add-on maximum delay as compared to previous experiments/tests. It is due to fact that reasoning and inference with semantics dynamics and context of the ongoing request/call are being taken into account simultaneously.

6.2 Future Work

Future work includes the development of an automated and unified lingua franca in order to specify goals, criteria, alternatives regarding the MCDM and business rules

specifications in addition to technology specific and technology independent configurational rules. The underlying lingua franca should have its deep roots inside the framework to avoid conflicts while making the rule specification native to the platform. The unified lingua franca will interconnect the conventional Policy-Based Network Management with MCDM framework. There are number of tools available for ontology specification and its management but an ontology development and management infrastructure in consent with MCDM framework is also one of the future landmarks. MCDM methods are integrated over the framework for decision computation and weight calculation of the corresponding attributes and alternatives respectively. Enhancement and tweaking of the underlying MCDM methods for subjective and objective weight computation at their own by complementing their built-in and native methodology rather than the methods integration is another future perspective.

7

List of Author's Publications During the Thesis

7.1 Publications During the Thesis

- INTERNATIONAL JUORNALS

[J_1] Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " Network Management and Control Framework for Hybrid Converged Environment ", Cyber Journals: Journal of Selected Areas in Telecommunications (JSAT), Vol. 2, No. 8: 45-55, 2011,ISSN: 1925-2676.

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[J_3] Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " Multi Criteria Decision Making Methods Adaptation, Enhancements, Integration and Comparisons for Dynamic Decisions Making Framework ". Springer Journal of Network and Systems Management, ISSN: 1573-7705, Journal no. 10922. (In Progress)

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[C_3] Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey. " A Framework for Unified Traffic Dynamic Routing at Private-Public Network Border " submitted in IEEE ICC, Conference; 10-15 June, 2012, Otawa Canada.

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[T_4] Sajjad Ali Musthaq, Christophe Lohr, Annie Gravey, Antoine Gatineau; " Module to Optimize IP Network Accesses (MONA) Architecture Document, 2007 ".

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