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A Heterogeneous Communications Network for Smart Grid by Using the Cost Functions

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A Heterogeneous Communications Network for Smart Grid by Using the Cost Functions

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And

Mahsa, my wife as a great gift of the God …

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Chapter 1

INTRODUCTION

1. INTRODUCTION

For several decades, the electric utilities built robust electrical power networks that are known as conventional power grid, by connecting electric grid subsystems to provide the required electrical power for feeding the factories, buildings and the other consumers [1, 2, and 3]. The conventional power grids are no more effective as a consequence of availability of small-scale distributed energy sources and increasing customer expectations. Important factors such as two-way information flow, well-built communication architecture including smart sensing and metering technologies must be incorporated into the current power grid [1, 2, and 3].

An essential and primary goal of Smart Grid (SG) is to expand and introduce the intelligence by the communications network and information technology to the different entities of power grid such as consumption segment (in the demand side of the power grid) [1]. Therefore, enabling a universal management and controlling system, and an appropriate communication networks for new generation of power grid are essential issues which should be investigated [2, 3].

An important key for SG deployment is the communications access technologies and networks in order to connect the SG different node types to the Control Station (CS) through the aggregators and collectors [4]. In other word, adequate transmission capacity must be provided to exchange information between all the devices in the grid and CS. [1, 5]. The first step for designing a robust and appropriate communications network for SG network is creating an architecture that manage data flow among various parts of the system in an efficient way [1,6].

The North American conventional power grids are made up of almost 3500 utility organizations [1, 4, and 7]. As the basic principle, the supplies and demand must be at equilibrium every time. An efficient reliable communication network helps to manage it. The wide communications networks that are extended hundreds of thousands of miles allow electricity grid operators and utilities to manage the demand and make supply demand equation in balance [4, 8].

Also, the Power Line Communications (PLC) of the existing communications architecture is very old and has not benefited from recent technology advances [1, 8, and 9]. In addition, the existing power grid should be connected to electrical substation through the operator centers. Thus, it leaves the distribution subsystem by lacking of adequate situational awareness [8, 9]. Thus, at the first step, all the SG different node types and their communication requirements should be determined. Also based on the future needs some new applications with different requirements will be identified and introduced to the system thus network design scalability must be considered.

Considering these matters, elaborating a communications infrastructure should be studied precisely. [6, 7, and 10]. Rather than this, it must be considered that there are plenty of different available RATs with different communication characteristics to support different types of SG nodes with different communication requirements.

How to assign a specific percentage of a certain SG user type to a certain RATs to use the spectrum of RATs in an efficient way is a challenge. The RATs spectrum as a rare source should be allocated to the certain SG node type based on the fitness degree between SG node type characteristics, density and RAT communication characteristics. It can be solved if the way is defined to identify the desirability value of different RATs for a certain SG node type. The solution can be implemented when the communication requirements of the SG nodes get identified and considered as the Key Performance Indicators (KPIs) in order to be used in the Cost Function, CF. Dealing with heterogeneous communication networks, the performance is usually evaluated by taking several Key Performance Indicators (KPIs) into account such as data rate, delay sensitivity, reliability and security. High Quality of Service (QoS) can be obtained by proper balance and compromise of these KPIs. All the KPIs are used in a CF model, which defines the numerical values for the evaluation of the system performance [11,12].

Besides, using higher modulation schemes that result in higher spectral efficiency is in with the cost of increasing joule per Hz per bit in a certain RAT. By defining a certain criteria to measure energy cost and communication CF, the finalized desirability value of different RATs for the SG node types can be achieved by using the communication CF in combination with energy CF. Thus, by using and defining the appropriate CFs, the most efficient resource allocation can be elaborated. As it was discussed, CF elements have variety parameters which should be defined [11, 12]. They are considered as the Key Performance Indicators that CFs should be defined based on them. Therefore, it is needed to introduce, determine and measure them for all different SG node types [11, 12, and 13].

Furthermore, introducing the ways for determining KPIs and normalized values for each different node type which is supported by a certain RAT is a challenging issue that will be discussed and elaborated in this thesis. In this chapter some key words of this thesis are introduced briefly. Besides, Cognitive radio, CR in SG is under study as well and the different type of CR which can be applied in SG different domain (HAN, NAN and WAN) has been well studied and is an outcome of this research as it is published in [211].

Another outcome of this dissertation is related to the number of SM's and the relationship between number of SMs and number of collectors as it is published in [112, 215].

In this work the efficient number of SM's which are supported by a single aggregator are achieved based on strategy that indicates the relationship of exponential decrease of data arrival period into a single aggregator and increasing of SM density. By using this specific assumption and using the case studies in which the number of SM and the data arrival period in a single aggregator are given for the certain number of SMs, the results are achieved. Then the number of SMs which should be supported by a single aggregator is defined. The results are discussed in this thesis briefly as another outcome of this research activity.

1.1 Novelty and the thesis contribution

The novelty of the work with respect to previous studies can be categorized in three main parts. The first contribution part includes the definition and elaboration of a Communication CF, CCF in which the desirability value of different RATs to support a certain SG node type communication requirements are measured; it is done for all the different SG node types.

The second contribution is the definition of the KPIs as a function of several RATs communication characteristics such as goodput, spectral efficiency, Packet Loss Probability, PLP, as a function of RAT base station buffer size, arrival rate and service rate, latency (as a function of transferring payload data time, propagation delay, processing delay and upper layer of protocols) and security elements (i.e., response time, encryption used algorithm and complexity). In other side, the KPIs should also be defined as a function of SG node type communication requirements and the number of the different SG node type as a function of node type density and area size.

The third main contribution is the definition of a comprehensive CF including CCF and Energy CF, ECF, to define the desirability value of different RATs for a certain SG node type. A comprehensive formula, including all above defined CFs, is elaborated and used to assign a certain percentage of a certain SG node types to different available RATs, in order to make a communication and energy based efficient heterogeneous network to support heterogeneous SG node types. The outcomes of this research activity can be exploited in assigning different SG node types among different RATs in a way that maximum communication efficiency is achieved in a Het-Net environment. The outcomes of the Ph.D research activities are reported in this thesis in the following publications:

- Vahid Kouhdaragh, Daniele Tarchi, Alessandro Vanelli Coralli, Giovanni E. Corazza,"Cognitive Radio Based Smart Grid Networks", Dept. Electrical, Electronic and Information Engineering University of Bologna, Bologna, Italy, IEEE conference, August 2013

- Vahid Kouhdaragh, Daniele Tarchi , Alessandro Vanelli-Coralli , Giovanni Emanuele Corazza ; " A Cost Function based Prioritization Method for Smart Grid Communication Network", Springer, EAI, SmartGIFT 2016 , Liverpool, UK

- V. Kouhdaragh, D. Tarchi, A. Vanelli-Coralli and G. E. Corazza, "Smart meters density effects on the number of collectors in a Smart Grid," *2015 European Conference on Networks and Communications (EuCNC)*, Paris, 2015, pp. 476-481.

- Vahid Kouhdaragh, "Optimization of Smart Grid Communication Network in a Het-Net Environment Using a Cost Function", JOURNAL OF TELECOMMUNICATIONS, VOLUME 36, ISSUE 2,2016

- Vahid Kouhdaragh, Daniele Tarchi , Alessandro Vanelli-Coralli ; "Using a Cost Function to Choose the Best Communication Technology for fulfilling the Smart Meters Communication Requirements", Springer, EAI, SMARTGIFT, 2016,Liverpool , UK,

- Vahid Kouhdaragh, "A Reliable and Secure Smart Grid Communication Network Using a Comprehensive Cost Function ", Journal of Energy and Power, JEPE-DPC, ISSN:1934-8975 ,Issue:2, Vol: 8, Jnuary 2017

- Vahid Kouhdaragh, Alessandro Vanelli, Daniele Tarchi, "The Comprehensive Cost Functions for different Node Types of Smart Grid Making an Efficient Het-Net Communication Network ", IEEE Transactions on Smart Grid submitted, 2017.

- Vahid Kouhdaragh, Daniele Tarchi, Alessandro Vanelli, "A Cost Function Based Node Assignment Method for Reliable, Secure and Energy Efficient Het-Net Smart Grid Communication Networks ", International Journal of Communication Systems, Wiley Journal publications, Submitted, 2017.

- Vahid Kouhdaragh, Daniele Tarchi , Alessandro Vanelli-Coralli , "A Cost Function Based Nodes Allocation Method for HetNet Smart Grid Communication Networks", Smartgridcomm, IEEE, Dresden, Germany, Submitted

Vahid Kouhdaragh, Alessandro Vanelli, Daniele Tarchi , " Nodes Allocation Method for Het-Net Distributed Energy Resources Communication Networks ", Journal of Telecommunications, (to be submitted),2017

- Vahid Kouhdaragh, Alessandro Vanelli, Daniele Tarchi, "Cost Function Based Optimization of Reliable and Secure Smart Grid Energy Efficient Heterogeneous ", Transactions on Emerging Telecommunications, Wiley Journal publications, (to be submitted)), 2017

- Vahid Kouhdaragh, Alessandro Vanelli, Daniele Tarchi, "Using Different Cost Functions to Make an Energy Efficient Het-NET for Different Node Types in Smart Grid Having Different Densities", IEEE Journal of Communication systems, (to be submitted), 2017.

Moreover, in a comprehensive study, the SG different goals are defined and the desirability of each different SG node type to fulfill these goals are studied and elaborated in order to prioritize the different SG node types in senses of fulfilling the SG system goals. This method also is aimed to be used in the situation that we are facing with BW shortage and thus the SG node type with higher priority are served earlier. The other original contribution on this work is given in [211] and [213]. In [211], "Cognitive Radio Based Smart Grid Networks" content and context includes the usage of different type of the cognitive radio methods that are appropriate to be used in different SG network domains. In [213], the number of required collectors as a function of SMs densities is discussed. Finally, presenting different original figures and contours (sub result part) make significant insights for M2M communication network designer.

1.2 Smart Grid versus Conventional Power Grid

An electrical grid is a unified system to deliver electricity from suppliers to the users. It contains generating entities that produce electrical power, high-voltage transmission lines that transmit power from suppliers to the demand parts, and distribution entities that are connected to the consumers and different node types.

In conventional power grid, power sources are located near the fuel source, water turbines in the dam site. They are often located far from city centers and urban area [1, 14]. Conventional power grids are not well equipped for future applications requirements due to their old infrastructure.

Therefore, improvement of current power grids is needed in order to meet the node types communication requirements. The United States electrical power grid, consist of over 5000 power plants, over 200000 miles of high voltage transmission and over 5.5 million miles of distribution lines. The majority of these structures are based on old infrastructure power grids, ironically called dumb grids that are old, dirty, inefficient, and vulnerable [15].

The conventional power grid is based on a centralized power generator and a weak distribution system toward the end users. However, this has become a drawback in the most recent power generating schemes based on distributed environmentally compliant generator (e.g., solar cells, wind turbines).

The expansion of conventional power grid requires higher renewable energy diffusion, power supply reliability and economic issues. Insertion of electric vehicles plug in and renewable power generation entities must be also considered in the future SG plan. This yields to difficulties arousing from the randomness of electric vehicle mobility and the intermittency of renewable power generation [1, 16].

Old-style power grid transmitting cannot meet this requirement. There are needs to have huge changes in power grid transmitting. Also making modern small and micro power grid dispatching, interruptible load management and the technology for power grid supporting would be prepared by SG [4, 17]. For this purpose, SG has been introduced in order to provide intelligence in the energy grid [1, 2, and 3].

The SG parts are divided into four core domains based on the functionality of the SG nodes: Generation, Distribution, Transmission, and Customer Domain [1, 2, 3, 17, 18 - 20]. Figure1.1 shows these domains and their connectivity scheme. Each of these domains has its own different communications requirements. Thus, the proper scenario should be defined for SG communications network to have reliable flow of electricity delivery; taking into account characteristics of different node type [4, 8].

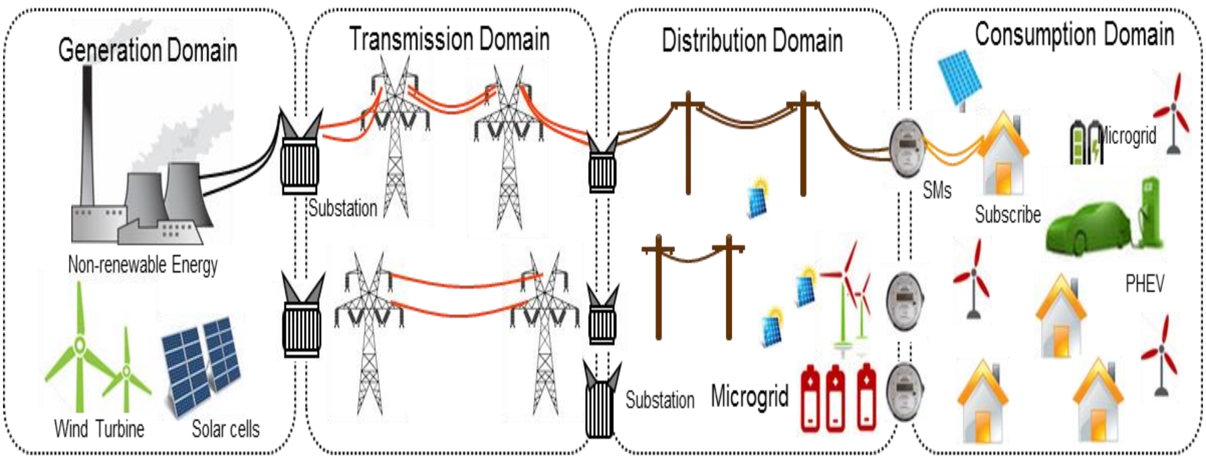


Figure1-1Smart Grid four core power domains

The main nodes in SG include Advanced Metering Infrastructure (AMI) which consist numerous Smart Meters (SMs) set, Wide Area Situational Awareness (WASA), Distributed Energy Resources (DERS), Distributed Grid Management (DGM) and Plug in Hybrid Electrical Vehicles (PHEV) nodes [1,2,3]. Each types of these different entities have different types of the nodes with different communication requirements.

They transfer power grid information to the control station (CS) through the collectors and aggregators in order to monitor, analyze and issue demand response, and issuing billing services information [1, 2]. Figure1-2 shows the SG communication domains.

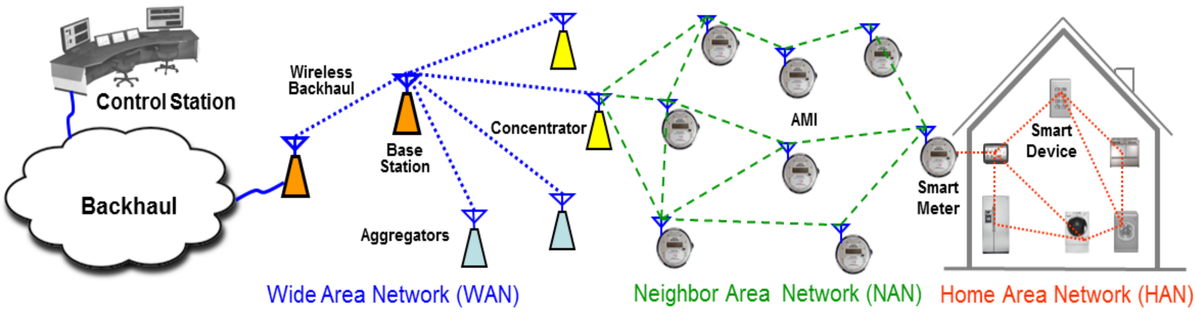


Figure1-2: Smart Grid communication domains [7, 10, 221, Modified]

SG in Electric power system, Control section and Communication sectors has been interesting for power grid designers. The concept of SG has explained in recent literature in senses of different aspects. Some of works referred to SG as intelligent power grid or future power grid. In this attitude, SG incorporates a two-way communication between the provider and consumers of electric power by using data collector and different communication access methods such as Radio Access Technologies (RATs) [1, 2]. In SG, the users are active actors in which they can take active roles to maximize energy efficiency by bidirectional collaborating with the provider [18, 20].

In addition, by introducing numerous applications in SG, communication network will be vulnerable to the security threats and cyber-attacks. As a result, it is essential to properly design SG communication network based on the secure network elements [21, 22].

To sum up, SG is a word which refers to the next generation of the conventional power grid in which the electricity generation, distribution, management, and consumption are upgraded by incorporating advanced bidirectional communications and huge computing capabilities to have improved control, efficiency, reliability, safety, and high quality services [18, 23].

It also controls intelligent appliances at the demand side to save energy, reduce cost and increase reliability, efficiency and transparency of energy consumption [20, 23, 24 and 154]. The need of SG to a robust communication network is a clear issue in which the network designer should elaborate such efficient network considering the spectrum scarcity problems. Figure 1-3 shows the general structure of SG in which all domains are combined.

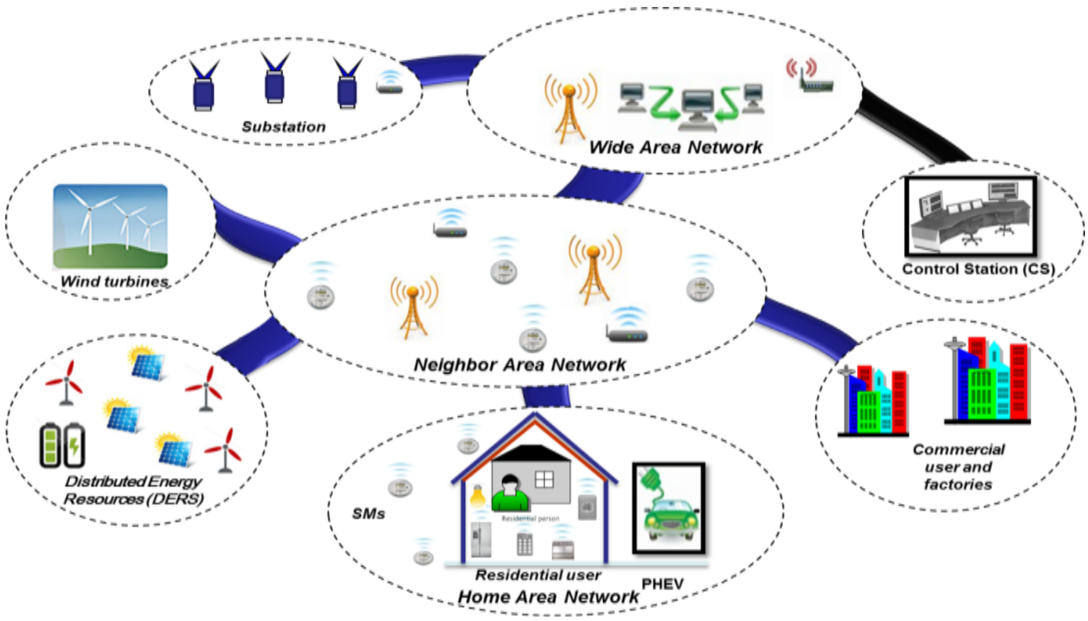


Figure1-3 Smart Grid, the general node location in its domain [34, modified]

1.3 Organization of the Thesis

Chapter 1: Introduction and motivations

This section describes why Smart Grid is needed and which inspirations are behind it and also which basic infrastructures (in specific communication structures) are needed to implement Smart Grid. Besides, the conventional power grid and its drawbacks are introduced. Then the Smart Grid concept is introduced and its relation with Machine to Machine communication is discussed. Then the radio access technologies and the importance of resource allocation for this aim are introduced briefly. Moreover, the state of the art and problem statements are discussed. Furthermore, the defined methodology which includes the cost function concept, Smart Grid nodes prioritization and synchronization method is introduced briefly. Finally, the proposed outlines and sections summary are described.

Chapter 2: Literature Review

The barriers of this research like multiple kinds of users with different requirements, communication limitations and other problems which have been studied are discussed. Moreover, the most important methods which have been introduced to elaborate the SG communication network infrastructure are introduced and their drawbacks are mentioned. Briefly, "what have been done so far and what are our plans to do for developing it and which are our goals in the sense of elaborating efficient resource allocation for SG communication network“ are discussed.

Chapter 3: Smart Grid Communication Network Model and Nodes Details

In this section, the different communication network domains structure and models in Smart Grid are introduced. Moreover, the different SG nodes and application types are introduced. Finally, their communication requirements are explained in details.

Chapter 4: Methodology

With respect to the different types of SG nodes requirements in SG network and the nodes densities and geographical characteristic of under studied area and the different types of RATs whose are available (e.g.; LTE, Wi-Fi, Satellite communications and etc.), their network communication requirements are defined as Key Performance Indicators, KPIs, and introduced. These KPIs have numerical values that mathematical formulating is used in order to help us to calculate and estimate these values. Then all the available and feasible RATs scenarios are introduced. Some specific strategies are used to introduce the scenarios which are evaluated by using the defined CFs.

Then the proper CFs based on defined KPIs are introduced. The energy CF of RATs is investigated as well and the different node types assigning methods to different RATs are introduced. Moreover, the SG node prioritizations are done with respect to the SG goals. In addition, the node synchronization method is introduced which results to have more efficient resource allocation. Finally, the RATs priority table for a certain node types by aiding of the achieved CFs and SG node prioritization is defined. The methodology and formulas which are given in this part have been published in several different conferences and journals. They can be tracked using the references are given in each part.

Chapter 5: Result and Discussion

Based on the defined cost function and smart grid node prioritization, the synchronization, energy cost evaluation and the other methods whose are described in the methodology part, the results are achieved by using MATLAB simulation. The Matlab Code is used to simulate some scenarios. Many different scenarios are defined and discussed and the impacts of the achieved results are described as well.

Chapter 6: Conclusion, Future work and Open issues

Importance of the introduced method to elaborate a strong communication network infrastructure that is the key point for implementing SG is discussed. Moreover, the future work of this research and open issues and also the potential and impact of using the achieved method for future machine to machine communication are discussed as well.

Chapter 2

LITERATURE REVIEW

Lots of survey papers have been published whose main content are focused on the SG communication node requirements, efficient infrastructure in network domain such as low scale communication for HAN, NAN and WAN for SG different node types.

In the literatures, there is the lack of a comprehensive communication network model in which different RATs communication characteristics desirability value being defined for different SG node types different communication requirements.

There are still a number of research challenges ahead such as a comprehensive network planning and optimization, assessment of functionality of the heterogeneous network as a function of node numbers, RATs characteristics and SG node types communications necessities. Besides, how to choose and assign the SG node types users among the different RATs that can fulfill the SG communication requirements is still an open issue.

Moreover, Eb/N0 as a very critical parameter has not considered as an input in combination with other communication characteristics to elaborate an efficient network model for supporting SG node communication requirements [162]. Finally, elaborating load balancing method in an application of M2M based system such as SG by considering all communication parameters is not well studied.

2. 1 Smart Grid Communication Infrastructure for Different Node Types

Plenty of studies and papers have been done regarding to introduce the different node types of the SG communication requirement and the suitable RATs to fulfill these requirements. The summary of some of them are given in this part.

There is a comprehensive study by B. Karimi et al. on AMI infrastructure investigating how to communicate and manage consumer data collected by utilities and managing inadequate communication network resources [42, 43].

Based on the these works, many data relay points, collector or aggregators are required to gather data generated by SMs to send them through a communication backhaul network to the CS. SMs message concatenation problem is studied in this work and a method to concatenate multiple small smart metering information arriving at data aggregators units in order to reduce protocol overhead.

Consequently, network utilization in case of lowering overhead (goodput increasing) effects is studied. To be added constraint respect to initiating message from its source that has its own stated deadline, it has been taken into account while the concatenation process is done.

This paper emphasizes on message concatenation algorithms that can be an important part of data concentrators deployed in SG to solve the challenge of transferring huge amount of data through last mile constrained backhaul networks. In this work by proposing an algorithm to reach to effective message concatenation, is shown that this method is capable to reduce overall data volume by 10-25% for each aggregator.

The most focus of the mentioned study is on protocol overhead with no compression of the original data sent by SMs [42, 43]. Thus, developing additional data concentration mechanisms has not been investigated. Even an efficient way to allocate the resources to support a certain number of SMs in an AMI system regarding to its somehow high delay tolerance has not being studied done. Another study by B. Karimi et al. has been done on the capacity of a backhaul to support the distribution grid in SG [43].

Several communication technologies have been suggested to meet the SG communication requirements as the backhaul that connects customer data collection points to the CS. In [43], the RATs are compared regarding to the fact that wireless communication is the most appropriate access method for transferring data. Linear chain multi-hop wireless communication architecture is proposed and its ability to meet application requirements of the communication backhaul is assessed by simulations.

Then, based on capacity limitations, a theoretical analysis have been done to determine the data capacity of using linear chain RATs as the communication backhaul. Finally, a case study to test the functions of any limitations imposed by the proposed communication architecture is investigated by using AMI requirements as the defined scenario. Despite of introducing several RATs that have been suggested to fulfill communication requirements at the distribution level, still the lack of a method to assign SMs among RATs must be studied well. The method to show the desirability of a RAT comparing with the other RATs can be useful to assign the users to different RATs based on their mutual fitness values. Thus [43] mentions that “Though one specific communication architecture for the distribution level of the power grid was recommended in this paper, an optimal architecture may vary widely”. Therefore, despite of the proposed method in this work and its contributions on providing a suitable communication network topologies and making an analysis of their technical feasibility, still a method for choosing the best choice among the wireless RATs is left behind and a precise study should be done. P. Rengaraju et al. have worked on the communication requirements and analysis of distribution networks by using WiMAX RAT as SG communication network [44, 158].

Their work has been done by considering this fact that the characteristics of communications in SG different node types vary. Then, the analysis the communication requirements of SG in power grid distribution domain and in consumer domain are investigated. The two more suitable RATs are considered as WiMAX and LTE as they fulfill the communication requirements of SG node types. In that paper, they measure the smart metering aggregator data rate and the Quality of Service (QoS) performance while using WiMAX.

The achieved results just show that the 4G technologies are (i.e. LTE) suitable candidate for implementing the distributed area network in SG without seeing the fitness degree between the RATs and different SG node types.

In this paper, all the SG node types have not been analyzed based on their different communication requirements. Just based on the general analysis, it is shown that the WiMAX and

LTE have similar performances for a certain node type. Also the resource allocation efficiency and RAT communication characteristics fitness with the certain SG node type has not been considered in this work. Also, these methods do not have an appropriate answer in case of increasing the SG nodes density. Besides, the scalability and performance analysis on LTE networks have been left as the future work.

There are the other general surveys on the communication architecture in SG. One of them has been done by W. Wang et al. [45]. Briefly, in this paper the network implementation considerations and challenges in the power system settings have been deeply studied in which the research outcomes are noticeable. Another survey on the communication architecture in SG was studied on Communication network requirements for the main SG applications in HAN, NAN and WAN by M. Kuzlu et al. [46]. Based on a variety of smart grid use cases and selected standards, this paper gathers information about different communication network requirements for different SG applications, at the three different domains, Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide-Area Network (WAN). An approach to support implementation of selected SG projects is discussed. Although this paper has gathered the database of RAT characteristics for designing a SG network but, still the different type of the SG nodes have not been introduced. Department of Energy Communication Requirements of SG technologies in USA has discussed the main issues in SG by introducing the main goal of SG and introducing the user types in SG in general [2].

Moreover, the communication requirements for a brunch of SG user in terms of data rate, delay sensitivity, reliability and security have been discussed. Although there is no introduced solution for elaborating or introducing a RAT for SG but, the bunch of SG user communication requirements give a good insight to SG communication network designer [2,149,150]. Network Theory and Smart Grid Distribution Automation is another study for SG network design which was investigated by S. Bush et al. [47].

The importance of this study is the premise that there is an essential relationship involving the eigenvalues of the power grid and communication network adjacency matrices. In addition, the relationship between power grid structure and communication network design is considered and investigated as an important step to design a well-structured communication network for SG. The focus of this work is more on latency rather than the other requirements.

Furthermore, three different RATs are investigated which leads designer to have a good insight on the communication network topologies in SG application. In addition, it is investigated that the mesh network displays the lowest latency with least variation due to having the idealized mesh redundant links. The efficiency of the SG network control architecture was studied in Z. Wang paper`s and et al. [48]. It is mentioned that in order to design efficient communication architecture, it is needed to characterize statistically power grid information source. It is based on investigating the statistical properties of power grids effects on providing a natural simulation platform, producing a large number of power grid test cases with realistic topologies, with scalable network size, and with realistic electrical parameter settings.

Moreover, the performance of decentralized control algorithms over information networks whose topology matches with the underlying power network is analyzed well. Both the topological and electrical characteristics of power grid networks based on a number of synthetic and real-world power systems has been studied in this paper. Based on the discoveries of this paper, an algorithm is introduced the random topology power grids featuring the same topology and electrical characteristics found from the real data. As a result, it is found that the power grid is sporadically connected with a low average node degree which does not scale with the network size. Also a method was proposed to estimate the power distribution parameters. An overview of SG reference model and a comprehensive survey of the available networks for the SG and a critical review of the progress of wired and wireless communication technologies for SG communication infrastructure have been studied well by S. Elyengui1 et al. [49].

The end to end communication architecture for HANs, NANs and WANs for SG applications is introduced as a useful insight for the SG network designer. Moreover, the advantages and disadvantages of these RATs for a variety of SG applications were discussed generally. Furthermore, a general end to end communication infrastructure was proposed. The outcomes of this study are required but, not enough to elaborate an appropriate communication network for the SG. In a technical report published by ETSI, Machine-to-Machine communications (M2M); Applicability of M2M architecture to Smart Grid Networks and Impact of Smart Grids on M2M platform has been explained [41]. The European commission issued a standardization instruction to European Standardization Organizations to support European Smart Grid deployment. The scope of "Smart Grid" for the determination of this mandate is as defined in the Task Force for the implementation of Smart Grids into the European internal market. These six high level services, the Smart Grids Task Force defined, are: enabling the network to integrate users with new requirements which is considered as the adoptability issues for future applications, improving efficiency in day-to-day grid operation, both power and communication issues, ensuring network security, system control and quality of supply, enabling better planning of future network investment as the trade market issues of the SG, improving market functioning and customer service, enabling and encouraging stronger and more direct involvement of consumers in their energy usage as one of the most important goal of the SG and controlling and management of the SG entities. The ETSI architecture for Smart Grids [41] is conceptually separated into three main layers as following: first, the Energy Layer which handles the energy (production/generation, distribution, transmission and consumption), i.e. sensors, electricity generation, storage and interconnection, transmission and distribution power systems; second, the Control and Connectivity Layer which ensures the energy control and connectivity including management functions such as substation automation, condition, monitoring/diagnosis, supervision and protection, time synchronization, metering, sanity check of sensors, traffic engineering, protection and restoration, virtualization, routing, access technologies (for geographical coverage purposes); and third, the

Service Layer which is composed by all services related to Smart grid usage, billing, e-commerce, data models, subscription management and activation, applications, and business processes.

In aim of designing a heterogeneous network some load balancing methods have been introduced. For instance, Round robin method in which the load balance will simply distribute the traffic evenly between all the available base stations, regardless of existing load and performance.

As it is obvious, this type of balancing regardless of RATs characteristics and SG node communication requirements and their adoptability, results in an inefficient heterogeneous network [216, 164-174]. Last connections balancing methods can be implemented if the new users traffic will be sent to the base station with the least connections. As it can be seen, the distance is just the main parameter to balance the network traffic [216, 164-174]. Another method of network balancing is Predictive nodes method in which all the available base stations are observed over time and the trends are analyzed. The load balance will be assigned traffic to the base stations that it is ensured to have the best performance as soon as possible. Managing such type of balancing is very complicated in both hardware and software sense. Moreover, this type of observation needs a cognitive process and sensing and finding that results in having higher delay [115,216, 217, 164-174].

In [195] Shahmeer Omar et al discusses about SMs which are being developed globally on a trial basis and are expected to enable remote reading and demand response among other functions, by setting up a two-way communication network. To determine how these meters transmit their data to an aggregation point is the point of focus in this paper. Their proposed solution is the use of cooperative communication in a neighborhood area network. This work experimentally compares cooperative networks, deployed in disparate environments, in terms of area size and energy consumption of the overall network. It is mentioned that data transmissions take place through the universal software radio peripheral platforms. The proposed method is implemented in both indoor and outdoor environments, with cooperative transmission (CTR) taking place over a multi-hop network, employing the binary phase shift keying scheme. The results of this paper show that CTR can be used to effectively and reliably relay data in SG communication network in NAN. Therefore the aggregators can collect data by this method and its result can be used as the input of the aggregators data rate for this thesis.

In [196] A. Ahmed et al describe a layered approach using available metering and distribution field automation and management components that can be built around in a staged approach. Transforming a utility's distribution network from its current state to a SG needs a comprehensive program of different projects which incrementally improve the distribution network. The paper offers a target SG infrastructure given stage intelligent that may not necessarily all be in sequence. Defining a collection of projects most utilities establish to evolve their distribution network from its current state to the SG target state are discussed in this paper.

In [207] Sarwar et al defined smart grid as “A modernized grid equipped with bidirectional power flow capability, inter-device communication, cyber and physical protection, autonomous fault detection, self-healing and integration of green energy resources to enhance energy efficiency, quality, reliability and system security is regarded as Smart Grid”. Revitalizing the conventional power grig through a paradigm shift from a traditional power system toward the SG is inevitable. The objective of this paper is to present a technological review of the researches being carried out on various domains of SG. Different technologies required to meet the SG revolution are discussed in this paper. Information and communication technologies necessary for SG development are discussed with reference to latest research in the field as a comprehensive source. The economic and environmental benefits of SG and different communicative and computational subsystems as the part of complex SG are explained in this paper. A theoretical model of SG vision which integrates different components, systems and networks to evolve into emerging SG is discussed in this paper as well.

2. 2 Smart Grid Market, Power and Communication Assessment

Lots of studies and papers have been done on Smart Grid Market, Power and Communication Assessment in which introduce the utility, marketing and power grid infrastructure of the SG node. The summary of some of them are specified in this part. Bodenbenner et al. worked on cost of integrating demand response system in electricity markets [50]. As a consequence of increasing renewable energies, balancing electricity production and delivery requires efficient electricity markets provide the good insight to elaborate SG system. This paper analyzes Information Systems that incorporate Demand Response into electricity markets, with a focus on both the associated costs and benefits. Thus, this cost in combination of a CF for communication issues can be a great future work which is worthy to be done. This would better reflect the effects of integrating renewable into the power grid communication aspects.

M. Souryal et al. studied on a methodology to evaluate wireless technologies for SG [51]. It just presents a methodology for assessing the suitability of various wireless technologies for fulfilling the communication requirements of SG node types regardless of defining the quantity for it and considering all RATs characteristics and SG node type requirements. It describes an approach for rendering application requirements to link traffic characteristics, determining the transmission range or coverage area of a wireless technology, and modeling the link layer to acquire performance measures such as message reliability, delay, and throughput, namely the KPIs. But, the performance of three representative application use cases have been analyzed just over an IEEE 802.11 link not the different RATs. This work is very worthy for giving a comprehensive perception because it is an approach to modeling wireless communications at the link layer that, first, detects the various applications utilizing a specific link. Then, it explains the requirements of these applications to link traffic characteristics in the form of a link layer arrival rate and average message size. Also, it uses a coverage analysis to determine the maximum range of the technology under the outage constraint for a given channel propagation parameters. Lastly, using the link traffic characteristics and coverage area determined above employs a physical model guideline to measure link performance in terms of reliability, delay, and throughput as the main communication KPIs of the SG goal.

P. Fuhr et al. had an overview on Smart Grid Communications Bandwidth Requirements [52]. In this study, a designed solution was introduced to minimize radio frequency coexistence/interference issues while providing edge-to-core-to-edge transport through the integrated operational networks. G. Castellanos et al. investigated WiMAX as a wireless communication technique for the SG applications, since it fulfills two of the most important requirements of SG, wide area connectivity and the quality of service differentiated services [53].

Performance of WiMAX-based network architecture on accomplishing communications requirements of the SG was investigated. OPNET simulation models was used on the proposed communications network architecture, and the results are compared with analytical calculations of network capacity, path loss and delay constrains for multiple smart grid applications, including consumer demand control, smart metering and emergency sensor messaging. Simulation results showed that WiMAX network could be used as an efficient and reliable communication network for the smart grid application.

Finally, communication network architecture was proposed and an appropriate network configuration was provided and necessary algorithms in the WiMAX standard to support the different needs of the SG were included. In this work, NIST proposals related to the development of a SG communication network were reviewed and seven domains in the smart grid networks were described and their communication needs were explained.

In that work, requirements for the SG were investigated and three application models were used to prove the network design functionality. The network entry procedures and their relationship with the received, transmitted power and the power control mechanisms were explained inside the physical layer. Some analysis was done on OFDMA frame structure and its design used in WiMAX determined that the maximum cell size for the proposed configuration to be about 16 Km. The resource allocation was described and it was observed that the partial usable of sub channels is an appropriate technique to reduce the allocation wastage.

In [54] Soltanmohammadi et al considers M2M communication as Internet of Things (IoT), that is a global network of devices such as sensors, actuators, and smart appliances which collect information, and can be controlled and managed in real time over the Internet through the CS. LTE-advanced standards have defined several quality-of-service classes to accommodate the M2M traffic based on the worldwide deployment of the fourth generation (4G) of cellular networks. This paper on M2M communication in LTE/LTE-A explores the issues, solutions, and the remaining challenges to enable and improve M2M communication over cellular networks. At the first step they present an overview of the LTE networks and discuss the issues related to M2M applications on LTE. Then the traffic issues of M2M communications and the challenges they impose on both access channel and traffic channel of a radio access network and the congestion problems are investigated. A comprehensive review of the solutions for these problems which have been proposed in the literature in recent years and discuss the advantages and disadvantages of each method is presented as well. The open issues in this field are discussed as well.

In [189] both ownership cost and integrated RATs in SG have been discussed in a paper written by R. Charni et al. in ”Total Cost of Ownership and Risk Analysis of Collaborative Implementation Models for Integrated Fiber-Wireless Smart Grid Communications Infrastructures”.

The total cost of ownership studies give insight into the overall costs of numerous communications network architectures under the assumption of the old-fashioned model. In this work, a novel collaborative implementation model for a shared infrastructure for both broadband access and SG communications has been proposed. Moreover, it is compared different SG communications configurations in terms of power service penalties, Fiber cuts related costs, and total cost of ownership.

It is shown that WiMAX is the solution which mostly affected by solar power intermittency. As it can be seen in this work, focusing on the cost and risk analysis of the communications part is more highlighted rather than power or communication perspective of SG.

Therefore, it just helps to have a comprehensive CF considering all issues of communication network marketing cost in sense of installation and ownership costs. Some works have been focused on micro grid concept and energy issues in the power grid. C. Wei et al. on their research On Optimally Reducing Power Loss in Micro-grids With Power Storage Devices have discussed in Smart micro-grids producing "renewable" energy and store them in power storage devices[55].

Their focus on designing a high efficient SG in the power domain to decrease the power loss is a significant research in power exchange among the micro-grids and between the macro-station and individual micro-grids which results in designing the appropriate communication network in SG communication parts.

The greedy coalition formation algorithm which is proposed in this paper, allows the macro-station to coordinate mutual power exchange among the micro-grids and between each micro-grid and the macro-station.

Although this algorithm optimizes the total power losses across the entire power grid and its focus is on the power domain of SG including the cost of charging and discharging power storage devices and power losses due to power transfers.

In [190] Yu et al working on avoiding from additional large demand charge introduced by the adoption of electric vehicles (EVs), A joint energy management problem for geographically distributed data centers (DCs) and EVs of the employees are investigated in this paper. To minimize the long-term total cost of DCs and EVs by jointly scheduling DC workloads and EV charging demands, without violating heterogeneous EV charging requirements and the given power limits in all geographical locations are discussed in specific. A stochastic programming problem with the considerations of uncertainties in DC workloads, electricity prices, and EV energy demands is formulated in the first step. As these uncertain system parameters are time-varying and the size of the problem which is formulated is large, a distributed online algorithm to solve the formulated problem based on Lyapunov optimization technique and a variant of alternating direction method of multipliers is defined. The effectiveness of the proposed algorithm is shown. A combination of the results presented in this paper and the thesis will have a great impact to elaborate future SG.

In [200] Qaddus et al mentions that in recent years there have been a huge argument regarding the mobilization of finest sustainable and economically feasible SG communication network. RATs are considered as one of the most suitable structures of communication technology for the future SG networks. HAN is discussed in this paper. Also direct connectivity between the utility power control distribution centre and Power generation facility is considered as well. The main disadvantages of Power Line Communication are discussed. The uses of two wireless communication technologies are evaluated in this paper. In first segment Digital Mobile Radio (DMR) a type of Very High Frequency (VHF) Land Mobile Radio system (LMRS), can be commissioned between the consumer premises and CS for the exchange of data traffic. In second segment Microwave Backhaul Transmission in Super High Frequency (SHF) band can be utilized as a backhaul connectivity solution between the utility power control distribution centre and Power generation. It is shown that by using Digital Mobile Radio and Microwave Transmission a SG green communication networks which will be economical with respect to deployment cost and efficient with respect to on line service availability can be established.

2. 3 Communication Network Analysis

Also lots of studies have been done regarding to introduce the different communication network infrastructure and their performance. The summary of some of them are given in this part. R. Surgiewicz studied on LTE Uplink Transmission Scheme. SC-FDMA is the multiple access technique adopted in the LTE uplink transmission scheme [56]. Compared with the popular OFDMA, which is used in the LTE downlink transmission and WiMAX, SC-FDMA has a better performance in SC-FDMA has a better performance in terms of peak-to average power ratio and Frame Error Rate due to its coherent 'single-carrier' property and built-in frequency diversity. In the mentioned paper, an overview of LTE and LTE uplink transmission are described. The advanced technology behind the uplink transmission: SC-FDMA is analyzed precisely. LTE UL source management is an important issue which will be discussed in the thesis.

S. Nithin studied SG test bed based on GSM [57,154]. This paper presents a SG test bed based on GSM technology which is capable of load management, fault detection and self-healing. The communication for the system is attained through GSM modules. This test bed let the implementation of various protocols and methodologies, which can be used for investigating the problems in SG.

In [194] Xie et al calculate and analyze the Substation Communication Network (S-CN) traffic flow efficiently by proposing a traffic-flow distribution analytical model, where the transmission process of traffic flow in a branch is described as the mapping relationship between the input node and output node. The transmission path of traffic flow and the topology structure of information communication network can be described based on this mapping method. Besides, the fault event analytical model of communication network is presented to show the possible fault scenarios in the traffic-flow transmission process. Moreover, a stochastic network calculus theory is employed to construct the architecture of the end-to-end delay analysis of traffic-flow transmission, and is used to evaluate the traffic-flow transmission performance in S-CN. The rationality of the traffic-flow distribution analytical model is verified by classical network performance analysis software Optimized Network Engineering Tool (OPNET). The defined traffic flow can be used as the input for the proposed CF in this thesis.

In [197] Sandoval et al investigate the SG communication network in a harsh multipath environment. This paper presents an exhaustive characterization of two representative scenarios, both in the transport and distribution segment of an SG: a 400-kV outdoor substation and a main power room. The 2.4-GHz ISM band—in which most wireless communication technologies applied to SG operate—is examined in detail to characterize the radio-propagation phenomena. Large and small-scale fading, delay, coherence BW, and electromagnetic interferences are investigated under different line-of-sight, polarizations, and frequency conditions to derive empirical models allowing estimating the aforementioned parameters in other SG. Finally, a RAT was simulated in a substation to examine the channel modeling impact on its suitable design and operation. The results in combination with the defined CF in this thesis help to solve the other problems of SG in a harsh environment.

In [205] Soufiane et al investigate an integrated communication infrastructure for SG in order to manage the operation of all connected components to provide reliable and sustainable electricity supplies. As utilities from all over the world are now facing the key challenge of finding the most appropriate architecture that can satisfy their future communication needs, the architecture models given by the international organizations of standardization are conceptual. In this paper, the current architectures proposed by international organizations, that is, NIST, ITU and IEEE are introduced. Also their limits which prevent us from understanding the communication flow in the system are highlighted. At the next step a communication infrastructure model based on these international roadmaps and guides is presented. The six functionalities that SG network must achieve are fulfilled. Finally, the communication technologies that can be used for interconnecting the components and standards for each section are presented. As it is mentioned in this paper, it is a preliminary step in this work. In fact, it is aimed in the future work to check the defined architecture by modeling the system and take the step of verification and validation. As it is described in this paper a comprehensive method is not completely elaborated.

In [208] Shabani et al investigate to optimize the operation of the legacy power distribution grids, the innovation of the state-of-the-art communication techniques play a vital role-leading to the creation of SG infrastructure. This paper reviews the development of wireless communication technologies envisioned as full-duplex information exchange medium in the on-going development of SG infrastructure and can be considered as a valuable work to have a great insight for deploying SG communication network.

2. 4 Reliability Assessment in Communication Network

Assessing the different communication network reliability is an important issue which has not been studied too much but, still some works can be found. Wireless Sensor Networks for Smart Grid Applications using a Case Study on Link Reliability and Node Lifetime Evaluations in Power Distribution Systems is a work was done by G. Tuna et al. [58].

This paper presents opportunities and design challenges of wireless sensor networks for SG applications. Prominently, SG node lifetime and reliability in wireless sensor networking for SG applications have been evaluated through case studies based on field tests in electric power system. Generally, this paper explains research challenges resulting from inherent properties of communication networks and SG propagation environments.

The most comprehensive work on determining the reliability of a RAT for a certain node type has been done by Rasmus Olsen et al. [98, 99]. In this method by using the most important criteria of network reliability such as buffer size, link utility, latency, node generating time period, system status changing and pocket loss probability, PLP, the reliability of different RATs for a certain node type is measured.

Although this model is able to measure the reliability of different RATs for just a certain node type because of using the certain distribution for the information modeling, but as the generating rate as an average can be considered for all types of distribution, and highlighting the PLP effect, using link utility and the latency of the network causes in equal evaluation of reliability in any RATs for a certain node type.

In [210] Rivera et al propose a cloud-based brokerage and analytics support system for SG, discuss a framework for implementing service level agreements in sg, and show through simulations the functionality and advantages of the system. The defined frame work in combination with the proposed method in this thesis will develop the functionality of SG communication network.

2. 5 Satellite Communication for Smart Grid

There are also some studies on Satellite Communications usage for Rural Smart Grid [156] which one of them was done by R. Mahadevan et al. [59]. This paper surveys the feasibility of using satellite communications for rural SG [156]. Satellite communications have always been spoken about for being used in SG communication network, but so far there have hardly been any efforts to make satellite communications an integral part of it. This is exactly shows the importance of studying more on feasibility of satellite communication for supporting the SG communication network. This paper was discussed the necessity of satellite communication for rural area. As one outcomes of this paper it can be understood that it is proper to say that satellite communications has all the features to be perfect for rural SG communication. For example, it has almost 100% continent wide coverage, the infrastructure is easy to deploy and it is ideal for SG redundancy and security issue as well.

A technical report by iDirect [60] has been investigated using Satellite Communications for the SG utility companies that are making significant progress in developing a next-generation communications network capable of supporting the SG and other critical applications. But many utilities still struggle with how to affordably and reliably extend this network to highest level of their service territories, especially to remote substations and customer locations that are beyond the reach of primary networks like monotonous places.

While an IP-based satellite communications system may make available utilities with the real time data exchange, operational visibility and broadband reach required for a SG communications system, there are numerous common misconceptions about satellite's capabilities, including reliability, latency, cost and security. The reality is that since its modest beginnings as a one-way distribution mechanism used primarily for back-up systems and consumer television service, satellite communications has undergone a main transformation in recent years, actually, that utilities can be well aided to seriously consider incorporating it into their SG communications architectures. Today's satellite networks have great potential to become bi-directional, enterprise-class platforms that provide terrestrial-grade broadband connectivity. They are high speed RATs that are built on IP and integrate seamlessly with core CS. iDirect, a leading manufacturer of satellite communications technology, is transforming satellite into a typical solution capable of extending high-speed, reliable, secure connectivity to any geography, environment or communications application [60]. Figure 2- shows satellite usage simple architecture to support AMIs.

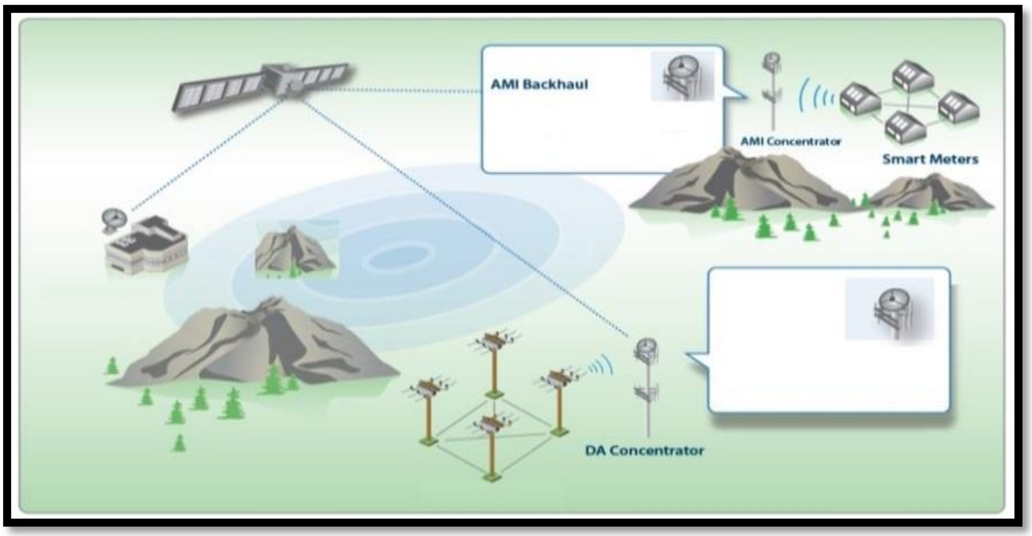


Figure 2- 1- [60] Satellite usage simple architecture to support AMIs

In [193] focusing on the use of satellite communication systems for the support of Internet of Things (IoT) is discussed. IoT paradigm is referred as the means to collect data from sensors and to send control messages to actuators. It is discussed that in many application scenarios, sensors and actuators are distributed over a very wide area; in some cases, they are located in remote areas where they are not served by terrestrial access networks and, as a result, the use of satellite communication systems becomes of paramount importance for the Internet of Remote Things

(IoRT). The enabling factors of IoRT through satellite are discussed as well. The interoperability between satellite systems and sensors/actuators and the support of IPv6 over satellite are considered. Furthermore in the proposed method, radio resource management algorithms are required (as it is proposed in this thesis) to enhance the efficiency of IoT over satellite. In this work, an integrated view of satellite-based IoT are represented by the following topics: MAC protocols for satellite routed sensor networks, efficient IPv6 support, heterogeneous networks interoperability, quality of service (QoS) management, and group-based communications.

2. 6 Surveying Different Communication Network over Smart Grid

Some studies have been done regarding to introduce the different communication network infrastructure survey over the SG. The summary of some of them are given in this part. Kuzlu et al. assessed the suitability of different RATs deployment for different SG applications from the enterprise level, generation, transmission and distribution levels, to the end customer level [61]. Data rates and coverage ranges of both wired and wireless communication technologies were compared in that work. An assessment is performed to evaluate suitability of different communication technologies for using to enable different smart grid applications based on specific network requirements.

Fiber optic, DSL, coaxial cable, and PLC are discussed as wired solutions and ZigBee, wireless mesh, WLAN, Z-Wave, WiMAX, cellular, and satellite as wireless solutions. Various requirements of the system including data rate, latency, reliability, security, and coverage distance are discussed. It is shown that the lower installation cost, faster deployment, higher mobility and flexibility of wireless system in comparison with wired one, makes wireless technologies a better solution for smart grid application. The assessment performed in method used in this study will be useful for selecting appropriate RATs for different SG node types. Wireless IP Networks in SG Applications [20] is a study which was done by M. Zillgith et al. [62]. This study provides an overview of requirements and implementation issues for specific SG applications of narrowbandwidth wireless IP networks. In this work, the most important KPIs which has been focused is security issue since the selected applications in this work are very security sensitive, special attention has been given to the implementation of security services [62]. This research provided an overview on relevant RATs and security services. Network designers and are every so often tempted to create highly optimized application specific protocols with sophisticated cross-layer optimizations. While this causes to higher (energy) efficiency for a very particular application it is on the expense of flexibility and extensibility in the future. Its results can be a gate to design the other Wireless IP Networks for different application in SG. John C. Hoag made a study on Wide-Area SG Situational Awareness Communications and Concerns. This report recognizes areas that potentially can affect performance adversely [63,154].

PMUs and the PMU data concentrators, network infrastructure, and hosts and applications were discussed in this report. The general expectation for wide-area situation awareness is to acquire more granular information to perform more complex control at tighter intervals over a wider area and in this regard, PMU is the first enabler for new classes of monitoring and control. This study indicates that applications PMU data should expect the latency ranging 125ms - 205ms for data to present itself to a CS. P. Kulkarni et al. proposed a Mesh-Radio-Based Solution for Smart Metering Networks [64]. It is made an overview of the available RATs for (AMI) networks, as the network infrastructure to facilitate transport of meter readings from meters to the utility provider. The strengths and weaknesses of the various smart metering communication mechanisms were discussed with regarding to the needs for simple and practical solutions which is low cost and easy to deploy as well.

They proposed a mesh-radio based technology as a winner candidate since it is enhanced version of the routing protocol for local area network and has self-organizing characteristics in addition to be practical from deployment perspective. Network operational issues for improvement of robustness and scalability [20], in addition to fault recovery due to link failure were discussed in that work. As an introduced method for defining appropriate network topology, this work is considered a worthy one.

In [191] Hirschler et al investigated Internet Protocol (IP) for being used in SG. It is mentioned that using IP for SG communication network is even more beneficial because it brings a unification aspect into a field characterized by a variety of heterogeneous communication protocols which are in use today for various functions and services inside a SG. This article therefore analyses the performance impact of IPv6 and IPsec on the end-to-end communication in resource-limited devices. The experimental results show that the influence of security features is very high that should be feasible for many SG applications.

In [199] Shahzad et al AMI issues is in the center of the focus. The security of AMI is one of the most concerning issue in SG implementation. Different types of security threats — like the privacy violations; altering pricing values; injecting false readings; denial of service and other kinds of malicious attacks in AMI are discussed. Such attacks always put down performance of SG system; causing failures; suspension of operations and create distrust between users and CS. In this paper, state estimation based clustered framework is proposed for AMI. A collector is responsible to collect data of SMs from cluster and forward it to CS, where trust value is evaluated by using state estimation method. The malicious meters are kicked out based on trust values, cluster of SMs which is declared by collectors. Also vice cluster head concept is proposed to be used to monitor the communication behavior of cluster head. The proposed security scheme could prevent and detect malicious meter with high probability and success and as a result the AMI traffic characteristics are changed and its results can be considered in the proposed methods in this thesis.

In [209] Calamaro et al discusses that SG cost is high and the development of ongoing operational benefits is a way to fund part of that cost, as well as to provide new sources of income to utility companies, transferring from a monopoly to liberalized market. The research point of view indicates that development of operational benefits involves serious scientific creative understanding, and electric algorithms development. In this paper four algorithms are presented to use existing electric knowledge for these applications such as algorithms for remote reverse extraction of grid load structure as a black-box, a non-intrusive load forecasting algorithm sensitive to weather and special days, an algorithm for urban fault location and for low voltage grid real-time fault alert that is both national and urban wide and yet exploits existing infrastructure and an algorithm for optimal energy management: national, district, and specialized niches. The nove results in implementations combined with novel algorithm in this paper and combination of the achieved results with the defined method in this thesis promote the proposed method in this paper in an efficient way.

2. 7 Home Area Network for Smart Grid

Also lots of studies have been done regarding to HAN domain for SG. The summary of some of them are given in this part. In [65] by R. Amin et al., a HAN communication infrastructure is investigated that is based on future next generation heterogeneous wireless systems. At the proposed method for HAN in SG, the use of co-operative networking paradigms such as Dynamic Spectrum Access, a centralized resource controller that is involved in resource allocation process at the global level and also the use of reconfigurable smart devices are considered.

It was shown that a two-step scheduling solution suitable for supporting real-time and best-effort traffic classes and an open spectrum access method supported by actual measurement studies increase in real-time traffic support and best-effort traffic support in a scenario that uses reconfigurable radios.

In this study the simulation scenario has been restricted just to HANs in which it has assumed several wireless access technologies exist that are subscribed to by the user. Short-Range Wireless Network Integration in Intelligent Environments was investigated by M. Mama et al. [66]. It has been investigated enabling access services on an integrated non-Bluetooth intelligent system via Bluetooth enabled device (Client-Server architecture) in the vice versa. The aim of that work is performing system integration to establishing additional communication link in short range wireless network that will enable automatic connectivity and immediately share data among them by considering all the reliability aspect (in HAN).

2. 8 Security Issue in Smart Grid Network

Evaluating the different communication network security is an important issue which has not been studied well for M2M but, still some works can be found. R. S. Stefanov investigated Security and trust in IoT/M2M Cloud based platform [67]. This thesis work studies M2M services policy on the local cloud infrastructure concept. The main objectives of the thesis are to analyze security needs of M2M services and based on this requirement, access control method in such platform were designed [67]. In this new method for local cloud infrastructure different access methods are analyzed to determine their security aspects.

It is essential to recognize new message protocols that are used for M2M communications. They have specific requirements and security aspects. The techniques used to secure local cloud model can be applied by means of network access, policies, authorization and authentication technologies or a combination of them. The system should communicate with outside environment and must be connected to the internet. Classic protection using security certificates and cryptographic algorithms are not enough to ensure the essential security level in the cloud. In M2M communications sometimes small embedded devices have no capabilities to support this type of certificates. Thus, a new challenge to the security of M2M/IoT environment is found. In this work, security trust values dividing in three major groups. The first one is the trust in human and how we can be sure that human communication with the system is correct. The second one is the trust in M2M and the third one is the network system.

The idea behind this work is to check the system and give some trust level values on different type of devices, connections and services. The system needs to be sure that the deployed application is not a risk for the environment and normal work of the other services and the local cloud. R. Mao worked on the Design of Wireless Communication Networks for Cyber-Physical Systems, CPS, with Application to Smart Grid [68]. CPS is the next generation of planned systems in which computing, communication, and control technologies are tightly integrated and unified. In addition, CPS is connected, and must be robust and responsive. SG is an example of emerging CPS that has significant and far-reaching impact on our daily life. In this work, wireless communication networks were designed for CPS. In this study, four layered structure, which includes physical layer, multiple access layer, network layer, and application layer are investigated. Based on this study, prioritized multiple access provides a method to select data that is more desirable for transmission when bandwidth is restricted. It has also discussed the integration of the mentioned wireless communication network into a micro grid, a typical SG system. The other aspect of study in SG issues like security issues has been done by Z. Ismail et al.[69]. A Game Theoretical Analysis of Data Confidentiality Attacks on SG`s AMI is studied on AMI privacy concerns.

The research is based on the analyzing the data collected from AMIs which can expose habits and can be potentially used to predict customers' behaviors. In this paper, the confidentiality of information in the AMI consisting of nodes with inter-reliant correlated security assets is analyzed. Moreover, several security modes are available which can be chosen by the defender users.

The authors try on formulating the problem as a non-cooperative game and analyze the behavior of the attacker and the defender. By the game theory, the minimum defense budget required and the optimal encryption rates on each device in the AMI are derived and by using a case study, it is shown that to configure encryption rates on network devices in the AMI is useful.

In [198] F. Jameel, et al investigates the security management of SG as a key challenge for the research community of the world. This paper provides the major security goals of SG systems along with classification of different vulnerabilities. Additionally, in these paper remedial measures to prevent these security threats is presented.

In [206] Ray et al discusses that a key aspect of realizing the future SG communication solution is a balanced approach between the network performance and the network security during the network deployment. A high security communication flow path is not useful when the network path cannot support capacity to fulfill SG different node types requirements. By focusing on both the network performance and the network security at the same time the deployment phase in communication network can be facilitated. In this paper, a use case of SG application where security, network capacity and reach ability needs to be optimal for successful network operation is described. The proposed balancing approach of the network performance and the network security which is beneficial for the optimal SG secure system design are explained.

2. 9 Fuzzy Logic Studies in Smart Grid

Assessing the different decision making for communication network based on the fuzzy logic concept [185] is an interesting issue that some works can be found on it. The work of M.A. Zamani et al. investigates a policy-driven decision making method based on a novel fuzzy approach to Tricotyledon Theory of System Design (Fuzzy- T3SD) for the choice of proper IT infrastructure for smart grid [70]. Different utility's policy can change the decision making result. In this work Fuzzy-T3SD is applied on a case study which is the practical data of the Greater Tehran Electrical and the results were tested by developed policies scenarios. P. Rafiee did a study on Evaluating the Reliability of Communication Networks Using their Fuzzy Fault Tree Analysis [71].

Keeping WAN in a reliable mode and evaluating their reliability is a vital task for network designers. The fault tree model is used to evaluate the reliability of an operational network. As there is often uncertainty in the estimation of failure probability of communication links are considered as a fuzzy system, thus, the system fault tree based has been evaluated on indefinite

Simple Network Management protocol by means of fuzzy logic concept. As an alternative this method can be used instead MMPR model.

In [201] M. Mendil et al propose a fuzzy Q-Learning based energy controller for a small cell powered by local storage, and the SG to simultaneously minimize electricity expenditures of the network operators and enhance the life span of the storage device. Simulation results show that the proposed solution in this paper achieves important cost reduction with respect to simpler approaches and performs very closely to the ideal strategy based on a perfect knowledge of the stochastic variables.

Lots of methods have been presented for designing a protection system for distributed networks included distributed grid up to now. But, the simplicity in configuration of distribution networks and expensive costs needed for changing the configuration makes these methods not to be used in practice in the most countries of the word. This is due to a wide area communication network is needed to protect a distribution networks so that operation of DGM in island mode can be obtained. This type of communication networks is also very expensive. Thus, presenting a method for allocation of protective devices in distribution network without changing the configuration and only by increasing, decreasing, or relocating the protective devices can be considered a good solution for distribution networks. In [202] Javadian et al propose a risk analysis and fuzzy calculation combined method that is used for optimal placement of protective devices in distribution networks. Fuzzy calculation is used for modeling in uncertainties of distribution networks in this paper. A risk analysis is used for optimization of the protection system's configuration.

2. 10 Available Studies on the Use of Resource Management and CF in Smart Grid

Plenty of studies have been done on the Use of Resource Management and Cost Function in Smart Grid. The summary of some of them are given in this part. T. A. Le et al. proposed a multi-variable cost function to build a media distribution tree, using in video conferencing services [72]. The CF considers the network resources and application's requirements. A scalable video conferencing service on an overlay network of a simulated Internet topology and a real WiMAX network was constructed since the participant may use different types of networks such as WiMAX or heterogeneous networks.

The defined CF was applied on the service and its performance was validated by the collected real measurement data in the rapidly changing heterogeneous network environment. The work of H. Liang et al. focused on development and resource management of communication networks for the environments where continuous end-to-end connections cannot be established between information sources and destinations [73].

Delay tolerant network (DTN) by a store-carry-and-forward routing scheme was proposed to fulfill the mentioned aim. However, for these kinds of networks (DTN) the management of network resources such as communication bandwidth and storage is a challenging issue since they are intermittent in nature. In this work the resource allocation was done by considering intermittent network connectivity and multi-service demands. Besides, two types of services which correspond to pedestrians and high-speed train passengers were considered as two kinds of mobile nodes. Although the mobility issues are useless to build a SG infrastructure but, the part of results on managing the resources to DTN can be helpful for even the fixed position nodes. The roadside wireless local area networks are used as an auxiliary communication infrastructure, dealing with pedestrian nodes, while on-demand data service delivery via a cellular/infestation integrated network was used for high speed train nodes. In the second part of this work, the resource management in SG such as optimal energy delivery for plug-in hybrid electric vehicles via vehicle-to-grid systems was investigated.

Also a case study was performed in which an exponentially weighted moving average algorithm is used for vehicle mobility and energy demand estimation by using a modified backward iteration algorithm. Heterogeneous wireless network architecture was purposed for micro grids to prevent a slow convergence speed of multi agent coordination. A tradeoff between communication and generation costs was done and the optimal number of activated cellular communication devices is determined. R.Webster investigated SG Communications in High Traffic Environments [74]. This work aims to optimally allocate radio resources such that the SG QoS requirements are fulfilled, with minimal effect on pre-existing traffic caused by the burden of SG nodes. Class queue latencies were reduced by smart scheduling of periodic traffic and forward allocation of resources. By using this method, system produced fairer performance for all users. The results obtained in this thesis have concluded that the Latency and Throughput requirements for SG applications have been satisfied, with minimized effect on pre-existing communications traffic. By mapping subcarriers based on a population dynamics model it is possible to optimally allocate users to reduce overall latency and increase total system throughput.

Despite of these achievements, the numbers of SG node types with their all communication requirements have not been considered in this work. Moreover ways to comparing the functionality of all RAT s that can support SG nodes communication requirements have not been studied.

In [192], high priority RATs were considered for abnormal events and system control operations, and low priority communication architecture was considered for asset management tasks. In order to increase the reliability and reduce the latency of event notification, three layers communication architecture is proposed. Several candidates considered for design and being investigated in terms of cost, reliability, and smart grid applicability. The concept of high and low priority communication architecture is a good assessing tool to have a well-designed RAT for SG.

H. Liang investigated Resource Management in DTN and Smart Grid [76]. DTN is proposed to succeed this objective by utilizing a store-carry-and-forward routing scheme. However, as the network connections in DTNs are irregular in nature, the management of network resources such as communication BW and buffer storage becomes a challenging issue. In addition, the SG should consider information and RATs in electric power grids to achieve electricity delivery in a more efficient and reliable way.

Though, the intermittency of renewable power generation brings new challenges to the resources management in the smart SG. In order to achieve efficient resource allocation with low computational complexity, the main problem is transformed into a single-machine proactive scheduling problem. In the second part of this study, the main focus is on resource management in the SG. For avoiding a slow convergence speed of multi agent coordination, it is proposed heterogeneous wireless network architecture for micro grids. The optimal number of activated cellular communication devices is obtained based on the tradeoff between communication and generation costs which considered a primary CF for marketing, installation, energy and communication KPIs. Resource management in DTNs and SG is a broad research part.

Several researches demonstrate that the power consumption of network devices of ICT is nearly 10% of total global consumption. While the redundant deployment of network equipment causes the network utilization is relatively low, which leads to a very low energy efficiency of networks. With the dynamic and high quality demands requested by users, how to improve network energy efficiency becomes a focus under the premise of ensuring network performance and customer service quality. In [75] an energy consumption model based on link loads, and use the network's bit energy consumption parameter to measure the network energy efficiency is proposed for this reason. This paper aims to minimize the network's bit energy consumption parameter, and then it is proposed the energy-efficient minimum criticality routing algorithm, which includes energy efficiency routing and load balancing. To further improve network energy efficiency, this paper proposes an energy-efficient multi-constraint rerouting (E2MR2) algorithm. E2MR2 uses the energy consumption model to set up the link weight for maximum energy efficiency and exploits rerouting strategy to ensure network QoS and maximum delay constraints. The simulation uses synthetic traffic data in the real network topology to analyze the performance of the proppossed method. The defined solution in this paper is commitment with the proposed method in this thesis.

For overhead transmission line monitoring, wireless sensor networks present a low-cost solution to connect sensors on towers with the control center. However, these networks cannot meet stringent QoS necessities, in terms of packet delivery ratio and delay. Also, it is essential to ensure strength such that data can be delivered when a tower fails. In view of the QoS and robustness requirements, WAN connections, such as cellular and satellite network are required on top of wireless sensor networks. Different WAN connections have different characteristics in terms of availability, performance and cost. In [203] Kong et al proposed a novel scheme, called Optimal Placement for QoS and Robustness (OPQR), which uses the canonical genetic algorithm to determine the numbers, locations and types of WAN connections to be deployed to minimize cost while satisfying the QoS and robustness necessities. Evaluation results confirm that OPQR can respect the desired requirements at minimum cost, and it is a very useful tool in cost efficient communication network designing for transmission line monitoring. Combination of these results with the results are achieved in this work can make a comprehensive CF including installation cost and marketing cost as well.

In the work of A. Serrador and L. M. Correia, [77, 157], an approach to simplify and unify a set of KPIs into a single one was used. This approach is allocation of a CF which embraces all the KPIs. These KPIs are considered for analyzing heterogeneous cellular networks performance and obtaining a balance to guarantee a desired Quality of Service (QoS). The purposed CF enables the implementation of different CRRM algorithms and policies, and manipulates KPIs based on user's characteristics and providing a better QoS. A compromise can be made between different players by taking into account both users' and operators' perspectives. Using set of KPIs makes it possible to introduce multiple policies in the CRRM management criteria [77].

Conflicting KPIs, when used only by users or operators, may produce higher differences over CRRM QoS. The worst result is produces when only users' guidance is assumed, since the global RAT QoS at the Radio Resource Management (RRM) level, or even less at the CRRM one are not considered as a concern by users. Majority of CRRM and some of RRM policies and strategies are based on this CF, since BSs and users use their own cost on the radio network. Using variety CFs, enables comparing and classifying nodes of the network, and helps in creating the candidate lists for a given strategy.

In this method, the priority [20] scheme plays an important role. Users are switched to a given RAT by this method thus; they are responsible for load distribution within the CRRM domain. The CRRM capabilities and overall QoS are enhanced by considering different policies based on this CFs model. As an example of this work, for changing associated CF policy, the median packet delay associated to operators or user's requirements can vary 3 times higher. It should be mentioned which the archived CF in this study is the basement of the comprehensive CF for being used in some parts of this thesis [77]. In [181] the very simple CF to choose the best communication architecture and technology for SG is discussed. In [182] the CFs elements values for delay are achieved just by allocating the numbers to the qualitative values instead of using a proper formula. The potential for an integrated wireless communication, energy management, and control services for the next-generation grid are addressed in [178].

In [188] Vardakas et al studied the performance of Machine-to-Machine (M2M) communications in LTE Advanced networks (LTE-A). The suggested analysis is applied to the random access procedure within LTE-A for the measurement of the average overall delay, by considering multiple classes of M2M devices with diverse Quality-of-Service (QoS) requirements as they are considered in this thesis in sense of different QoS criteria. For the packet arrival process of M2M devices they consider an ON-OFF arrival process as a realistic approach, especially for M2M communications in Smart Grid environments. Moreover, the proposed analysis is suitable for smart grid communication networks, where multiple M2M gateways are installed in different points of the network. The high accuracy of this model with simulations show its adavantages and it could be a good support for the proposed method in this thesis.

Cloud computing data center as the optimization infrastructure is used to support a cognitive radio network for AMI. The goals include developing persistent SG information network using different CFs. Nowadays ICT infrastructure causes 2% increasing in world CO_2 emissions. The transmitted data-volume increases fast and RATs are used extensively while network design rules have practically disregarded the energy efficient network design approach is named Green Communications. Significant energy savings in RATs can be expected by defining and standardizing energy efficiency metrics in combining with CCFs. The paper [159,163] discusses several techniques such as cross layer approach, multiple antennas, from the system energy efficiency aspect, outlining challenges and open issues respect to the Eb/N0.

2. 11 Summary

To the best of our knowledge, the other methods proposed in the literature are not efficient resource allocation methods for respecting the SGCN requirements with the given constraints.

Moreover, a method to compare all RATs who can support different SG node communication requirements and choosing the best and most efficient one in sense of communication issues and spectral efficiency has not been introduced so far.

Finally, an efficient method to make a HET-NET for SG communication network and assigning the different SG node types to different RATs based on the communication criteria of both users and RATs has not been elaborated and studied well. Moreover, as higher spectral efficiency, SE, results in lowering power efficiency and increasing in spectral efficiency causes to have increasing the energy per bit, Eb/N0. Few subjects in RF design elicit as many blank looks as Eb/N0. Low Power Communication is the key to realization of a little power sensor node. The method to combine all these criteria into a unified model to elaborate an efficient HET-NET for SG node communication requirement fulfillments should be determined and defined. The state of the art outcomes and methodology helps to defined a comprehensive method to make an efficient Het-Net to support different SG node types with different densities.

Chapter 3

SMART GRID COMMUNICATION MODEL AND REQUIREMENTS

3.1 Domains in Smart Grid

Smart Grid function can be categorized in four different domains that should be elaborated in both power and telecommunication part to have to be efficient. These domains are generation, distribution, transmission and customer domain [6, 12, 18, 34, 45, and 46]. Each of these domains consist of different node types each has its own different communications requirements. The proper methods should be defined for whole Smart Grid communications network to have reliable and secure communication network to support different SG node types requirements. Communication networks must be elaborated as the secure and reliable path of transferring information from all network parts to the CS. In CS all the required information and control messages are transmitted to the whole SG node types. A reliable, universal and secure communication infrastructure that fulfill the nodes traffic requirements are the goals for designing an efficient and robust network architecture which enables SG for managing operation and control of the power system [18,45,46]. Different kinds of communication access methods exist to support SG applications but in the most of them all the focuses are in wireless communication due to its advantages. The coverage area of the SG application varies and they can be included into one of the domain of SG Area Networks namely WANs or Wide Area Networks, NANs or Neighbor Area Networks, NAN and Home Area Network, HAN [10, 18, 34, 45, and 46,151,152]. For HAN, short range wireless networking like Zigbee , Wi-Fi, Bluetooth, Infrared or mixed of them can be used together to fulfill all the SG applications requirements in HAN. HAN collect the consumption and power related data from different electrical devices at the building and by using the SMs and then these data will be sent to the CS by using aggregators or collectors [10, 18, 34, 45, and 46]. Elaborating an appropriate method for designing NAN and WANS in SG in which all SG applications requirements get fulfilled in an efficient way in different aspects (including spectrum efficiency, high Quality of Service (QoS) and energy issues)are the major focus of this thesis.

The huge number of SMs and SG nodes that each of them produce short data in a certain period of time should be managed in a way that maximum throughput could be obtained when a certain RAT is used. In this part, the main types of the node in SG and their communication requirements are introduced. However, prior to that the main SG communication structures for SG are discussed.

3.2 Smart Grid Communication Structure

The data transferring links from SG nodes types to the data aggregators and then through the aggregators to the CS in an area are typically realized using an elaborated Het-Net. Different RATs characteristics could be an indication of how much they can fulfill the different SG node type communication requirements [25-41].

As an instance, SG node type delay sensitive requirements can become the important issue in the data collection and transmission part, specifically for certain node types in WASA part [10, 12, 18, 20, 45, and 46].

These data are required to be transmitted to the CS, and control commands are required to be issued and implemented within a certain short time period to avoid cascading outages [18, 34, and 45].

To meet such high requirements for WAN and NAN SG node types, it is generally preferred to use appropriate well designed communication structures networks consisting of a single RAT, a combined different wireless RATs or even a combined wired and wireless RATs communication because of its ability and advantages to deliver high data rates for long-distance communications. In following some of important structures are discussed briefly.

3.2.1 TCP/IP BASED

The node data are collected by the collectors through short range RATs like Wi-Fi and then through the TCP/IP should be sent directly to the CS [79]. The AMI simple infrastructure is connected to the CS using TCP simple structure and is shown in the Figure 3-1.

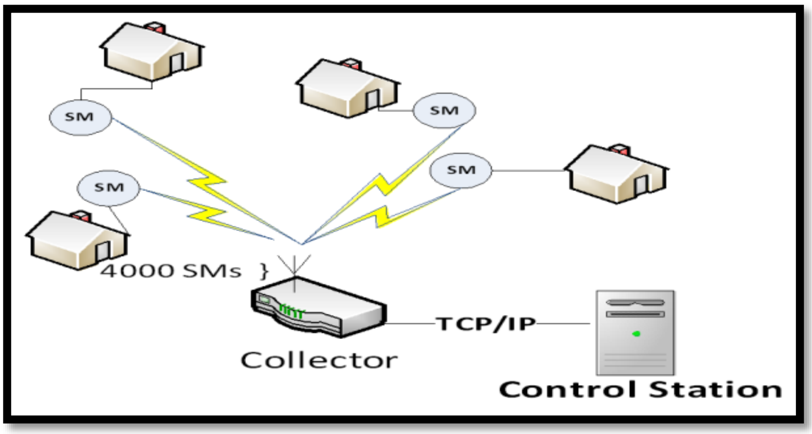


Figure 3-1 The AMI simple infrastructure connected to the CS using TCP simple structure

3.2.2 Mixture of different RATs and weird communication access methods

The different node types data are collected by the collectors through short range RATs like Wi-Fi or even the wired RATs and then should be sent directly to the BS through the wired RATs or fiber optic [18, 20,34,45,46, and 183,184]. Then the BS which is near to the CS will transfer all the data by a wired, wireless or fiber optic RATs. A figurative model of this structure can be shown in Figure 3-2.

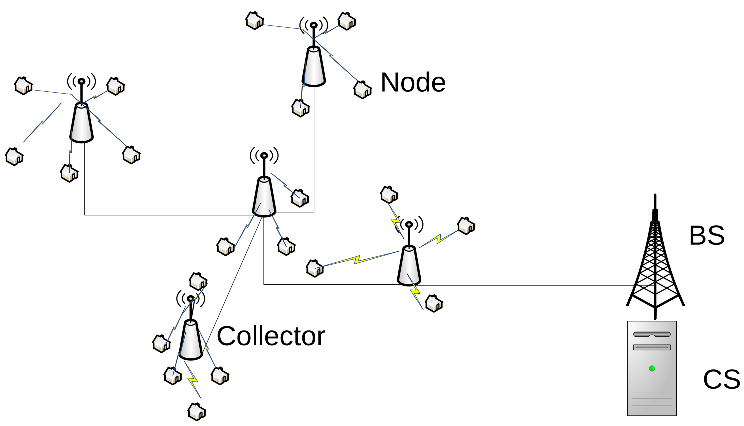


Figure 3-2 Mixture of different RATs, Wired and Wireless RATs

3.2.3 WAN, Wireless- BS to CS Wired

The node data are collected by the collectors through short range RATs like Wi-Fi and then through the high range RATs like LTE or WiMAX should be sent directly to the BS [18, 34, 35, and 183,184].

Then the BS will transfer all the data by a wired, wireless or fiber optic RATs. A figurative model of this structure can be shown in Figure 3-3.

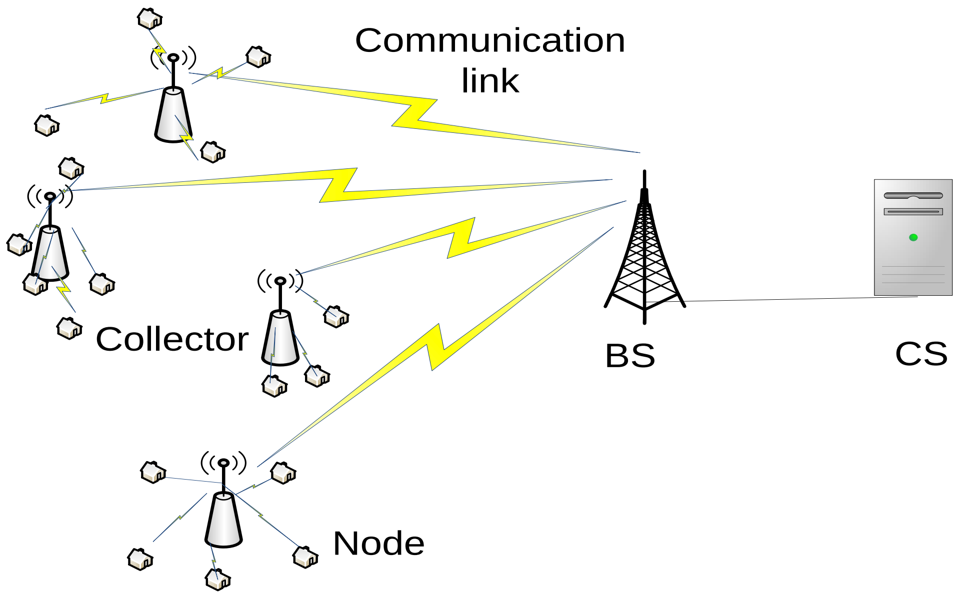


Figure 3-3 WAN, Wireless- BS to CS Wired

3.2.4 Satellite Based

The node data are collected by the collectors through short range RATs like Wi-Fi or even the wired access methods and then through the satellite communication as a backhaul can be sent directly to the CS [59, 60]. A figurative model of this structure can be shown in Figure 3-4.

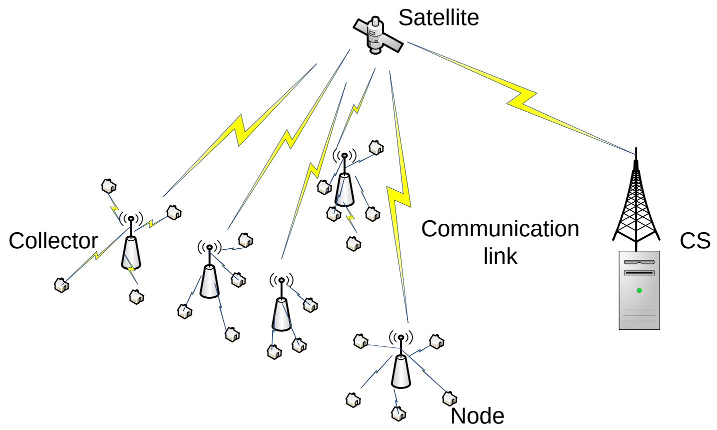


Figure 3-4 Satellite Based Communication Network for SG

3.2.5 Cellular, Mesh Based

The node data are collected by the collectors through short range or the wired access methods RATs and then can be sent to the BS through the mesh topology.

Then the BS which can be near or far to the CS will transfer all the data by a wired, wireless LIKE WiMAX or fiber optic RATs [18,26,44].

Frequency reused technique can be used in this structure. As an example three sectored LTE can be chosen as the broad band and high coverage RAT. A figurative model of this structure can be shown in Figure 3-5.

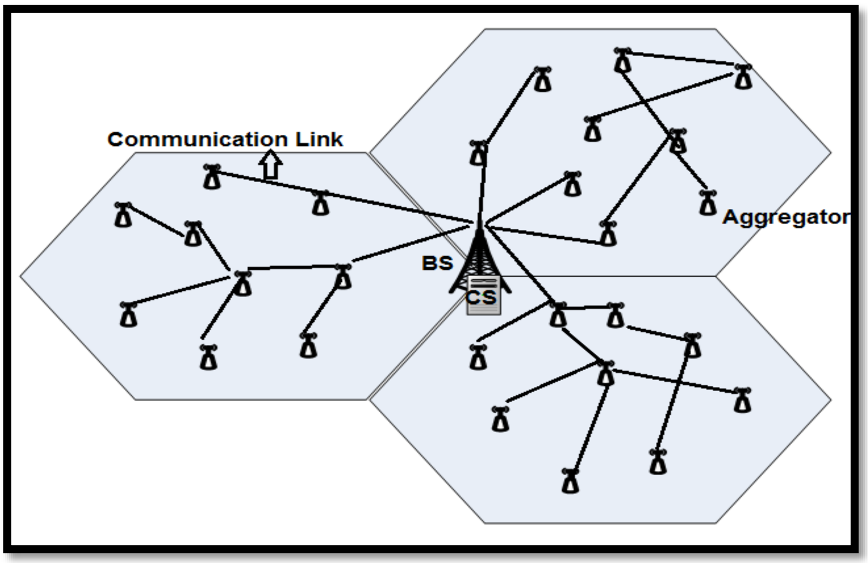


Figure 3-5 Cellular Based Simple Communication Network structure for SG

3.2.6 Totally Wireless Based

The node data are collected by the aggregators through short range RATs and then through the high range RATs like LTE or WiMAX the total data can be collected by BS in the CS [18, 26, 44, and 45, 183, 184]. A figurative model of this structure can be shown in Figure 3-6.

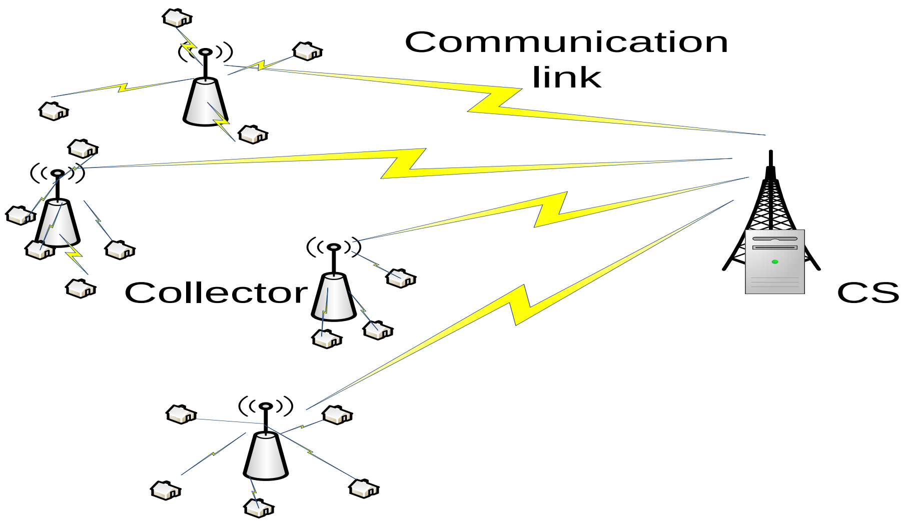


Figure 3-6 Wireless Based Communication Network structure for SG

There are 5 main SG node types in SG, each including the sub node types, which are connected to the CS. They are described briefly as following [2, 18, and 46].

3.3 Smart Grid Different Node Types Category

3.3.1 Advanced Metering Infrastructure (AMI)

In a figurative way, a simple AMI infrastructure in NAN domain of SG is shown in Figure 3-7.

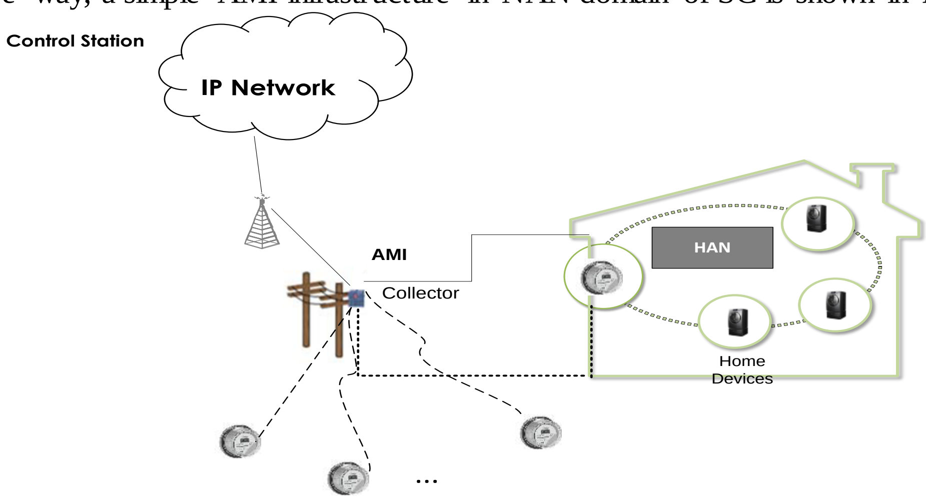


Figure 3-7 a *simple AMI infrastructure in NAN domain [18, 12,20,45,46 modified]*

Smart Meters and its network structure, Advanced Metering Infrastructure, AMI, are considered as the backbone of the SG.

Their important role on the SG demand side is notable. Their function allows to the users to cooperate on the power demand controlling. It results to decrease the fuel consumption. Besides, it utilizes the power distribution management. Due to the huge amount of users, these issues will result to decrease of greenhouse gases. Although distributed energy resources are mostly the sustainable and green energy resources and have higher effect on green energy issues, but AMI plays a good rule to fulfill this goal of SG somehow better than the other SG node types by using meter readings. Meter reading allows a utility to collect data from electric, gas, water meters and transfer data to a CS for billing and analysis.

A SM can implement prepaid meter functions with the ability to remotely connect or disconnect the service [18, 45, 46, 80]. With Advanced Metering Infrastructure (AMI), a utility can perform real-time bidirectional communications between meters and a centralized management site, thus it results in improving meter reading accuracy and function ability, and reducing operational costs. With the capability to monitor electricity usage in real-time, customers can be informed of their own usage, thus allowing better management of their electricity consumption.

Network requirements for meter reading applications vary reliant on service types but, defining an assigned period time and message size to each SMs make the communication network more efficient [80]. On-demand SMs reading lets readings to be taken whenever needed.

A typical payload and latency requirement and the other communication requirements are given in Table. 3-1a, b, c, d. Scheduled meter interval reading provides the capability to collect usage information from a meter to an AMI several times a day.

Interval readings are normally stored automatically at the SMs, and later retrieved by the utility through the aggregators.

Payload data includes meter reading information from a number of meters, different type of user request and the information related to power status on the demand side of SG. Generally, the payload size depends on the number of meters scheduled to be read [80].

3.3.2 Plug-in Hybrid Electric Vehicles (PHEVs)

Electric transportation applications involve both electricity flow from vehicles to the power grid (vehicle-to-grid, V2G) and electricity flow from the power grid to vehicles (grid-to-vehicle, G2V). These applications allow various electric vehicle technologies (based on battery, hybrid, plug-in hybrid, fuel cell, and plug-in fuel cell) to become mobile distributed generation resources. Electric transportation applications may include a utility sending inquiry to obtain knowledge of vehicle battery state-of charge, informing vehicles about electricity prices; as well as an electric vehicle sending messages back to a utility in response to received commands. Pricing applications contain broadcasting of price information to meters and devices like smart appliances, plug-in hybrid electric vehicles (PHEVs) and load control devices, at customer premises. These are typically associated with time-of-use, real-time pricing and critical peak pricing programs. Customers can use this information to reduce electricity bills by handling their energy consumption. Efficient functions are typically used during times of high peak demand [2, 81].

3.3.3 Wide Area Situational Awareness (WASA)

For making the SG largely reliable, WASA related nodes are the key points to be implemented in the SG. In conventional power grid, unplanned power outages are mostly infrequent and irregular which distress the small part of the power grid. Furthermore, in some countries utilities have selective blackouts due to that, the power generation are not able to support the whole demand. However, increasing the power demand over the time and the next century, in combination with the other sophisticated problems like the lack of corresponding increase in the power grid transmission capacity may happen. These issues have affected plenty of outages which were unwanted. The concept of interconnecting so many utilities of the power grid may seem a good solution. On the negative side, an unwanted, unpleasant and unprecedented event in any utilities, if not got corrected in the proper time; surely affects the other grid functionality. Such type of faults affects efficiency of the power grid and functionality which is one of the most important goals of SG. Therefore, an elaborated design should be planned to avoid or decrease these unwanted events for disaster prevention. Wide Area Situational Awareness is an entity in the SG whose functions modify the system drawbacks. It has several different types of the UL nodes with different communication requirements [2, 18, 9, and 63]. The Northeast blackout of 2003 caused in a $6 billion economic loss to the province which might have been avoided by having a better communication network across system operators.

Using a PMU which is a part of WASA in SG makes it easy to detect unusual waveform shapes, which is described and called mathematically called a phasor [2, 9, 18, and 63]. There have been five huge blackouts over the past 40 years, three of which have happened in the past ten years. Several blackouts and brownouts occur because of the slow response times of mechanical switches, a lack of automated analytics, poor visibility, and a "lack of situational awareness" on the part of grid operators. WASA represents the monitoring of the power system across wide geographic areas. These broad area outlooks are necessary to keep up system knowledge and decisions that go beyond conventions of individual corporations or even Return to Origin (RTO) borders. The needs for WASA are architecturally important from the perspective of requiring uniformity across old-style systems operation boundaries.

Dealing with WASA based nodes needs unique requirements and challenges for the SG infrastructure in sense of communication issues. WASA supports real-time monitoring, control and protection applications, which can help prevention of flowing outages with real-time information related to the state-run of the power grid. It also makes available communication links for SG backbones; and covers long-haul distances from NAN to the CS. WASA applications, including wide-area monitoring, wide-area control and wide-area protection, have been identified as the next-generation solution to improve power system planning, operation and protection in the SG. These applications include the use of system wide information and selected local information to respond the propagation of large disturbances. Shorter response time and higher data resolution than classical supervisory control and data acquisition (SCADA) and energy management (EMS) systems are provide by Wide-area monitoring, control and protection applications. Using SCADA/ EMS causes measurement update interval of several seconds or even minutes. In addition, by using wide-area monitoring, control and protection applications, high-resolution data such as 60 samples per second can be obtained [2, 9, 18, 45, 46, and 63]. By using Wide-area protection a fully automatic protection can be obtained which is useful for power systems protection toward widespread blackouts, transmission congestion and stressed conditions, or unexpected events. Dealing with unpredicted contingencies that require fast reaction to avoid widespread failures or blackouts, is much easier with wide area protection system functions. These protection applications generally involve adaptive islanding and load shedding. Besides, automatic self-healing capabilities can be obtained by Wide-area control. This surpasses functionalities obtained by local control and responds faster than manual control by a control center which is used in conventional power grid. Using this way, a flexible platform for fast implementation of generator tripping, reactive power compensation switching for transient stability and voltage support of a large power system can be obtained. Real-time instability control is used as an additional layer to prevent possible blackouts and facilitates electrical commerce.

Wide-area control applications enables control of fast controllable equipment, such as high-voltage direct current (HVDC) and flexible-AC transmission system (FACTS) devices, etc. Wide-area control applications includes also wide-area damping control with respect to oscillations in large-scale electrical transmission systems, stability control frequency to avoid potential damage to generation and load side equipment in addition to voltage stability control in order to sustain active and reactive power flows for transmission corridors. Using wide-area protection and control applications, more advanced protection/control systems can be obtained in comparison to traditional power systems.

However, more strict performance and availability requirements are needed. As an example, the range of milliseconds to minutes (e.g., <0.1 s<2 min) as response time, and the very high reliability (e.g., >99.9%) are required for wide-area protection and control applications. Typical message sizes of this system are variable for different communication protocols implemented [2, 63, and 82]. Moreover, the aim of wide-area monitoring is providing system data in a real time from a group of intelligent electronic devices (IEDs) which transmit snapshots of device status and measurement data to SCADA/EMS over a WAN and PMUs and enable time-synchronized snapshots of a power network including voltage and current phase angles, such as, wide-area measurements [2,18,45,63,82]. Enhanced stability assessment with respect to state estimation, system parameter estimation and post-fault analysis are obtainable as a result of availability of wide-area measurements.

Some example of wide-area monitoring are monitoring of power frequency oscillation and system voltage stability. Therefore, wide-area monitoring gives the power grid opportunities to enhance voltage stability and detect frequency oscillations/ instability. The IEEE Standard for Synchrophasors for Power Systems (IEEE Std. C37.118) can be used to obtain this information, which defines measurement, and data transmission formats for real-time data reporting in electric power system [2, 18, 45, 63, and 82]. Primary requirements by these applications including their typical data sizes, sampling rates, and reliability and latency requirements, in addition to communication technologies that can support these applications are listed in Table 3-2.

3.3.4 Distributed Grid Management (DGM)

There are lots of challenges for distributed management of SG. Distributed Grid Management (DGM) provides the power distribution management through the CS, Self-management and self-healing as means to handle unpredictable behavior. The unpredictable behaviors is caused by individual users cyber-attacks or extreme weather conditions. As an instance, they can make blackouts power peaks with possible cascading failures. This Bi-directional communication and coordination are crucial to manage power distribution.

The real-time operation of grid structure, automation control, and data communication and information management to monitor and control the distribution grid can be feasible by using Distribution grid management (DGM).

DGM systems help utilities to make their distribution assets by allowing control of distribution- level devices, such as capacitor bank controllers (CBC), fault detectors, reclosers, switches, and voltage regulators. Major DGM applications include distribution system monitoring and maintenance, Volt/VAR control, distribution system demand response and fault detection, clearing, isolation and restoration.

Distribution system monitoring and maintenance includes self-diagnostics on equipment, polling equipment status (open-closed, active-inactive) at scheduled intervals, and retrieving sensor data to monitor equipment conditions.

Equipment to be monitored may include fault detectors, reclosers, switches and voltage regulators. Volt/VAR control aims to reduce energy loss, regulate voltage along a distribution circuit, and compensate load power factor. For a distribution system, Volt/VAR management includes both monitoring of feeder line devices and their control issues.

The applications aim to reduce distribution grid voltage to help manage system load during peak periods.

It includes control of capacitor banks, automated feeder switches and voltage regulators [2, 18, 45, 46, and 83].

The specific applications manage the detection, isolation, and restoration of a power grid after the amount of a fault on a section of the grid to minimize the effect of service interruptions to customers. The DGM system consists of intelligent communications and automation devices and low-latency network communications backbone.

A typical data size for DGM applications ranges from 25 bytes to 1000 bytes, and the data latency requirement is less than 4–5 s while the reliability requirement is high. The four main DGMs node type requirements are given in Table.3.1. Outage and Restoration Management (ORM) allows an electric utility to detect an outage as soon as the power is lost via devices, such as outage detection units.

These devices can also report over and under voltage situations [2, 18, 45, 46, and 83]. Classically, an additional interface module is added to a SM to enable the outage detection function. A utility usually places more than one outage detection units on every branch of a distribution network to avoid false alarms. Based on detailed study on DGM [2, 34, 46, 80, 81, and 82], the values in Table3.1.c got considered for this thesis.

3.3.5 Distributed Energy Resources (DERS)

Distribution customer storage applications arise as a technological solution that can address operational challenges by providing power, energy and fast response time to a distribution network allowing an efficient incorporation of renewable resources.

These storage applications include the use of storage devices installed along distribution feeder circuits or laterals for peak load shaving, voltage support, power quality, demand control, and interruption protection (DERS) [2,18,19,78].

The communication requirements of this node are given in Table 3-2 b.

Table 3-2 Some SG node Communication Requirements

a)SMs

Smart Meters	**Reporting time period:** Every 15 Minutes	**Data size:** 125 Bytes (1000 bits)

b) SG Nodes Characteristics [46, 186]

	SG node type	*Typical Data Size(Bytes)*	*Reporting Time Periode (s)*	*Latency(s)*	*Reliability (%)*	*Security*
AMI	SMs Infrastructure	125	900 Minutes	15 Secondss		High
Wide Area Protection						
	Adaptive islanding	4-157	0.1	<0.1	>99.9	High
	Predictive under frequency load shedding	4-157	0.1	<0.1	>99.9	
Wide area control						
	Wide area voltage stability control	4-157	0.5-5	<5	>99.9	High
	FACTS and HVDC control	4-157	30-120	<120	>99.9	
	Cascading failure control	4-157	0.5-300	<5	>99.9	
	Pre-calculation transient stability control	4-157	30-120	<120	>99.9	
	Closed loop transient stability control	4-157	0.02-6	<0.1	>99.9	
	Wide area power oscillation damping control	4-157	0.1	<0.1	>99.9	
Wide area monitoring						
	Local power oscillation monitoring	>52	0.1	<30	>99.9	High
	Wide area power oscillation monitoring	>52	0.1	<0.1	>99.9	
	Local voltage stability monitoring	>52	0.5-5	<30	>99.9	
	Wide area voltage stability monitoring	>52	0.5-5	<5	>99.9	
	PMU-based state estimation	>52	0.1	<0.1	>99.9	
	Dynamic state estimation	>52	0.02-0.1	<0.1	>99.9	
	PMU assisted state estimation	>52	30-120	<120	>99.9	
PHEV	Electric transportation (utility interrogates PHEV charge status)	>100	2–4 per PHEV per day (7 am–10 pm)	<15 s	>98	Relatively High
DERS	Distribution customer storage (charge/discharge command from DAC to the storage)	>25	2–6 per dispatch period per day (discharge: 5 am–9 am or 3 pm–7 pm; charge: 10 pm–5 am)	< 5 s	>99.5	High

c) Distributed Grid Management (DGM) [2,34,46,80,81,82, 186]

Fault Location, Isolation and Restoration (FLIR) ,DGM1	To control protection/restoration circuits	10 to 30kbps	A few 100ms
Optimization, DGM3	volt/var optimization and power quality optimization on distribution networks [2,46,80,81,82]	5000 bps each node	10 ms

Workforce Access, DGM4	Provides expert video, voice access to field workers	250kbps	150ms
Asset Management, DGM2	For predicatively and pro-actively gathering and analyzing non-operational data for potential asset failures [2,46,80,81,82]	5000 bps each node	25 ms

d)[2]

	Reliability	*Security*
AMI	*99-99.99%*	*High*
WASA (All node types)	*99.999-99.9999%*	*High*
DERS	*99-99.99%*	*High*
PHEV	*99-99.99%*	*Relatively High*
DGM (All node types)	*99-99.999%*	*High*

As it was described before, the nodes in the Tale 3-1,b and c which have the same communication requirements may being considered the same node types for calculation of the traffic details of the nodes to achieve the CFs values. It should be mentioned that for the nodes which have higher generating rate than their delay sensitivity, the data can be buffered. For instance if a node type generate data every 0.1 sec and its delay sensitivity is 5 sec, the data from plenty nodes can be buffered for 2.5 sec and then can be sent to the CS (including processing, propagation time and so on) at 2.5 sec.

Adaptive islanding, Predictive under frequency load shedding, wide area power oscillation damping control, Wide area power oscillation monitoring and PMU-based state estimation all communication characteristics in WASA domain are the same as each other and can be considered as a certain node type named WASA1. Using the same concept ac described for WASA1, Wide area voltage stability control and cascading failure control both can acts as WASA2. Also FACTS and HVDC control and Pre-calculation transient stability control can acts as one node type as well named WASA3. For all above node types the sums of all same node type data size are rounded to the higher value to have the good margin of the data size. The other node types in WASA part are named WASA4-WASA5 from up to down.

Chapter 4

METHODOLOGY AND SYSTEM MODEL

4.1 METHODOLOGY

To support Smart Grid different node type communication requirements by using different RATs, it is needed to define a method to assign the certain percentage of each SG nodes type to the divers RAT to make a heterogeneous network in an efficient way. Using a Cost Function, CF, which is a function of all SG node types communication requirements and RATs communication characteristics is an appropriate method to evaluate the desirability value of RATs for a certain SG node type. The CF is characterized by some parameters being known as the Key Performance Indicators (KPIs) that are the SG node type communication requirements. The communicational KPIs are data rate, delay, reliability and security which are the main communication requirements parameters of SG node types [20].

The main parts of the CF KPI`s are weight and normalized values. The lower weight values indicate the node type which its corresponding communication requirement is lower or low sensitive, thus it is more desirable.

In order to guarantee a desired Quality of Service (QoS) for SG nodes an appropriate balance of these parameters is required in order to have the desirability value of each RAT with specific communication characteristics that supports the certain SG node type with certain communication requirements.

In other word, by using these desirability values which can be defined by using the CFs values, the certain type of SG node can be assigned to the different RATs based on these desirability values to make an efficient heterogeneous network in which the most matched are achieved between the SG node type communication characteristics and RATs communication requirements. Besides, another different policy can be done for user assigning among the different

RATs. In this policy, it is needed to prioritize the SG node types based on the SG goals. Then by combination of the SG node types prioritization and the achieved CFs, a priority table can be introduced for fulfilling the SG node types requirements efficiently.

In another method Communication CF (CCF) concept is used in combination with energy CF in which the spectral efficiency relation with energy per bit per noise spectral density is defined as the energy CF, ECF. In other word, may the higher spectral efficiency cause to decrease some KPIs in the CCF which results to decrease the CF but on the other hand, the Eb/N0 of the transmitter is increased [157, 162].

By using the CCF in combination of ECF a good, elaborated and efficient method is introduced to make a heterogeneous network for heterogeneous SG nodes in an efficient way in which several tradeoffs are considered and respected. At the first steps these KPIs should be defined and then their weight and the normalized values in a certain communication network should be determined.

Then, an approach is needed to integrate a set of KPIs into a comprehensive formula which determines a single quantitative value (by using a Communication based Cost Function, CCF, that takes these KPIs into account to prepare a single assessment parameter). These KPIs also should be formulated in a precise way. Each KPI has two main elements namely weight and normalized value which should be formulized as well. The proposed model enables the implementation of different RATs to support heterogeneous SG nodes in sense of communication requirements. Besides, by manipulating KPIs according to nodes or RATs perspectives, based on the proper definition of weight and normalized value the SG node types communication requirements are satisfied and in the meanwhile avoiding resource inefficiency usage benefits is achieved.

In fact, the different scenarios can be defined in sense of different SG node types densities. However the Utilities Telecom Council (UTC) has defined such communication requirements based on detailed studies for each Smart Grid application, by considering an average number of nodes and collectors per branch of the network. [72,77,99]. The benefits of using CFs are that SG node types densities and their data generating details such as generating period, data size are included in the introduced model. In this case, by using different method the SG different types of the nodes generated data rate are calculated.

The available RATs and their communication characteristics are investigated to be used in the defined CFs. KPIs elements namely weights and normalized values are defined and formulized. At the next step the CF is defined and formulized as the function of the KPIs value. Then, the desirability values of RATs to support different SG node type communication requirements can be calculated based on the defined formula and node assigning can be done based on the achieved desirability values. Lower value of CF for a RAT supporting the certain node type corresponds to higher desirability of the mentioned RAT and vice-versa.

In the defined method, the RATs that are not eligible to fulfill each type communication requirements of the nodes are excluded from the available RATs. Furthermore, the generated data by the nodes are accumulated to the aggregators and collectors using different short range and medium range RAT such as Wi-Fi or even wired communication method in HAN domain.

4.2 The Algorithms

At the first step, the different SG node types and their communication requirements (the main KPIs) are defined. These main KPIs are mentioned before. Moreover, the SG goals are defined. . Furthermore, the desirability values of the SG node types to fulfill the SG goals are defined as well. Besides, the RATs communication characteristics are cleared. Then the density of the different node types of the SG in under studied area size should be known [53, 135, 153, 157]. After defining the data rate or generated bulk of data size for each type of the SG nodes, the weights for the KPIs are defined.

Then by considering the available RATs and their communication characteristics, the KPIs for the RATs supporting the certain SG node type are calculated based on the proposed method. Figure 4.1 shows the flowchart of the primary model and method of using SG node types prioritization. Further, Figure 4.2 shows the diagram of the CF and its inputs. It shows simply how the CF works. To evaluate reliability in the system, due to the reasons MMPR is used to evaluate it. Alternatively two other different methods [71], fuzzy logic based method, and anther defined formulated solution (which is defined) can be used instead MMPR model.

The novelty and innovative contribution of the work with respect to previous studies can be categorized in three major parts.

First major contribution part includes the definition and elaboration of a CCF in which it measures the desirability value of different RATs to support and fulfill a certain node type of SG communication requirements (it is done for all the different SG node types).

The defined CCF is sensitive to the density of different SG node types (as a function of SG node type density) in which all SG node type communication requirements are defined as the KPIs of the defined CCF. To do this, it is needed to define the KPIs elements namely weight and normalized values for a certain RAT with a certain communication requirements. The weights and normalized values are formulated in an appropriate way to be used in the CCF. Second main contribution part is to define the KPIs as a function on several RATs communication configuration such as goodput, spectral efficiency, overhead size, PLP as a function of RAT base station buffer size, arrival rate and service rate, latency of the mentioned RATs (as a function of transferring payload data time, propagation delay, processing delay and upper layer of protocols which are used in a certain RAT), the elements of a secure RAT (response time, encryption used algorithm and RAT system complexity). In the other side the KPIs also should be defined as a function of SG node type communication requirements and the number of the different SG node type as a function of node type density and area size.

Third major contribution part includes defining a comprehensive CF including both CCF and ECF to define the desirability value of different RATs for a certain SG node type. Then a main formula including all above defined CFs is elaborated and used to assign a certain percentage of a certain SG node types to deferent available RATs in order to make a communication and energy based efficient heterogeneous network to support heterogeneous SG node types. Moreover, in a comprehensive study, the SG different goals are defined and the desirability of each different SG node type to fulfill these goals are studied and elaborated in order to prioritize the different SG node types in senses of fulfilling the SG system goals. This method also is aimed to be used in the situation that we are facing with BW shortage and thus the SG node type with higher priority are served in order of their priority. The other original contribution on this work is given in [211] and [213]. In [211], "Cognitive Radio Based Smart Grid Networks" content and context includes the usage of different type of the cognitive radio methods that are appropriate to be used in different SG different network domains. In [213], the number of required collectors as a function of SMs densities is discussed. Finally, presenting different original figures and contours (sub result part) make significant insights for M2M communication network designer. Here the general description of the flowchart in Figure 4.1 is given. In the first step the SG different node types are defined and prioritized respect to the SG system goals and the SG node types priority table is generated. Moreover, the different SG node type communication requirements are defined.

Then the different RATs and their communication characteristics are given. Also the numbers of different SG node types are given (density of each SG node type and specific area). Its algorithm is extended and is shown as following. This algorithm is combined with the SG node type prioritization. Just as an indicative description, after defining all SG node type communication characteristics and node density and moreover defining all RAT communication characteristics, at first step the CCF value is achieved by using the appropriate formula. Then the CCF of different RAT for a certain node types is achieved. These processes are done for all node types. Then , if just the CCF values are considered, the certain node type assigning percentage to different RAT are achieved using the appropriate formula by using the desirability value of each RAT to support a certain SG node type. The same process are done for the comprehensive CF including both CCF and ECF.

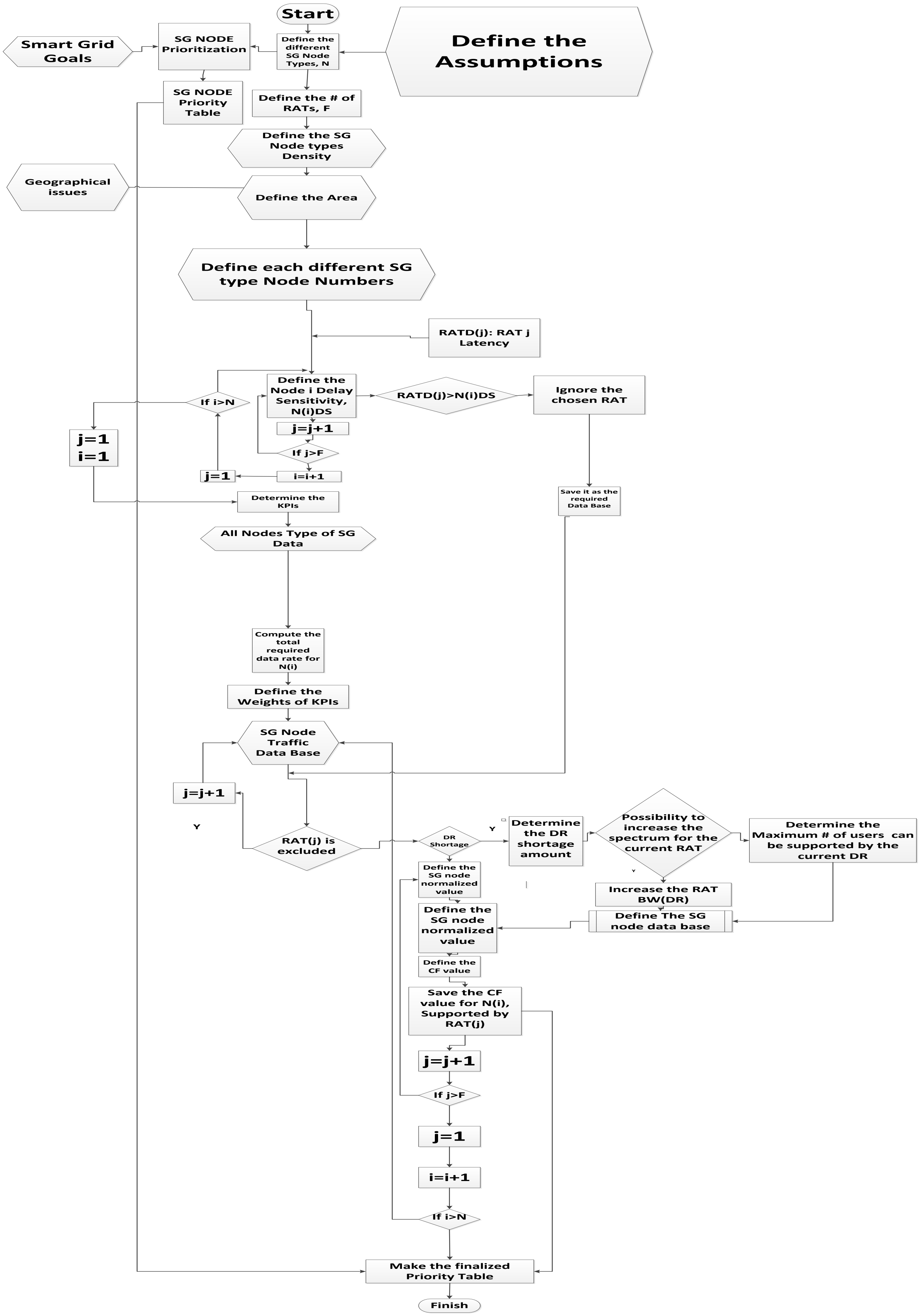


Figure 4- 1 The flowchart of the comprehensive model

SG different node type assigning to different RATs needs CFs to evaluate the desirability value of different ARTs for the certain SG node types. In other word, an optimization method is applied on multi criteria network design problem regarding to both node types communication requirements and RATs communication characteristics and configurations.

The primary goal of this study is to present the different CF based methods to define the desirability values of different RATs for different SG node types based on their fitness degree in sense of communicational aspects such as delay, data rate, coding rate, goodput, processing time, buffering time, buffer size, packet length, size and duration, security issues and several communicational aspects in which increasing or decreasing each of them has the different effect on node assigning policy for different node types to different RATs .

The efficiency of defined optimization algorithm on the design of a network infrastructure would be more significant by including the spectral efficiency and its tradeoffs with energy per information of bits into the comprehensive CFs in which the Eb/N0 effect is considered as well as the other communication criteria. A complementary goal is to also address Quality of Service issues in the design process [20] in a way that maximum fitness between RATs communication and intrinsic characteristics such as latency in satellite communication, and SG different node type communication requirements being established while are the node types communication requirements are respected. Optimization objectives in this case are the node assigning percentage to different RATs based on the criteria which were discussed. Rather than making an efficient heterogeneous network, another CF based method is proposed to prioritize SG different node types based on the SG goals. Using all of these methods in combination with each other makes priority tables which are useful and ubiquitous to be used even in the routers, resource allocation management part, BW shortages management due to disasters, outage controlling and many other usage and applications.

Therefore a multi-objective algorithms and methods are achieved. In the proposed solutions by using the fitness degree between nodes communication requirements and RATs communication characteristics, an efficient node percentage assigning to different RATs is defined in order to avoid non efficient load balancing.

4.3 COST FUNCTION AND KPIs

The SG node communication requirements are defined as Key Performance Indicators (KPIs). There are four main KPIs for SG nodes which are data rate, delay, reliability and security. As different RATs have different communication characteristics, finding the best RATs to fulfill each SG node requirements is the most important step to design a well elaborated communication network for SG. In addition, increasing the number of M2M communication users with different requirements results in spectrum scarcity that is a huge challenge. The defined CFs values are an indication of the desirability of RATs which supporting a certain type of the SG node types (with respect to the SG node types requirements and characteristics of RATs). In the case of not working with the given communication and data rate of the branch of the different SG node types (in which the data rate of all SG node types are given) the first step (of this algorithm) is to obtain the information about density of the SG node types [20] (differs for different node types and each geographical area and area size). Then, the weight of each KPI for different SG node types will be defined. KPIs values are the degree of fulfillment of each SG node requirement using different RATs. Some assumption should be considered to have such kind of algorithm which is discussed in this chapter. Besides, the SG goals defined the different SG nodes and are prioritized based on them. In a different SG node assigning method, by using the SG nodes prioritization and the proposed CF, a priority table is defined in which the nodes and the RATs are put in order. In other words, finding a way to allocate the spectrum as the scarce resources to fulfill all SG node type communication requirements in an efficient way is a significant research challenge. An elaborated method is introduced and investigated to properly choose the best RATs considering their communication characteristics for different SG branch of the node types with different communication requirements while all users type meet their communication necessities in an efficient way in combination with SG node prioritization. This method is explained based on two different types of input data. At first one, the given SG node types values has been defined by the Utilities Telecom Council (UTC). UTC has defined such communication requirements based on detailed studies for each SG application, by considering an average number of nodes and collectors per branch of the network nodes.

At the second one based on the SG node types densities, data generating rate and generated data size, the data rate and traffic rate of the nodes are calculated and the same CF method are applied. Then other comprehensive models get introduced. In this comprehensive method, the SG node types prioritization has not been used directly to assign the different SG node types to different RATs. Instead, CF values are used to define the desirability value of the RATs to support the certain SG node type. This method is explained based on two different types of input data as well (were described above).

In another comprehensive method, the Eb/N0 for each certain RAT is used to define energy CF. Then it got combined with the defined communication CF and a user assigning methods were introduced to assign the different SG node types to different RATs fairly based on two different types of input data as described in this section. Fgure 4-1-1shows the different part of a CF which includes even the marketing part (marketing part is not discussed in this thesis).

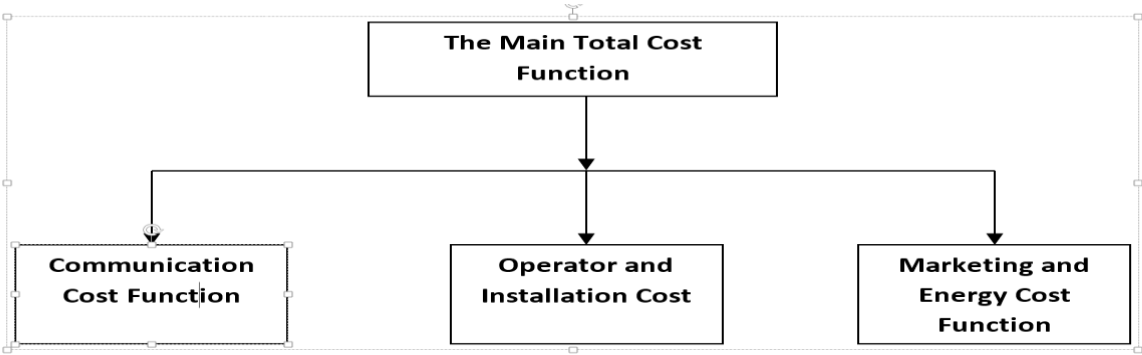


Figure 4-1-1Different part of a CF

The CF that the proposed comprehensive communication CF is achieved based on [11, 77] it is shown in *Eq 4.1*.

$$C_{NT} = \left[\frac{1}{W_o + W_{u_1}}\right] \cdot \left[W_o \frac{1}{\sum_{r=1}^{N_{RAN}} W_{o_r}} \cdot \sum_{r=1}^{N_{RAN}} \left(W_{o_r} \left(\frac{1}{N_{BS_r}} \cdot \sum_{b=1}^{N_{BS_r}} \left(\frac{1}{\sum_{i=1}^{N_{KPI_r}} W_{r.i}} \sum_{i=1}^{N_{KPI_r}} (W_{r.i} \cdot K_{b.i}) \right) \right) \right) + W_{u1} \frac{1}{N_{u1}} \sum_{NBS_r=1}^{NBS_{rt}} \sum_{n1=1}^{N_{u1,NBS_r}} \left(\frac{1}{\sum_{i_1=1}^{N_{KPI_u}} W_{i_1}} \cdot \sum_{i_1=1}^{N_{KPI_u}} \left(W_{i_{1,n1}} \cdot K_{NBS_{r,n1}, i_1} \right) \right) \right]$$

(4.1)

Where: C_{NT} : Total cost function for the system including different nodes Communication infrastructure, W_o : Operators weight, N_{RAN}: Number of radio area technology, $W_{r.i}$: The weight of each KPI, NBS_r among all the base stations, $K_{b.i}$: Normalized value of each KPI $0 \leq K_{b.i} \leq 1$

W_{u_i}: The weight of the i-th Smart Grid Node will be allocated a value based on the application priority

W_{o_r}: Operators weight for each radio area technology, N_{BS_r}: Total number of base stations for a given radio area technology, N_{KPI_r}: Total number of key performance indicators for BS of each given radio area technology (RAT), N_{KPI_u}: Total number of key performance indicators for each given RAT users, NBS_{rt}: Total number of base station of all RANs, $N_{uf_{,NBS_r}}$: The number of users of application f in area which is covered by the base station number , $W_{i_{f,nf}}$: The i_f the weight of N_{KPI_u} numbers of KPIs of the user number nf of total users $N_{uf_{,NBS_r}}$, $K_{NBS_{r,nf}}, i_f$: The i_f th normalized value of N_{KPI_u} numbers of KPIs of the user number nf of total nodes $N_{uf_{,NBS_r}}$.This is the communication part of the CF that comes as following Eq 4.2 if operator CF will be excluded ($W_o = 0$). If a certain node type using just a certain RAT CF being considered, the equation can be written as Eq 4.2.

$$C_{NT} = \left(\frac{1}{\sum_{i_1=1}^{N_{KPI_u}} W_{i_1}} \cdot \sum_{i_1=1}^{N_{KPI_u}} \left(W_{i_{1,n1}} \cdot K_{NBS_{r,n1}, i_1} \right) \right) \quad \text{Eq 4.2}$$

The equation is used in the thesis has been defined as following which is a same format of above CF and just for communication issues 4.3.1. The indexes are changed for simplicity. Eq 4.2 can be rewritten as eq 4.3.1.

$$CF_{ij} = \frac{\sum_{q\in\{KPI\}}\left(W_{qi}\cdot N_{q_{ij}}\right)}{\sum_{q\in\{KPI\}}\left(W_{qi}\right)} i \in \{1, \ldots, N\} \quad j \in \{1, \ldots, F\} \qquad \text{Eq 4.3.1}$$

q : Key Performance Indicators (KPIs) type q ∈ {Data rate, Delay, Reliability, Security}

where N_{KPI_i} corresponds to the number of KPIs node type i taken into consideration, W_{q_i} is the weight of the q-th KPI for the i-th node type, $N_{q_{ij}}$ *is* the normalized value for the q-th KPI regarding the i-th node type and j-th RAT type.

The cost function allows giving a cost to the RATs that supports a certain SG nodes types , where the higher value corresponds to have a higher cost in such allocations. In the following, the cost function is supposed to be based on the main KPIs: data rate, delay, reliability and security. Hence, Eq(4.3.1) is rewritten as4.3.2:

$$CF_{ij} = \frac{\left(W_{R_i}\cdot N_{R_{ij}}\right)+\left(W_{D_{ij}}\cdot N_{D_{ij}}\right)+\left(WRE_i\cdot NRE_{ij}\right)+\left(WSE_i\cdot NSE_{ij}\right)+\cdots+\left(Wq^{N_{KPI_i}}{}_i\cdot Nq^{N_{KPI_i}}{}_{ij}\right)}{\left(W_{R_i}+W_{D_i}+\mathrm{WRE_i}+\mathrm{WSE_i}+\cdots+Wq^{N_{KPI}}u_i\right)} \qquad \text{Eq 4.3.2}$$

where $W_{R_{ij}}$ and $N_{R_{ij}}$, are, respectively, the data rate weight and normalized value between node type i and RAT j, and $W_{D_{ij}}$ and $N_{D_{ij}}$ are the delay weight and normalized value between node type i and RAT type j, respectively. WRE_{ij} and WSE_{ij} are reliability and security weights respectively. NRE_{ij} and NSE_{ij} are the normalized values between node type i and RAT type j, respectively. The overall cost function, considering all the nodes and all the RATs can be written in a matrix form as:

$$CF = \begin{bmatrix} CF_{11} & \cdots & CF_{1j} \\ \vdots & \ddots & \vdots \\ CF_{i1} & \cdots & CF_{ij} \end{bmatrix} \qquad \text{Eq 4.3.3.}$$

Before explaining the CF algorithm, by using a figure, the process of generating CF for each certain RAT , SG node types are explained as it is shown in Figure 4-2. N types of the nodes in SG have been defined. For each certain node types which are supported, the CF value is achieved in case of the certain node type communication requirement got fulfilled by a certain RAT. A_i is a set in which its members is the CF value for a certain Node type i in which $i \in \{1, \ldots, N\}$ $for\ all\ of\ j\ different\ RATs, that\ j \in \{1, \ldots, F\}$. The A_i members are the CF values of different RATs which support node type i. Higher value of CF shows the lower desirability value of the corresponding RAT to support node type i.

The CF values for each node type can be ordered from the lowest one to the highest one which are corresponding to the highest desirability value to the lowest one respectively. It is shown in a figurative way in Figure 4- 1 and Figure 4- 2. Thus there are N sets with F member in each indication on N different SG node types.

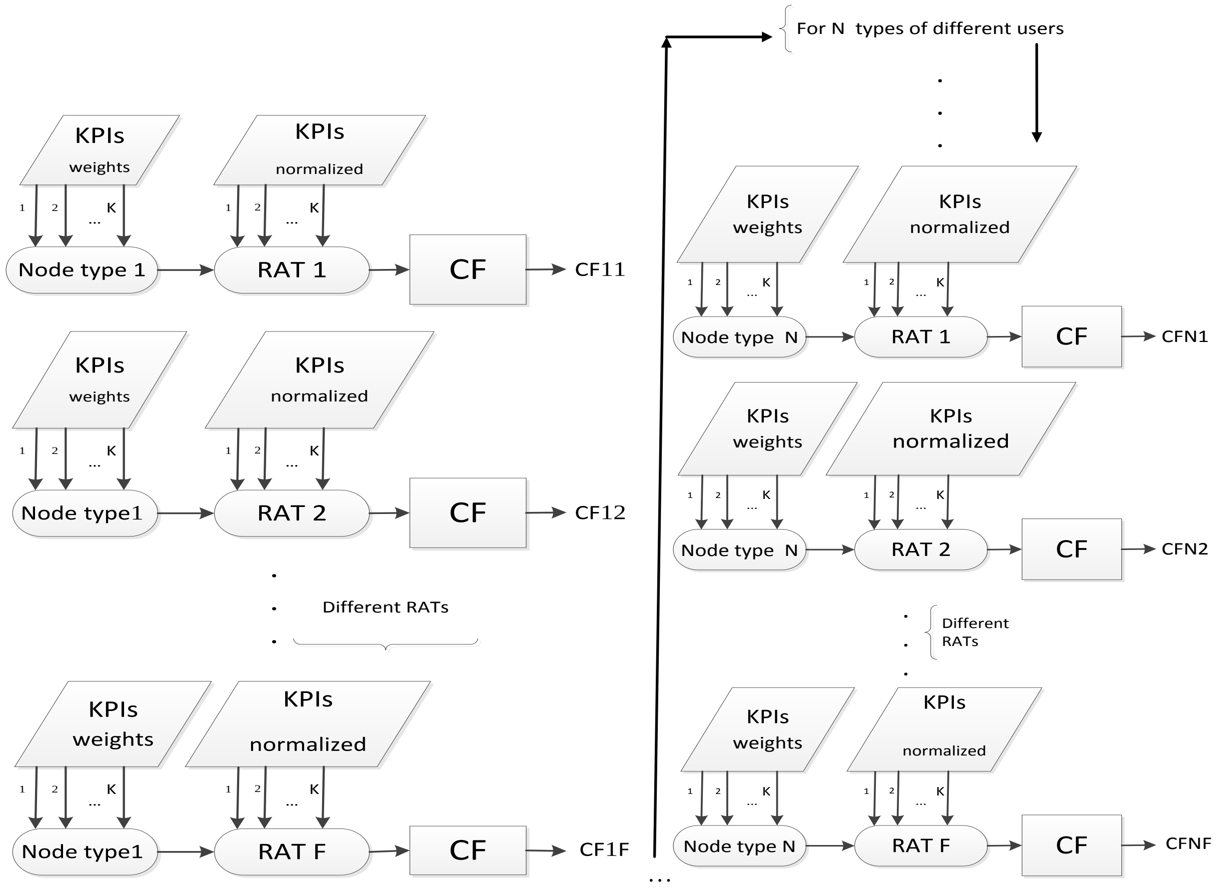
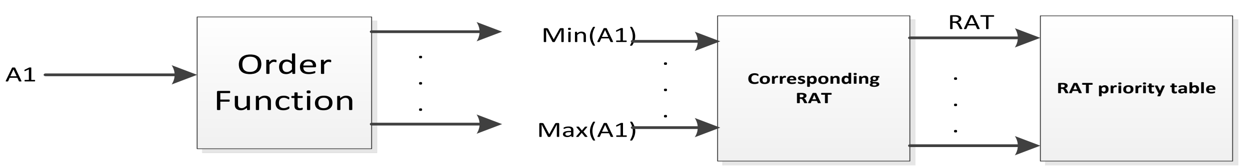
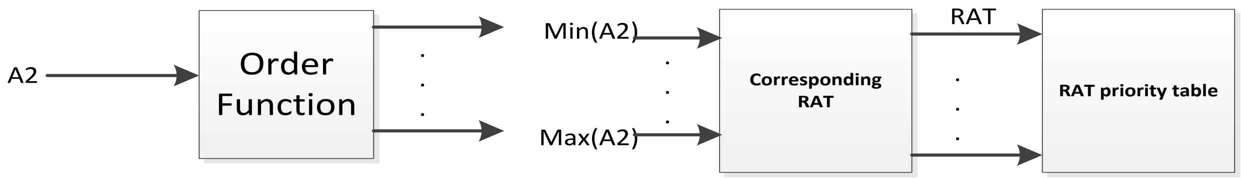


Figure 4-5 Comprehensive Chart for the CF part, K= 4 KPIs)[220]

Order function is used for putting in the order all members of a set from minimum to maximum value. Figure 4-6shows chart inputs functionality. $A_1 = \{CF_{11}, CF_{12}, \ldots, CF_{1F}\}$



$A_2 = \{CF_{21}, CF_{22}, \ldots, CF_{2F}\}$



...

$A_N = \{CF_{N1}, CF_{N2}, \ldots, CF_{NF}\}$

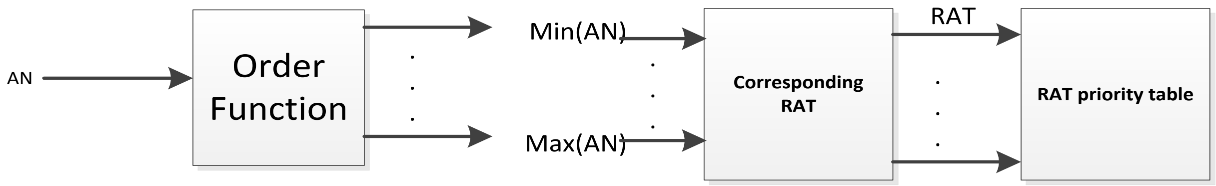


Figure 4-6-1Main chart inputs functionality

A1 is the set which its values are the results of the CF for the node type 1. The lower value in set A1 shows which RATs are more desirable. This process will be done for F different types of the SG node. For each certain node i, the F numbers of RATs have been considered. Table 4-1shows the functionality of priority table without considering SG node types prioritization. It is one step before the priority table in combination with SG node types prioritization is produced.

Table 4-1 One step before completing priority table, ordering function

Node 1	**Node 2**	**...**	**Node N**
RAT_{1r1}~RAT: Min (A_1) ... RAT_{1rF}~ RAT: Max (A_1)	RAT_{2r1}~ RAT: Min (A_2) ... RAT_{2rF}~ RAT: Max (A_2)	...	RAT_{Nr1}~RAT: Min (A_N) ... RAT_{NrF}~RAT: Max (A_N)

Table 4-2shows priority of choosing RAT for each type of SG node types based on CF value which are ordered from Minimum to Maximum.

Table 4-2 Schematic of a primary priority table

	PRIORITY 1	**PRIORITY 2**	**...**	**PRIORITY F**
Node type 1	RAT_{1r1}	RAT_{1r2}	...	RAT_{1rF}
Node type 2	RAT_{2r1}	RAT_{2r2}	...	RAT_{2rF}
...	...	...	...	
Node type N	RAT_{Nr1}	RAT_{Nr2}	..	RAT_{NrF}

In the first column of Table 4-2the SG node types has been prioritized and ordered from first to the N th row in which the most important Node types in the first row and the lowest row shows the node type with lowest important node type. $\mathrm{RAT_{NrF}}$ indicates to the RAT order among all the available RATs who supports the node type N. rF indicates to the RATs order in which $\mathrm{rF} \in \{1, \dots, \mathrm{F}\}$ and RAT with index rF priority order is less than the RAT with index $\mathrm{r(F-1)}$.In other word, may the 5the RAT is the first priority for node type N, thus rF is equal to r1.

4.4 The Methodology Chart

The Communication CF part for a certain node type supporting by the certain RAT diagram is shown in Figure 4.4.2. This is the CF block which is highlighted in red color in Figure.4.4.3.Both of these figures show how Communication Cost Functions (CCFs) values are generated.

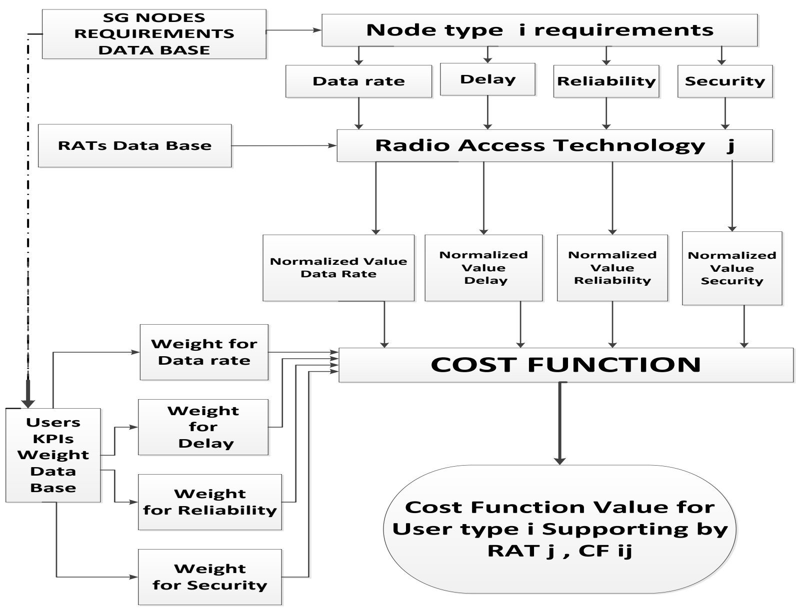


Figure 4.4.2 The Methodology Chart

The Figure.4.4.3 shows both flowchart of generating CF values in combination with SG node types prioritization. How the SG nodes are prioritized based on the SG goals fulfillment degree is shown in this chapter. Again, still in these methods Energy Cost Function, ECF has not been defined which is defined in this chapter as well.

The ECF is evaluated for different RAT s separately. This is done because it does not belong to four major KPIs of the different SG node types. Their result in combination with CCF leads to elaborating efficient heterogeneous network in which any types of subjection can be considered to implement the SG communication network. Figure.4.4.5 shows the general flowchart of comprehensive CF which is a combination of CCF and ECF and will be explained in this chapter in details. Coding rate is used in this method to achieved useful data rate.

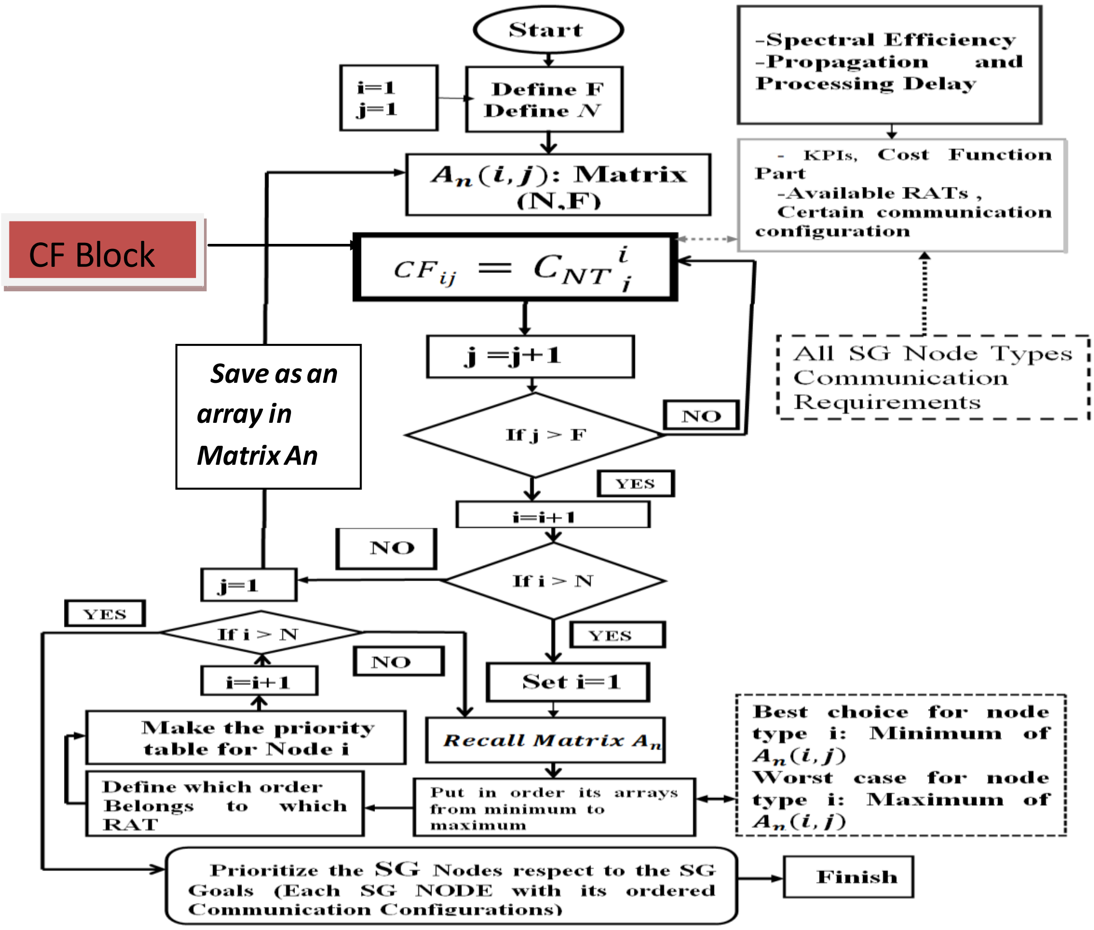


Figure.4.4.3 Introduced Method`s Flowchart

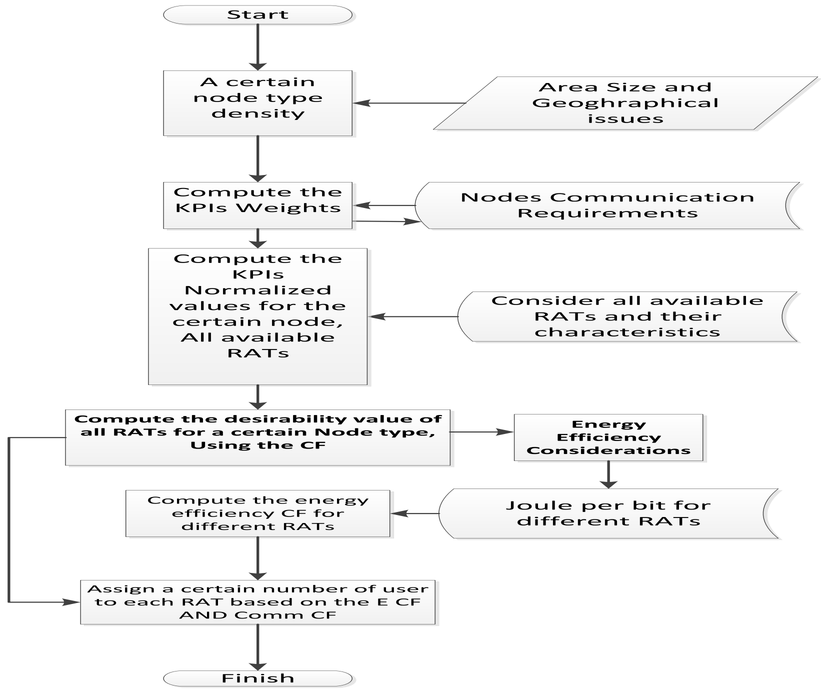


Figure.4.4.5 Introduced Method`s General Flowchart Including ECF

4.5 The Key Performance Indicators (KPIs) Definitions and Formulizations

4.5.1 DATA RATE

Data rate weight in Eq 4.3.2 for each node is defined by equation 4.4:

$$W_{R_{ij}} = \frac{\mathrm{R_{Ni}}}{\mathrm{M}} \qquad (4.4)$$

where R_{Ni} is the data rate required by the *i*-th node type, and

$$M = \max_{i}\{\mathrm{R_{Ni}}\}$$

The desirability of RATs that support a certain type of SG nodes can be assessed by their CF value, where the lowest CF value has the highest priority. Consequently, the nodes with the lowest data rate have the lowest weight although data rate weight can be chosen as the fixed values and it depends on designer point of view[215, 155], however due to the discussed reason it is defined as equation (4.4). As it can be seen from equation 4.5, the nodes with lower data rate have lower weight. Data rate Normalized value for node i in Network j is defined by equation 4.5.1:

$$N_{DR_{ij}} = \frac{\mathrm{R_{Ni}}}{DR^{g}_{(j)}} \quad (4.5.1) \text{ that } DR^{g}_{(j)} = \prod_{s=1}^{S}(1 - Co_s) \times BW_j \times CDR_j \times \eta_j \, (4.5.2)$$

where $DR^{g}_{(j)}$ is the proportional useful data rate, Goodput, for certain amount of BW, BW_j, η_j is spectral efficiency as a function of modulation scheme. Co_s is the coefficients for different variables related to the headers which are added to the packets(Capacity reduction coefficient due to overhead ;pilot, signaling, etc.). CDR_j is coding rate of used in RAT j. In 4.5.2 , $CDR_j = \frac{k_j}{n_j}$ 4.5.3 [39] in which n_j is the total bits in a packet or frame and k_j is the useful data in bits.

$n_j - k_j$= the redundant bits which are used for different purposes such as forward error coding for error detection and correction. Equation (4.5.1) can be rewritten as:

$$N_{DR_{ij}} = \frac{\mathrm{R_{Ni}}}{\prod_{s=1}^{S}(1-Co_s)\times BW_j \times CDR_j \times \eta_j} \qquad (4.5.4)$$

Although without considering goodput , still the model works properly, but bringing the channel coding and coding rate to account , the different upper layers protocol issues are considered at the introduced model and makes it more efficient and more comprehensive. Worst case scenario with highest CF is achieved when all N certain node types assigned to a RAT [216]. In this case, lowest % assigning to the best RAT (results considering the highest CCF), indicates that for lower node number assigning.

4.5.2 LATENCY AND DELAY

Latency of a RAT transferring an amount of data denote to the end to end delay to send the generated data to the CS including the processing time. It includes round-trip time including propagation delay, payload time specifically, the time for the packets data to reach its destination, buffering time, and the processing time at CS. The total delay can be achieved by sum of dividing payload to the data rate, the propagation delay and processing time delay. It should be mentioned in general Round Trip Time, RTT is included propagation and processing time as well. Thus the delay can be achieved by (4.6).

$$Dtot_{ij} = Buf_{ij} + prop_j + proc_j \qquad (4.6)\ [216]$$

in which: $Dtot_{ij} = Total\ Delay$, $Buf_{ij} = \frac{payload}{DR^{g}_{(j)}}$,

$prop_j = propagation\ delay$, $\mathrm{proc_j} = \text{processing time delay}$. As it was discussed earlier to have a well-defined weight and normalized value for delay, the weights should be defined in a way, in which the nodes that can tolerate higher delay got considered favorable and result in lower weight. As the same concept, for defining the normalized value among the all feasible RATs, that can support a certain type of the node, the RAT whose latency value is closer to delay sensitivity of the mentioned SG node is favorable and should have lower normalized value which results in having lower CF. Delay weight for node i is defined by equation 4.7:

$$W_{D_i} = 1 - \frac{D_i}{D^{max}+\epsilon} \qquad (4.7)$$

In which D_i is the delay sensitivity requirement for node type i and

$$D^{max} = \max_i\{\mathrm{D_i}\}$$

is the and ε is a very small arbitrarily value (close to 0) which avoids W_{D_i} to be equal to 0. As mentioned before, the lower weight or normalized value results in lowering CF value that signifies better SG node types communication requirements and RATs communication characteristics fitting. So as it can be seen from equation 4.8, the node with higher difference between the delay requirements and delay of allocated RAT, have higher weight. It should be mentioned that, the RATs with latency higher than the maximum delay sensitivity of a certain node are omitted and not be considered to support that node since it cannot fulfill the latency requirement of that node. Latency Normalized value for node i in RAT j is defined by equation 4.8:

$$N_{delay_{ij}} = 1 - \frac{D_{ij}}{D_i+\epsilon} \quad in\ which \quad D_{ij} = Buf_{ij} + \alpha_{ij}.(proc_j + prop_j)$$

$$\alpha_{ij} = \min_j\{\frac{D_i}{Dtot_{ij}}\} \quad [216]\ (4.8)$$

D_{ij} is network latency with highlighted effect of processing and propagation delay.

$$proco_{ij} = \frac{D_i}{(Buf_{ij}+proc_j+prop_j)} \qquad (4.9)$$

The α_{ij} is The coefficient that can be assigned by designer to emphasize/deemphasize propagation delay effect especially when the satellite communication is considered as the communication network. In other word, deliberately the sum of propagation and processing time is multiplied by α_{ij} times to consider the non-ideal case of data delivery. So, the effect of propagation delay on CF respect to the node type delay sensitivity will be impacted in a way that the RAT with high intrinsic delay like satellite communication (i.e., GEO) yield to lower the CF value for the nodes with lower delay sensitivity requirements. Moreover, it should be notified that using Stop and Wait ARQ (SAW ARQ) strategy also is applicable to the introduced models in which different RATs with different communication characteristics are used. It could be useful when a certain protocol is used (Acknowledgment message issue). It is shown in the equations (4.9.1) and (4.9.2).

$$S_j = \frac{1}{T_j} \times \frac{k_j}{n_j} = \left[\frac{(1-P_{bj})^{n_j}}{\left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right)} \right] \times (\frac{k_j}{n_j}) \qquad (4.9.1)\ [119\text{-}131]$$

$$T_j = \left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right) \times P_{ackj} + 2 \times \left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right) \times P_{ackj} \times (1-P_{ackj}) + 3 \times \left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right) \times P_{ackj} \times (1-P_{ackj})^2 + \cdots + \propto_j \times \left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right) \times P_{ackj} \times (1-P_{ackj})^{\propto_j} = \frac{\left(1+\frac{D_j^{RTT} \times R_{bj}}{n_j}\right)}{(1-P_{bj})^{n_j}} \qquad (4.9.2)\ [131]$$

In which: S_j: Throughput, T_j Average transmission time in terms of block duration, n_j: Number of bits in a block, k_j: Number of information bits in a block, D_j^{RTT}: Round trip latency, R_{bj}: bit rate, P_{bj}: BER probability of the channel, P_{ackj}: $(1-P_{bj})^{n_j}$. At the end of this part it should be mentioned that the delay due to any reasons can be used in the delay KPI formula to achieve the CF value for a certain RAT. The proposed method has the ability to be used in the routers to choose the most efficient path to the last mile node or CS [216].

4.5.3 RELIABILITY

Reliability evaluation in a RAT is not easy to be defined. There are lots of issues and parameters which should be evaluated in the different fields in order to evaluate RAT reliability [20]. The reliability in a network is often defined in terms of network availability in an end to end connectivity that is a function of PLP , latency and system status changing. Reliability primary weight for each node type is defined by equation 4.10:

$$W_{RE_i} = \frac{\mathrm{WRE_i}}{M_{REL}+\epsilon n} \ (4.10)$$

Where i is the i-th types of the SG nodes and $\mathrm{WRE_i}$ is the minimum reliability value for nodes i.

$$M_{REL} = \max_{i}\{\mathrm{WRE_i}\}$$

ϵn is the value that designer using to avoid WREn_{i} to be equal to 1..The SG node type reliability weights, WRE_{i} are defined in relationship with different SG node type required reliability percentage, $\mathrm{WRE_{Ni}}$; by using 4.10 as it is mentioned in Table 4- 1. The required reliability of different SG node types is categorized from high to fairly medium and a numerical value is allocated to each one based on the qualitative definition. These values are allocated as the weights to the SG reliability requirement values. Due to very close percentage as the requested reliability by different SG nodes, after defining the weight (non-normalized values) by using (4.10 as the values are so close to each other, the finalized reliability weight is defined in a way that the defined issue would be solved . Thus regarding to their decimal places (reliability percentage) a value is allocated to reliability weights show the accuracy. It should be emphasized that the node with lower reliability percentage are more favorable and thus their weight value should be lower. Let say Node A requirement for reliability is 99.9% and node B requirement for reliability is 99.99%. Therefore it can be said node A is 10 times lower reliability sensitive than node B. Thus lower weight should be allocated to the Node A (Table 4-1 , (4.10)).

Table 4- 2 KPIs Weight for Reliability

WR i% **WREn_{i}**	***High,*** **1-0.99999**	***Fairly high,*** **0.99999-0.9999**	***Medium*** **0.9999-0.999**	***Fairly medium*** **0.999-0.99**
$\boldsymbol{WRE_{i}}$	1-0.8	0.6-0.8	0.4-0.6	0.2-0.4

Therefore, as it can be seen from equation 4.10 and Table 4- 3 , the nodes with lower reliability value have lower weight. The RATs that provide higher reliability are more desirable thus; their normalized value should be lower if the RAT reliability is better. Reliability Normalized value for node i in RAT j can be defined in three different ways: 1) Using Mismatch Probability (MMPR) concept, 2) Using Fuzzy Logic Method and 3) By using numerical based on the defined formula. These three methods can measure the reliability of a communication network system. The first method is introduced by Rasmus Olsen at Aalborg University and it is based on all the QoS factors for the node and reliability of a certain RAT can be defined for a certain node types by using both node communication requirements and RAT communication characteristics. This tool is so sufficient for addressing all reliability issues. Alternatively the method in [71] can be used instead MMPR model.

- ***Mismatch Probability (MMPR)***

Context-awareness is a key requirement in many of today's networks, services and applications. Context Management systems are in this respect used to provide access to distributed, dynamic context information. The reliability of remotely accessed dynamic context information is challenged by network delay, packet drop probability, information dynamics and the access strategies taken [98, 99]. QoS sorting and system configuration of context management traffic is in this aspect important in order to efficiently balance generated access traffic between network delay, packet loss probability, information dynamics and reliability requirements to the information from the applications [98,99]. Besides, the measurement tools to measure the reliability of a RAT for a node type with its own communication requirements is a challenge. Thus a QoS Control network concept for context management systems is needed in this case. The concept includes a soft real time algorithm for model based context access configuration and QoS class assignment that allows to set probabilistic bounds on the information reliability which is so-called mismatch probability, MMPR [98, 99]. The ability of the RATs to adapt to the communicating nodes requirements is often referred to as context awareness, and is becoming a key factor for nodes to be able to efficiently interact with applications and platforms in a highly dynamic world [98, 99]. The reliability of the accessed information is the key to the success of any context aware applications, since application adaptation should respond to current events and not earlier ones. The node generating period is considered as the status changing in the system. The delay sensitivity of the node is considered as the acceptable delay to be used in MMPR formula. The MMPR value analyzing depends on the system characteristics and properties. For example, if a node`s data generating period is short and its delay sensitivity is higher than its generating time period, the MMPR will be high but, still it is acceptable. It depends to such type of the factors. The delay sensitivity of the node is considered as the minimum acceptable delay to be used in MMPR formula and indicating that if MMPR is higher than this threshold value, the RAT for the mentioned node type is not reliable. As it is described in the system model, the MMPR value depends on the system characteristics. In Figure 4-5 , T_S line in the sender part (left side line) indicated on the node time status in sender side and T_r line (right side line) indicates the CS status on the received data. Considering five different generating data period, B, C, D, E, F. The data size is $N\ bits$ in which the first data block is generated at time A.

It receives to the receiver at time A' and the processing time is finished at time E' and the response is sent to the Node at time E (The signal which is sent to CS is marked with q number of stars and its corresponding response signal arrow is marked with q number of black filled circles). Now consider five different scenarios in each a certain generating data period of time among B, C, D, E and F is chosen. If the next data block is generated at time B, it means that before receiving the first block of data which was sent to the CS at time A, the status of the system is updated. If the next data block (after time A) is generated at time C, it means exactly at receiving the first block of data which was sent to the CS at time A, the status of the system is updated. If the next data block (after time A) is generated at time D, it means exactly after processing the received the first block of data which was sent to the CS at time A, the status of the system is updated and this discussion can be discussed for the other different times. This is exactly the situation that can be seen in different node types information updating status in SG (It is discussed in the synchronization part in detail). The important point is that for some node types in SG generating rate period is too short and delay sensitivity is too low. Although in this case the MMPR is very high, but as the nodes can be served at their delay sensitivity time, the mentioned RAT is reliable.

In some node types the delay requirements is much lower than data generating period time. In this case there is no buffering time (very small) in the node side needed and channel data rate should be high to fulfill the delay requirements of the node (by considering the other delay causes such as propagation time). In this case MMPR value is very low (lower node status changing in the delay sensitivity time of the node).

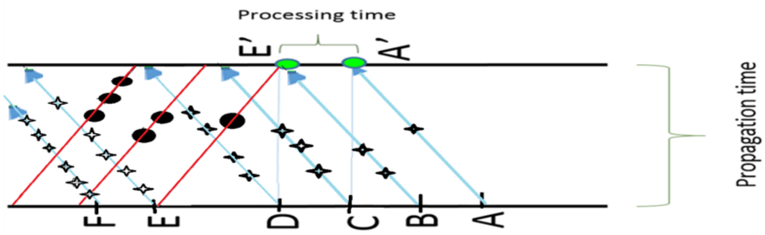


Figure 4- 5 MMPR descriptions

The mismatch probability is reliant on not only on the two stochastic processes, network delay and information change process, but also on the strategy by which the information is accessed. The reliability value of a certain type of the nodes with a specific communication requirements (when got supported by different RATs which have different communication characteristics) can be achieved by the Formula 4.11. The node generating period, Λ_i, is considered as a variation of the system. The delay sensitivity of the node is considered as a sufficient value for the target MMPR and RAT latency is $Dtot_{ij}$. MMPR has another variable, Ploss_{ij}, Packet loss probability, in literature usually considered equal to.01 [216, 218]. Hence, the MMPR between the SG node type i and the RAT j can be defined as:

$$\mathrm{MMPR}_{ij} = 1-\left(1-\mathrm{Ploss}_{ij}\right)^2 \times \left(\frac{v_{ij}}{\Lambda_i+v_{ij}}\right)(4.11.1)$$

where: $v_{ij} = \frac{1}{Dtot_{ij}}$.

It should be notified by using the minimum delay that the node can tolerate in the MMPR formula; the MMPR value is the minimum reference value for respecting the minimum reliability which the certain node needs while supported by a certain RAT. Thus if a link with higher data rate is used, then Ploss_{ij} can be manipulated into higher values since the minimum MMPR is respected. It is useful to set the buffer size and service rate at the CS based on the minimum required MMPR as packet loss probability is a function of buffer size and service rate. Table 4.4 shows a summary the

SG node types requirements, where the values have been defined by the Utilities Telecom Council (UTC); Table [2]. UTC has defined such communication requirements based on the specific studies for each SG node type, by considering an average number of nodes per branch of the network users ($\lambda_i$is the arrival rate to the CS)[2].

$$\mathrm{MMPR_{ij}} = 1-\left(1-\frac{((1-\frac{\lambda_i}{\mu_j})\times(\frac{\lambda_i}{\mu_j})^{K_j})}{(1-(\frac{\lambda_i}{\mu_j})^{K_j+1})}\right)^2 \times\left(\frac{\frac{1}{Buf_{ij}+prop_j+proc_j}}{\Lambda_i+\frac{1}{Buf_{ij}+prop_{ij}+proc_{ij}}}\right) \quad (4.12)$$

Table.4.4 Communication requirements of the SG nodes [2,219,221]

	AMI	*WASA*	*DERS*	*PHEV*	*DGM*
Selected Delay [s]	2	0.05	1	5	0.5
Data Generating Period [s]	900	0.1	14400	12000	1

$$NMAX_{ij} = \max_j\{\mathrm{MMPR_{ij}}\} \ (4.13)$$

$$N_{RE_{ij}} = \frac{\mathrm{MMPR_{ij}}}{NMAX_{ij}+\epsilon n} \qquad (4.14).$$

As it was mentioned, $\chi_{ij}^{mmPr} = \min\{\mathrm{MMPR_{ij}}\}\,\forall\, \mathrm{v_{ij}} = \frac{1}{D_i}$ and $\mathrm{Ploss_{ij}} =$ minimum PLP acceptable for node type i By having χ_{ij}^{mmPr} buffer size and link efficiency, $\frac{\lambda_i}{\mu_j}$, can be a part of network design [221].Normalized value for reliability achieved from (4.14). Also reliability can be evaluated using alternatively:

$$NRE_{\mathrm{ij}}^{\mathrm{alt}} = \frac{\alpha_{rp}\times \mathrm{Ploss_{ij}}+\alpha_{rd}\times\frac{D_{ij}}{D_i+\epsilon}}{(\alpha_{rp}+\alpha_{rd})} \ (4.14\text{-A}).$$

α_{rp} *and* α_{rd} are PLP and latency weights. If the MMPR is not be used to evaluate the normalized value then it can be evaluate using (4.14-A), $\mathrm{NRE_{ij}^{alt}} = \mathrm{NRE_{ij}}$.

4.5.4 SECURITY

Security in a network and assessing it is not a straightforward issue an as the best of our knowledge there is no work to evaluate it for a certain type of the RATs [20]. As it can be seen in the literature studies, for a certain SG node type security requirements there is no numeric value but instead the qualitative values of required security have been mentioned for each different type of SG node type. Its non-numerical inception value can be mapped in the shape of numerical value to be evaluated. It is done as following (Depending to the designer).

The SG nodes security requirements exist in the literature and are evaluated by these terms: high very high and medium.

The reliability weight numeric values proportional to the quality scale of security are given as follows (the same approach as fuzzy logic concept).

$$\boldsymbol{WSE_i} := \begin{cases} 1 \quad \text{if} & \text{Node i security requirement is High} \\ 0.8 \text{ if} & \text{Node i security requirement is Slightly High} \\ 0.6 \text{ if} & \text{Node i security requirement is Medium} \\ 0.4 \text{ if} & \text{Node i security requirement is Low} \\ 0.2 \text{ if} & \text{Node i security requirement is Very Low [216]} \end{cases}$$

Security in network communications is a term which is counted in the concept to the data communication technology where support stronger verification, encryption , hacker`s attack avoidance, attack surface minimization, the time and exertion required to compromise the network increasing and the time and action necessary to response to compromise the network falling [100,101,102]. The security issues should be considered in different zones in SG like enterprise zone, transmission zone, distribution zone and inter connected zone. Respect to the SG entity location and its importance, their weight have been already defined. To define the normalized value for each different type of the nodes in SG which is supported by different communication technologies, some RATs characteristics should be considered [216].The 3main security elements in a RAT which should be notified are the response time, RST, encryption policy, ENP, and complexity of communication technologies and their standards and protocols, COMC [216]. In the Table. 4-7, the values of satisfaction of each security criterion for a certain RATs are shown [102, 103,104, 105, 106, 107 and108].

Table 4- 5 Satisfaction of each security criterion for a certain RATs [216]

	RST	***ENP***	***COMC***
LTE	Very low	High	Very High
GSM	Low	Fairly high	Fairly High
SAT, LEO	Fairly high	Fairly high	Very High
SAT, MEO	High	Fairly high	High
SAT, GEO	Very High	Fairly high	Fairly High

Encryption is the procedure in which the data get twisted in a way that just the planned receiver could decrypt the message to get its information. Encryption makes a way for securing information and data. As more data is stored on computers or communicated via computers, the necessity to be sure that this information is safe to snooping and altering becomes more relevant. With the fast progression of digital data exchange in electronic way, Data Security is becoming much more important in data storage and transmission. Information Privacy has a prominent importance in the study of ethics, law and most recently in Information Systems [103,109,110,111,112]. With the evolution of human intellect, the art of cryptography has become more complex to make information more secure. Arrays of Encryption systems are being deployed in the world of Information Systems by various organizations.

The encryption, delay and complexity assessment for different RATs based on the literature studies are shown in Table 4- 6. To evaluate the normalized value of each RAT it is needed to find out the main security issues in each RAT. Based on the ENP mode in a certain RAT, the complexity of the RAT, using symmetric and asymmetric cryptography model [216, 148], the value can be given to each parameter. The weights of ENP based on these algorithms are given, $encal_j$. r_{ep_j} indicates the number of using consecutive encryption algorithms. ENP_j is defined using formula (*4.15-1.a*),

$$ENP_j = encal_j^{\left(\frac{1}{r_{ep_j}}\right)} \quad (4.15\text{-}1.a)$$

As it can be seen by increasing the number of consecutive encryption algorithms, ENP_j, decreases significantly that indicates to increasing the security level in the system and its default value is 1.

Table.4.6.1 Various Encryption Algorithms

	RSA	DES	3DES	AES
Speed weight	Slowest	Slow	Very slow	Fast
SECURITY weight: $encal_j$	4-5 Least Secure	3-4 Not Secure Enough	2-3 Adequate Security	1-2 Excellent Security

Encryption is the procedure of scrambling a message in a way which only the intended recipient can read it. Encryption can provide a means of secure information. As more and more data is buffered or communicated via RATs, the necessity to insure that this information is untouchable to snooping or tampering becomes more significant. Information Security is becoming much more important in data storage and transmission and is considered as a communication KPIs. The skill of cryptography has become more complex in order to make information more secure. Various Encryption Algorithms details are given at Tab.4.6.1 [116,117, 119-131].

Table.4.6.2 RST Normalized Value

Very low	*Low*	*Fairly high*	*High*	*Very High*
~1	~2	~3	~4	~5

Table.4.6.3 ENP and COMP Normalized Value

Very low	*Low*	*Fairly high*	*High*	*Very High*
~5	~4	~3	~2	~1

$\mathbf{NSE_j}$,security non-normalized value for RAT j is:

$$\mathrm{NSE_j} = \frac{(\propto_{\mathrm{EN}}.\mathrm{ENP_j}+\propto_{\mathrm{COM}}.\mathrm{COMC_j}+\propto_{\mathrm{RST}}.\mathrm{RST_j})}{\sum_{\mathrm{SEC}=1}^{3}\propto_{\mathrm{SEC}}} \quad (4.15\text{-}1.b)[216]$$

$\propto_{\mathrm{SEC}}$ is the weight of each security KPIs $\propto_{\mathrm{EN}}, \propto_{\mathrm{COM}}$ and $\propto_{\mathrm{RST}}$ are encryption, complexity and response time weight)and then by making a set, **SEC** using (4.15-1.b), then the normalized value for security is acheived from (8) and is shown in Tab.8. ($0<\propto_{\mathrm{SEC}}<1$)

SEC= $\{\mathrm{NSE_1}, \mathrm{NSE_2}, \dots, \mathrm{NSE_j}\}$,

$$\boldsymbol{Nsec_{max}} = \max_j\{\mathrm{NSE_j}\}$$

$$N_{SE_j} = \frac{NSE_j}{Nsec_{max}} \quad (4.15\text{-}2)$$

Then to a maximum value that is 1 for LTE, the lowest number should be assigned as the normalized value. An approximation is used.

$$\mathrm{NSE_j} = \frac{\left(\propto_{\mathrm{EN}} \times \frac{encal_j}{max_{\,encal_j}}^{\left(\frac{1}{rep_j}\right)} + \propto_{\mathrm{COM}}.\mathrm{COMC_j} + \propto_{\mathrm{RST}}.\mathrm{RST_j}\right)}{\sum_{\mathrm{SEC}=1}^{3}\propto_{\mathrm{SEC}}} \quad (4.16)$$

4.6 Synchronization and Data Rate Estimation

There are different nodes in each specific part of the Smart Grid which have different communications and traffic characteristics. As several SG node types generate low size data so based on their delay sensitivity and data generating period, a certain number of them can be organized to generate their data at the certain time period.

The synchronization between the nodes is an efficient solution. Before doing it lets explain the variable and elements are needed to be accounted. If Minimum Transfer Unit , MTU, for a certain RAT using a certain protocol has size MTU_S Bytes (i.e.,. LTE MTU is a Resource Block, RB) and its duration (frame duration) is t_p and the number of the transfer units in 1 second equals to N_{mtu} , therefore in 1 seconds , DR_{syn} Bps can be transferred which is obtained from the following formula 4.16: Figure 4- shows physical format of frame and RBs configuration in LTE , 1.4 MHz BW.$DR_{syn} = MTU_S \times N_{mtu} \times 8$ Bps (4.16) .

RB6	**RB6**	**RB6**	**RB6**	**...**	**RB6**
RB5	**RB5**	**RB5**	**RB5**	**...**	**RB5**
RB4	**RB4**	**RB4**	**RB4**	**...**	**RB4**
RB3	**RB3**	**RB3**	**RB3**	**...**	**RB3**
RB2	**RB2**	**RB2**	**RB2**	**...**	**RB2**
RB1	**RB1**	**RB1**	**RB1**	**...**	**RB1**

0.5 ms   1000 ms= 100 frame each 10 msec

Figure 4- 6 RBs configuration in LTE, 1.4 MHz BW

If a certain nodes generate Bps_{Ni} bits every D_i^g seconds and $proc_j$ is Processing delay , $prop_j$ is Propagation delay D_i: Delay sensitivity regardless of considering propagation and processing delay,

$$D_{sen} = D_s - \left(proc_j + prop_j \right) \quad (4.17)$$

in which D_{sen} is delay sensitivity of the node by considering the propagation and processing time delay, then: ,

$$D_{min} = \text{Minimum}\left\{ D_i^g, D_{sen} \right\}$$

$$N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \quad (4.18)$$

in which N_{DR} is Minimum allocated data rate to fulfill a single node communication requirements (4.18).

$$N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times \frac{Num_{Ni}}{N_{sync}} \times \quad (4.19).$$

Minimum allocated data rate to fulfill Num_{Ni} nodes communication Requirements is shown by (4.19). It should be mentioned using the weights and fitness degree by defining the formula is an approach which is going to be developed within the time for complicated system [146,147]. N_{sync} , is the maximum number of the same node that can be syncronized.

$$N_{DR} = \frac{Bps_{Ni} \times Num_{Ni}}{(D_{min})} \times \frac{1}{N_{sync}} \ (4.20) \ \rightarrow \ N_{sync} = \text{Floor}\left(\frac{D_i^g}{D_{sen}}\right) (4.21)$$

in which these number of the same nodes are synchronized and every $\mathfrak{z}$ seconds each diferent node generate its own data and the data are accumulated in an aggregator: $t + \mathfrak{z}$, $t + 2 \times \mathfrak{z}, \ldots, t + N_{sync} \times \mathfrak{z}$ in which: $\mathfrak{z} = D_i^g$. For example if a node generate $Bps_{Ni} = 10000\ \text{bits}$ every $D_i^g = 0.1\ \text{sec}$ and $D_{sen} = 0.1\ \text{sec}$, then $N_{DR} = \frac{10000}{(0.1)} = 100000\ \text{Bps}$ and $\frac{D_i^g}{D_{sen}} = N_{sync}$ is the number of the nodes which can be synchronized to use the whole allocated bandwidth to this specific node. In this example $\frac{0.1}{0.1} = 1$. Now consider if a node generate $Bps_{Ni} = 10000\ \text{bits}$ every $D_i^g = 1\ \text{sec}$ and $D_{sen} = 0.1\ \text{sec}$, then $N_{DR} = \frac{10000}{(0.1)} = 100000\ \text{Bps}$ and $\frac{D_i^g}{D_{sen}} = N_{sync} = \frac{1}{0.1} = 10$ and it means 10 different nodes can be supported by this amount of data rate if each one generates their data 100 msec after the previous data generated by the different node. Also if a node generate $Bps_{Ni} = 10000\ \text{bits}$ every $D_i^g = 0.1\ \text{sec}$ and $D_{sen} = 1\ \text{sec}$, then: $N_{DR} = \frac{10000}{(1)} = 10000\ \text{Bps}$ and $\frac{D_i^g}{D_{sen}} = N_{sync} = \frac{0.1}{1} = 0.10$ and it means 10 different nodes can be supported by this amount of data rate if each one generates their data 100 msec after the previous data generated by the different node. For the SG node types whose delay sensitivity is not high, some strategies and methods can be used to collect the data and deliver them to the control stations.

As some examples, the data which is generated by each user can be buffered at the aggregator and the buffer size depends on the delay sensitivity of the nodes, density of the nodes, the time period that each node generates the data, the synchronization among the nodes, the data size, and the allocated spectrum from a certain type of communication technologies. The data rate should be allocated to support a certain number of a specific node depends to issues already described. There are 3 different states for the different nodes in SG in sense of its delay latency and period of generating data or data rate.

The nodes which their data should be buffered for a certain time before getting sent to the control station are connected to the aggregators through a Wi-Fi communication technology or Ethernet or even through the wired communication technology. The aggregators communicate with the control station directly by using LTE, GSM, and satellite communication. Figure 4- 10 shows the comparison between data rate and different delay sensitivity intuitively. Here a simple example is explained. In PMU part, specific types of the nodes generate 200 Bytes every 0.1 sec. It is assumes it generates 2000 Bytes per sec.

But the latency requirement for this node is Just 0.1 second (including the UL issues, processing and response from CS) . Thus by considering half of this time ($\frac{0.1}{2}$=.05) 0.05 is the latency requirement for this node Thus , instead 2000 Bytes per sec, the allocated spectrum for just one of this node is $\frac{2000}{0.05}$= 40000 Bytes per second. It seems to be efficient that synchronization issue got considered for gathering data from SG node in a specific time period. In case of using synchronization, 200 numbers of this type of the nodes can be supported by this amount of data rate. This is just a simple example to show that how a synchronized group of the nodes, in sense of data generating time, should be done. Figure 4- 3.1 is shown the above description in a figurative way. The important point that should be mentioned is that when generating rate is higher than the delay sensitivity of the node, the data can be buffered. The first received data by a certain node can be buffered at the aggregator for just a defined limited time. Moreover, the figure 4- 4.1 in combination with its categorization gives a figurative way to elaborate the buffer size, synchronization time and the other communication configuration characteristics. $D_g = D_i^g = \Lambda$ in Figure 4- 5.1 for simplicity.

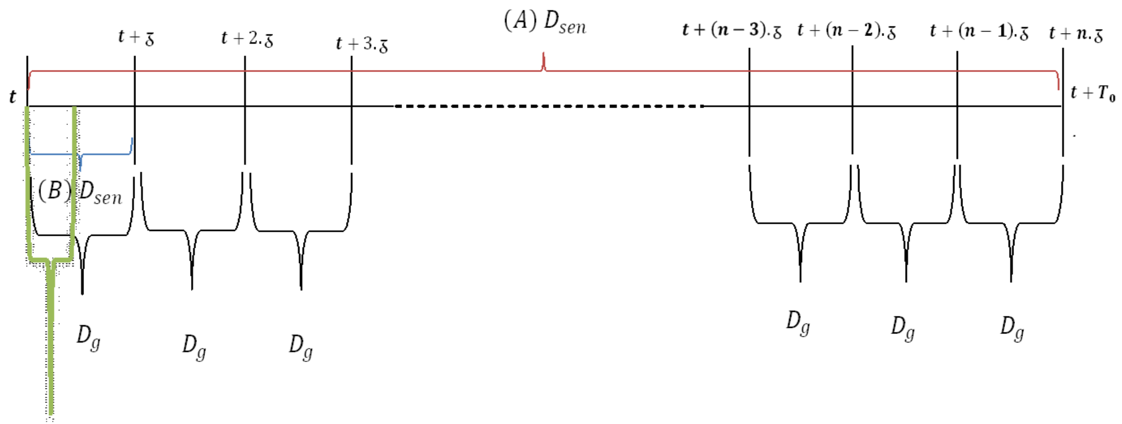


Figure 4-10-1The comparison between data rate and different delay sensitivity intuitively

Above figure are briefly categorized as following [216,218].

A) $D_i^g < D_{sen}$

- ➢ Buffering
  - Maximum time for buffering: $Buf_t = D_{sen}$
    $N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times Num_{Ni}$ (4.22)
  - Regular time for buffering: $D_i^g < Buf_t < D_{sen}$
    $N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times Num_{Ni}$ (4.23)
- ➢ No Buffering: $D_i^g = Buf_t \rightarrow N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times Num_{Ni}$ (4.24)

B) $D_i^g = D_{sen} \rightarrow N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times Num_{Ni}$ (4.25)

C) $D_i^g > D_{sen}$

- ➢ Nodes without synchronization: $N_{DR} = \frac{Bps_{Ni}}{(D_{min})} \times Num_{Ni}$ → Worst case scenario to support Num_N nodes (4.26) (happening probability for the defined distribution is near 0)
- ➢ Nodes with synchronization: $N_{DR} = \frac{Bps_{Ni}}{(D_{min})}$ → to support $Num_{Ni} = N_{sync} = Floor(\frac{D_i^g}{D_{sen}})$ (4.27)

Since these nodes have the ability to tolerate delay, and its delay sensitivity is larger than its generating rate, the algorithm was written in a way that these nodes accumulate (buffer) data and transfer data to CS all together slightly before its real delay sensitivity time. Consider a PHEV node generate 25 Bytes every 14400 seconds and its delay sensitivity is 3 seconds that means the generated data should be sent to the CS in 3 seconds after it is generated. If an LTE RB (1.4 MHz BW) is allocated for this aim the MTU in LTE has 800 bits capacity in each RBs. Allocating 1 frame or time slot in each second to collect the generated data by DERS nodes in case of having 12 different DERS node which are synchronized is done. 12 different synchronized nodes that generate 200 bits (25 Bytes) at the same time and accumulated in a buffer of the collector, then 12×200=2400 bits are buffered and if a RB in each second is allocated to collect the data from aggregator, it takes 3 seconds to send the data to the CS. (The propagation delay is ignored because is very small and can be neglected for a terrestrial RAT like LTE).

In this case by synchronizing 12 DERS nodes and allocation 800 bps data rate to the collector, our nodes communications requirement are fulfilled. In general the number of the same node type that can be synchronized in a time slot, $N_{sync}^{ts_{ij}}$, can be achieved by using Eq.4.27.1 as follows:

$$1 \leq N_{sync}^{ts_{ij}} \leq floor[RBs_{num}^{MHz_j} \times ts_{num}^{j} \times \frac{D_i^{sen}}{D_i^g}] \quad 4.27.1 \; [216,218]$$

While $RBs_{num}^{MHz_j}$ is the number of Resource Blocks or minimum packet unit number that can be allocated to a user in a sub time slots , ts_{num}^{j} is the number of sub time slots thath generates a time slot, D_i^{sen} is the delay sensitivity of node type i, $\lambda_i = D_i^g$ which is data generating time period for node type i.

The data rate can be measured by certain simulation tools. Also the data rate that the certain number of the nodes with same generation characteristics such as generating period and packet size produces can be achieved through several solutions. Considering data rate in average for different node types causes to have the generated average data rate. Synchronizing them is one of these solutions. Also using equations and the achieved formula in [213] knowing the number of the certain nodes and its generating rate information, the required data rate is achievable. As an example, SMs data reporting arrival time in a collector follows a certain distribution, (i.e., Poisson distribution) then if the event reporting time increases by a times, the number of events occurrence in time unit is $\frac{1}{a}$. It is proved in [213].

The collectors collect the data received from certain node types (i.e., SMs) for sending it to CS. The inter arrival rate in the collector follows exponential (Poisson as its especial case) distribution [33, 112]. If it assumes the report generation period follows a Homogeneous Poisson process whose events occurs at a constant rate $\lambda = D_i^g$, (equal to 15 minutes for each SM). To drive the number of events in time interval $[t, t+\tau]$, $N(t)$ is number of events (i.e., SMs data inter arrival in a collector) at time t. $N(t+\tau)$ is the number of events in the interval $(t+\tau)$. Thus, $N(t+\tau) - N(t) = u$, corresponds to the number of events in the interval $[t, t+\tau]$. The mean arrival rate for each SM is supposed to be λ [213]. It should be mentioned that $N(t)$ is a sample of a homogeneous Poisson process (not density or distribution function). The homogeneous Poisson process probability for u events can be derived as [213]:

$$P[u] = \frac{e^{-\lambda \times \tau} \times (\lambda \times \tau)^u}{u!} \qquad (4.27.2)\ [112, 177]$$

It should be mentioned that the inter-arrival time in Poisson follows an exponential distribution [33, 112]. This is how the incoming traffic from those SMs can be determined for a single collector. In consequence, the data generated by a huge number of M2M devices like SMs, are determined and defined by knowing the number of nodes and their traffic generating characteristics [33, 112]. Thus, the data rate of a collector can be determined with the inter arrival rate of each node to a single collector.

It the other word, the relation among node (i.e. SM) number (as a function of SM density and area size) and its data rate should be defined in advance. At the first step, the area size and nodes` density are defined. The model is defined by the aid of both mathematical and experimental results. Thus, experimental results in the literature [6, 33, and 112] are helpful to measure the required collector data rate for a given number of nodes (SMs). Assume there are N_{sm} number of nodes that each generates a certain amount of data, ps bits , every 15 minutes (i.e. SM). It is assumed the size of the packets generated by each SM is constant and equal to 125 Bytes [213]. If a collector, receives the data every τ sec from one node in average, thus:

$$R_{Ni} = \frac{Bps_{Ni} \times \alpha_{cof}}{\tau_i} \ (4.27.3)[112].$$

To increase the reliability of the model, a confidence coefficient equal to α_{cof} is often multiplied to $\frac{Bps_{Ni}}{\tau_i}$ to define a more reliable R_{Ni}, to support the nodes [213]. As an example, for 4000 SMs in AMI, a collector receives data from 200 numbers of SMs (in average) in a second. In other words, $\tau = 0.005$ sec [33, 112]. By assuming $\alpha_{cof} = 2.5$ and using [43, 42, 112 and 141] , 500 kbps is quite good enough to support 4000 SMs [43, 112]. Additionally, since the nodes data reporting arrival time in a collector follows the Poisson distribution then if the event reporting time increases by a times, the number of events occurrence in time unit is $\frac{1}{a}$. It can be proved as following:

$$F_Y(y) = P(Y \le y) = P(a \times X \le y) = P\left(X \le \frac{y}{a}\right) = 1 - e^{-\lambda \times \frac{y}{a}} \quad (4.27.4)\ [5,218,187]$$

$$f_Y(y) = \frac{dF_Y(y)}{dy} = \frac{\lambda}{a}\, e^{-\lambda \times \frac{y}{a}} \quad (4.27.5)\ [5,218,187]$$

where $P(Y \le y)$ is the probability of a Poisson random variable Y [5, 218]. In consequence, a solution is presented to define the certain number of the certain SG node type data traffic in (4.27.6).

$$R_{Ni}\ \text{kbps} = \frac{Bps_{Ni} \times 0.125 \times Num_{Ni} \times (15 \times 60)}{1000 \times D_i^g} \simeq \frac{0.125 \times Bps_{Ni} \times Num_{Ni}}{D_i^g}\ kbps$$

(4.27.6)

As it is known that all the node types do not generate data at the same time, easily the data rate of the defined scenario can be defined. As an example consider, 8000 nodes generate 1500 bits data every 5 minutes, thus based on the (4.27.6) and also having the assumptions same as SMs scenario, these nodes generate 5 Mbps. It is fit with the way which SMs data rate are calculated based of the rational and the defined assumptions. In case of not using the synchronized nodes, this method can be used as a one has been periodically being used in the literature and related works [6, 33, and 112].

4.7 Bit Error Rate (BER) and Packet Error Rate, Buffer Size and Pocket Loss Probability (PLP)

4.7.1 Bit Error Rate (BER) and Packet Error Rate

BER_j is Bit Error Rate in RAT j. If the bulk of data being received in the CS with error , this error may not be fixed through error correction methods (Forward Error Correction, FEC). Using coding is in the cost of decreasing the goodput. The collected data which are sent to the CS can be considered as eq. 4.28 in which Packet Error Rate as PER_{ij} , the collected data which are sent to the CS can be considered as eq.4.28 in that n_{bits} is the packet size [161] .

$$PER_{ij}=1-(1-BER_{ij})^{n_{bits}} \qquad (4.28)$$

$$ND_{ij,PER} = floor(n_{bits} \times (\frac{ND_{ij}}{n_{gp}} + \alpha_{nc}.PER_{ij})) \qquad 4.29\ [216]$$

in which α_{nc} is the percentage of the packets which have not been recovered and should be resent again (it depends to plenty issues which are out of the scope of this work [175, 176]), n_{gp} is goodput (in packet), which ND_{ij} is the data buffered size of a node and n is the number of bits per packet. $ND_{ij,PER}$ in 4.29 is the total data considering data which should be resent. Statically, the same amount of the data will be affected with the same BER. It will be helpful to even consider the defined CF for RATs with different BER.

4.7.2 Buffer Size and Pocket Loss Probability (PLP)

Packet loss probability is a function of receiver buffer size and link utilization or ρ_j.

$$\mathrm{Ploss_{ij}} = \frac{((1-\rho_{ij})\times\rho_{ij}{}^{K_j})}{(1-\rho_{ij}{}^{K_j+1})} = \frac{((1-\frac{\lambda_i}{\mu_j})\times(\frac{\lambda_i}{\mu_j})^{K_j})}{(1-(\frac{\lambda_i}{\mu_j})^{K_j+1})} \quad (4.30\text{-}1)$$

in which all variable of PLP are defined as the function of receiver buffer size, arrival rate and service rate in which $\rho_{ij} = \frac{\lambda_i}{\mu_j}$ that λ_i and μ_j are arrival rate and receiver service rate respectively. Moreover, K_j is the buffer size (Packets or blocks numbers). Moreover in MMPR formula the latency can be alternated by (4.30-2) if just the below information would be available at CS (useful for very low delay sensitive node types).

$$delay_{i'} = \frac{QL_j}{\lambda_i \times (1-\mathrm{Ploss_{ij}})} \quad (4.30\text{-}2)$$

in which QL_j is Que Length and is achieve by using (4.30-3).

$$QL_{ij} = \frac{\rho_{ij}}{1-\rho_{ij}} - \frac{(K_j+1)\times({\rho_{ij}}^{K_j+1})}{(1-{\rho_{ij}}^{K_j+1})} \quad (4.30\text{-}3) \quad , \quad delay_{i'} = \frac{\frac{\frac{\lambda_i}{\mu_j}}{1-\frac{\lambda_i}{\mu_j}} - \frac{(K_j+1)\times((\frac{\lambda_i}{\mu_j})^{K_j+1})}{(1-(\frac{\lambda_i}{\mu_j})^{K_j+1})}}{\lambda_i \times (1-(\frac{((1-\frac{\lambda_i}{\mu_j})\times(\frac{\lambda_i}{\mu_j})^{K_j})}{(1-(\frac{\lambda_i}{\mu_j})^{K_j+1})}))} \quad (4.30\text{-}4)$$ [98, 99]

ρ_{ij} is the service rate.

4.8 Smart Grid Node Prioritization

Smart grid different nodes communicate power grid information to the Control Station. There are many communication technologies with different Quality of Service characteristics that can support the SG Node Communication Requirements. Besides, the spectrum is being a rare source due to its demand exponential increasing.

Thus, the spectrum allocation to support a certain type of the SG nodes should be done in a way that the highest spectrum efficiency be achieved to fulfill the requirements of smart grid requirements.

Defining a cost function helps to accomplish this goal. For this aim also there is needed to prioritize the different nodes in smart grid based on its goals. The mixture of these efforts defines a priority table in which the nodes and RATs are put in order based on their weights to fulfill these aims although; this method is used in one sub methods which are defined in this thesis. As it was discussed, there are 5 main nodes or entities in SG which are connected to the control stations and work on the demand, distribution, and control and generation side of SG. Considering a single SG goal, the desirability of any of the SG nodes to fulfill that aim is different from the other node. Therefore it seems to be reasonable to evaluate the importance of different node, from desirability aspects, in sense of fulfilling SG goals.

The SG nodes prioritization results in developing of controlling process at the SG and resource allocation in an efficient way. Therefore there is needed to define a CF to prioritize the SG nodes. Thus by defining the different type of the nodes in SG and defining the SG goals as the KPIs, the SG node prioritization can be done. CF approach is allocating a numeric value to each RATs in order to assess how much it is effective in satisfying the goals of SG [214,215, 216].

4.8.1 The Prioritization Method

The prioritization of the SG nodes for respecting their requirements allows selecting the most important nodes. The nodes having a higher priority in the SG will may be served earlier.

For a certain type of nodes, giving more importance to a certain KPI depends on how much that node can fulfill that KPI. The different types of nodes functionalities, to respect a certain SG goal, are compared among them in order to respect the intuitive and empirical concept in the literature by using the quantitative values [214,215, 216].

4.8.2 Smart Grid Goals

In the following, a description of different types of services relying on the SGs is done, and a qualitative prioritization is performed. There are major important goals for SG applications [2,13,18]. Green Energy, Disaster Avoidance, Minimize Consumption Cost, Automated Maintenance, Users Cooperation, Outage Avoidance, Security and Reliability are among the most important goals of SG nodes or applications. Each of these goals and its fulfillment value by the different SG users is explained in the followings.

- ***Green energy*** This concept in SG is generally defined as any action , plan and method to decrease the energy consumption , increase energy usage efficiency , decrease using of fossil fuels and try to use the sustainable energy that comes from resources which are naturally renewable such as sunlight, wind, tides, rain, geothermal heat and the other same type of the energy sources .Decreasing the energy consumption depends on many issues. There are lots of users who use the electrical devices such as air condition, heater, and washing machine and so on. In the conventional power grid, the users are not aware of the spot prices especially at the pick hours. Thus if they know the spot prices for electrical power, they decrease their consumption and as its results the demand for energy and as its consequence, energy consumption is decreased. Beside it, the number of users in each SG node type or entities is very important factor. More users energy consumption controlling has more effect of having green energy benefits. Moreover, DGM should lead the distribution industry in the development of advanced applications for distribution system in a way that based on the demands and availability of the electrical recourses and their low air pollution in sense of making greenhouse gas emission the best and efficient power distribution is done. Beside it, renewable energy resources exist over wide geographical areas where any type of sustainable energy resources can be made, in contrast to other energy sources, which are concentrated in limited areas. The deployment of renewable energy is resulting in significant energy efficiency , energy security, climate change mitigation, and economic profit. Thus renewable energy resources are strong support for promoting green energy.

Moreover, being aware of status of electrical power in power lines may help to electrical generation entities to avoid injecting redundant power to the grid and also it helps to detect the faults in the grid which results in having more efficient power usage. The SG different nodes have different effects on satisfying these goals [214,215, 216].

- ***Disaster Avoidance*** Smart grids can also quickly respond to natural failures "Disaster Avoidance" by rerouting around problems or closing down the network totally. They also manage rolling brown outs to keep electricity when demand exceeds production. Therefore, the electrical power status controller and phasor measurement unit have the crucial role in disaster avoidance. Beside it, distribution management entities in SG by balancing the power distribution can be helpful to avoid the brown and black outs. In crucial situations, the users at the demand side are beneficial by receiving the grid status and power price through the CS [214,215, 216].

- ***Minimize Consumption Cost*** The SG platform helps users schedule electrical appliance issues, minimizing variance in power consumption which results in saving money. During electricity peaks demand, generators are inefficient, wasting fuel and increasing expenditures for both electric utilities and the users. Electric companies keep generators on and make them ready to respond to unexpected upswings in electricity consumption. These inefficiencies cost billions of dollars in fuel consumption and oblige electric companies to charge households more at peak consumption hours. SG different nodes types cause to decrease peak power consumption across the power grid by distributing scheduled jobs of the power grid, electrical energy statuses in power lines and affecting the other part of the SG. CS decision maker part determines the usage patterns of SG different nodes type schedules electrical tasks to achieve minimum variance in power consumption.

  It results to have a better performance in terms of user consumption cost, peak power consumption and fuel costs and so on to minimize peak energy consumption and maximize savings for the user and utility company. The most part of the generated electrical power is used by the consumer at buildings and factories. Energy consumption in such buildings represents approximately 74 percent of the nation's electricity consumption.

  As a fact, the demand is not the same in a day different time. Usually by increasing the demand, the price is increased. Therefore, if the users get aware of the real time electrical power price, they avoid using more electrical devices and mostly do not use the high consumption devices during the pick hour. SG demand side nodes have more effects on decreasing the consumption cost comparing with the other SG node types. Controlling the status of the electrical power at the power lines is also useful to decrease wasting the electrical power energy by detecting the fault over the power grid and report their status to the CS to make the best decision in sense of electrical power usage efficiency. The other non-centralized distributed energy resources near to the users can have significant effects to decrease the power losses over the power line come from the centralize generation part . Moreover, their sustainability characters decreases the usage price because of not using fossil fuel or the other non-sustainable and expensive energy resources. Distribution part is helpful to decrease the consumption cost as well. By balancing the injected part at the distribution level, the required power based on the demand is distributed [214,215, 216].

- ***Automated Maintenance*** Automated maintenance system is an intelligence and detective system whose actions are started automatically at regular intervals to perform maintenance operations on the damaged, imperfective and faulty part of the SG. For this aim, SG should monitor all critical components of the power grid to enable automated maintenance and preventing the outages. Therefore, the entities who involve in monitoring and controlling the power line status and distribution part, are more involved for automated maintenance system services. The demand side of the SG like AMI or PHEV or even DERS are not involved to SG automated maintenance same as the other SG nodes types [20,214,215, 216,145].
- ***Users Cooperation*** As this term meaning shows, this goal of SG mostly can be fulfilled by the demand side of the SG. Moreover, the users who can have access directly to the distributed energy resources can fulfill this goal. System status controlling also has indirect effect on user cooperation. Its status makes information as a feedback to the CS and then CS demand response changes based on it. In this case, even distributed grid management may play a role to fulfill user cooperation as one of the goal of SG [20,214,215, 216,145].
- ***Outage Avoidance*** Outage avoidance can be fulfilled by all SG node types. But, electrical power status controlling is a main and important action can be done to avoid outages. Users in the demand side also have a good role to avoid the outages by controlling their consumptions. The other sustainable energy resources can provide more power for the grid to avoid outages as well [216].

- ***Security*** As the technology develops, reliant on the secure electricity supplies, transmission and distribution are increased. The power grid infrastructure can be damaged and destroyed in several different ways. For instance nuclear weapon, a geo-magnetic storm from the sun or even direct physical attacks that generates an Electro-Magnetic Pulse effect is dangerous for power grid security. Also, the cyber-attacks on the electric grid system are increasing in both frequency and sophistication. Moreover, a natural occurrence because of sun regularly is shooting off geo-magnetic storms in every direction may result in a disaster in power grids. For example, in 1859, a massive solar flare that came to be known as telegraph offices the "Carrington Event" struck the earth and generated fires in as well as extraordinary northern lights displays. If such a solar storm strikes the earth today, the damage will be tremendous and societies all over the world would be overwhelmed.

  Utility companies confront security challenges daily. Improved security in devices or grid equipment vendors makes primary steps to build security into the power products and architectures. Doing so will continue to improve the products entering the market and will help products in the market to lock the gap on the vulnerabilities in the power grid. Enhancing the security visibility for controlling power statuses will continue to develop technologies that will enhance the system logging and monitoring functions available to security personnel. Technology also provide improved behavioral analysis to guarantee that only authorized commands and regular reporting flow through the control system networks in a secure manner. It's clear that the power grid will continue to face new and sophisticated threats as technology continues to evolve. Thus, comprehensive security plans including cyber security across the networks and the generation, transmission and distribution systems should be implemented. In consequence, the electrical power status in the power line makes the grid more secure. Beside it, the distribution and demand side of the SG have the good effect on the grid security. The decentralized energy resources have also effect on the power grid. As they are not a vital part of the SG and may there are no sustainable energy resources in some geographical areas, their role on having a secure power grid is not as effective as the situational status controlling entity in SG [20,214,215, 216,145].

- ***Reliability*** A more reliable and resilient grid are the ones with fewer and shorter power interruptions and better prepared to recover from bad events like severe weather, restoration time . Without reliable power grid, the lights brown and black outs happen, electrical transportation stop running and factories shut down. Grid reliability analyzing can be done by using three reliability indicators. The first one is an estimation of energy not supplied to the final customers due to incidents in the transmission power line. The second is the total loss of power and is a measure of generation shortfall. Finally, the restoration time corresponds to the time from the outage or disturbance until the system frequency returns to its nominal stage. The double-risk tendency of being more dependent on electricity and more renewable and sustainable resources is using continuous and increasing stress and pressure on power grids at both transmission and distribution levels and it can be a cause for concerning for all grid operators since it impacts reliability. At the same time the availability and security issues, in particular the growing cyber security threat; capacity issues, as cables and equipment increasingly operate close to their limits; and the growing challenge of keeping voltage and power quality within bandwidth should be addressed. In the face of all of this, maintaining effective protection and control of the power grid is becoming increasingly difficult and, in the future, may be faced with lots of challenges. Beside it, unprecedented power system change is unavoidable. As it can be resulted from this part, the controlling and distribution grid management have the main role in the reliability of the power grid. Increased reliance on electricity and the transition to renewable are trends that improve, not least because of the need to reduce the emissions that accelerate climate change and the associated extreme events. At the same time, electric vehicles sales have grown exponentially, multiple new electricity storage technologies are reaching maturity and there is a global approval that it is needed to shift the existence energy approach to making demand match supply in order to increase energy efficiency. Therefore, the effect of the SG devices in the demand side and also renewable energy resources in the SG power reliability is high, although the controlling and distribution entities in SG role are more notable. It should be mentioned that there is no one tool sufficient for addressing all grid reliability issues but its intuitive concept help us to categorize the role importance of them in SG [214,215, 216].

- ***AMI*** Dealing with smart meters and its network structure, Advanced Metering Infrastructure, AMI, are considered as the backbone of the SG. Their important role on the SG demand side is notable. AMI can be seen as a combination of SMs, communications networks, and data management systems, for facilitating and enabling SMs to have two-way communications with the CS [1,3]. AMI allows the users to cooperate on the power demand and it results to decrease the fuel consumption and manage the power distribution effectively which leads to decrease of greenhouse gases, although distributed energy resources are mostly sustainable and coming from green energy resources and have higher effect on environmental issues, AMI plays a significant rule to fulfill this goal of SG. Green energy concept in SG is generally defined as any action , plan and method to decrease the energy consumption , increase energy usage efficiency , decrease using of fossil fuels and try to use the sustainable energy that comes from resources which are naturally renewable such as sunlight, wind, tides, rain, geothermal heat and the other same type of the energy sources. More users energy consumption controlling has more effect of having green energy benefits. Decreasing the energy consumption depends on many issues. There are lots of users who use the electrical devices such as air condition, heater, and washing machine and so on. In the conventional power grid, the users are not aware of the spot prices especially at the pick hours. The SG platform helps users schedule electrical appliance issues, minimizing variance in power consumption which results in saving money. The big fraction of the generated electrical power is used by the consumer at buildings and factories. Energy consumption in such buildings represents approximately 74 percent of the nation's electricity consumption. As a fact, the demand is not the same in a day different time. Usually by increasing the demand, the price is increased. Therefore, if the users get aware of the real time electrical power price, they avoid using more electrical devices and mostly do not use the high consumption devices during the pick hour. Thus if they know the spot prices for electrical power, they decrease their consumption and as its results the demand for energy and as its consequence, energy consumption is decreased. Besides, the number of users in each SG node type or entities is very important factor. AMI as the demand side part of the SG has a good role on energy sustainability. Since AMI enables the users to benefit from receiving the grid status and power price through the CS. User cooperation goal of SG mostly can be fulfilled by the demand side of the SG [18,45,46,80] . Outage avoidance can be fulfilled by all SG node types. Users in the demand side also have a good role to avoid the outages by controlling their consumptions. Automated maintenance system is an intelligent and detective system whose actions are starts automatically at regular intervals to perform maintenance operations on the damaged, imperfective and faulty part of the SG. The demand side of the SG like AMI is not involved to SG automated maintenance same as the other SG nodes types [214,215, 216].

- ***PHEV*** The Plug in Electrical Vehicle (PHEV) nodes role in smart grid system is respect to emissions and fossil fuel energy dependency reductions since they can manage and provide the information about the electrical device charger for electrical vehicles. Automated maintenance system is an intelligence and detective system whose actions are started automatically at regular intervals to perform maintenance operations on the damaged, imperfective and faulty part of the SG. The demand side of the SG like PHEV is not involved to SG automated maintenance, similar to the other SG nodes types [214, 216].
- ***WASA*** The Wide Area Situational Awareness (WASA) nodes monitor the power system across wide geographic areas. Thus, WASA has the crucial role in SG status and surveillances issues. For making the Smart Grid (SG) largely reliable, WASA related nodes

plays an important role in SG implementation. In conventional power grid, unplanned power outages are mostly infrequent and unpredictable whose distress the small part of the power grid. Furthermore, in some countries utilities have selective blackouts due to power generation are not able to support the demand. However, increasing the power demand over the time, especially at the late twentieth century and beginning of the next century in addition to the other sophisticated problems such as the lack of corresponding increase in the power grid transmission capacity caused plenty of outages which were unorganized. The idea of interconnecting so many utilities of the power grid may seem a good solution. On the negative side, an unwanted and unpleasant event in any utilities, if not be corrected in time, will affect the other grid functionality. Such type of faults affects the power grid efficiency and functionality [2,18,9,63] . Therefore, an elaborated design should be planned to avoid or decrease these unwanted events. Wide Area Situational Awareness is an entity in the smart grid whose functions modify the system drawbacks which were discussed above. Wide Area Situational Awareness the Northeast blackout of 2003 which resulted in a $6 billion economic loss to the region could have been avoided by better communication across system operators. There have been five massive blackouts over the past 40 years, three of which have occurred in the past ten years. Many blackouts and brownouts occur due to the slow response times of mechanical switches, a lack of automated analytics, and poor visibility (lack of situational awareness) on the part of grid operators. Wide Area Situational Awareness (WASA) represents the monitoring of the power system across wide geographic areas. These broad area perspectives are necessary to maintain system knowledge and decisions that go beyond conventions of individual companies or even RTO boundaries. The requirements for WASA are architecturally significant from the standpoint of requiring uniformity across traditional systems operation boundaries. Enabling WASA based applications brings forward unique requirements and challenges for the Smart Grid infrastructure. Moreover, being aware of status of electrical power in power lines may help to electrical generation entities to avoid injecting redundant power to the grid and also it helps to detect the faults in the grid which results in having more efficient power usage. Smart grids can also quickly respond to natural failures (Disaster Avoidance) by rerouting around problems or closing down the network totally. They also manage rolling brown outs to keep electricity when demand exceeds production. Therefore, the electrical power status controller and phasor measurement unit have the crucial role in disaster avoidance. Controlling the status of the electrical power at the power lines is also useful to decrease wasting the electrical power energy by detecting the fault over the power grid and report their status to the CS to make the best decision in sense of electrical power usage efficiency [2,18,9,63] . Automated maintenance system is an intelligent and detective system whose actions are started automatically at regular intervals to perform maintenance operations on the damaged, imperfective and faulty part of the SG. For this aim, SG should monitor all critical components of the power grid to enable automated maintenance and prevent the outages. Therefore, the entities who involve in monitoring and controlling the power line status and distribution part, are more involved for automated maintenance system services. System status controlling also has indirect effect on user cooperation. Its status makes information as a feedback to the CS and then CS demand response changes based on that. Outage avoidance can be fulfilled by all SG node types. But, electrical power status controlling is a main and important action can be done to avoid outages.

- ***DGM*** The Distributed Grid Management (DGM) section allows utilities to remotely monitor and control the parameters in the SG distribution network. There are lots of challenges for distributed management of SG. Distributed Grid Management (DGM) provides the power distribution management through the CS, Self-management and self-healing as means to handle unpredictable behavior [2,18,45,46,83]. The unpredictable behaviors cause by individual users cyber-attacks or extreme weather conditions. As an instance, they can make blackouts power peaks with possible cascading failures. This Bidirectional communication and coordination are crucial to manage power distribution. DGM should lead the distribution industry in the development of advanced applications for distribution system in a way that based on the demands and availability of the electrical recourses is done [2,18,45,46,83]. Besides, distribution management entities in SG by balancing the power distribution can be helpful to avoid the brown and black outs. Distribution part is helpful to decrease the consumption cost as well. By balancing the injected part at the distribution level, the required power based on the demand is distributed. In User cooperation goal, even distributed grid management may play a role to fulfill user cooperation as one of the goal of SG.

- ***DERS*** Distributed Energy Resources (DERS) are used for enabling renewable energy resources as a part of the future SG and integrate them into the power grid infrastructure. Also, DERS role as the power supply resources for emergency usage during outages and disasters are notable.

  Renewable energy resources exist over wide geographical areas where any type of sustainable energy resources can be made, in contrast to other energy sources, which are concentrated in limited areas. The deployment of renewable energy is resulting in significant energy efficiency, energy security, climate change mitigation, and economic profit [2,18,19,78] . Thus, renewable energy resources are strong support for promoting green energy. The other non-centralized distributed energy resources near to the users can have significant effects to decrease the power losses over the power line come from the centralize generation part.

  Moreover, their sustainability characters decreases the usage price as a result of not using fossil fuel or the other non-sustainable and expensive energy resources. Automated maintenance system is an intelligent and detective system whose actions are started automatically at regular intervals to perform maintenance operations on the damaged, imperfective and faulty part of the SG. The DERS is not involved in SG automated maintenance same as the other SG nodes types [2, 18, 19, 78]. Moreover, the users who can have access directly to the distributed energy resources can fulfill User cooperation goal. The other sustainable energy resources can provide more power for the grid to avoid outages as well.

The prioritization of the SG nodes based on the SG goals allows selecting the most important nodes. The nodes having a higher priority in the SG may be served earlier. Therefore, it is needed to define the SG goals as the KPIs for finding the weight of the SG nodes. Then, it is needed to give a value to each different KPI for a certain node type. For a certain type of the SG nodes, giving more importance to a certain KPI depends on how much that node can fulfill that corresponding goal (KPI). The perceptive concept we propose is proportional to a quantitative value in sense of SG goal satisfaction, as follows: Very high: 5, High: 4, Medium: 3, Low: 2 and Very low: 1. SG node prioritization effectiveness depends strongly on how much they can fulfill the SG goals. The main goals of SG have been declared in many references. They are considered as the KPIs for prioritization method. In the following, a description of different types of SG goals and the services relying on the SGs are presented, and a qualitative prioritization is performed.

At first step , it is needed to identify the main goals of the SG as follows: Green Energy, Reliability in power grid, Security in power grid, Outage Avoidance, Users Cooperation, Automated maintenance, Consumption cost minimizing and Disaster Avoidance. Green energy concept in SG is generally defined as energy usage efficiency, decrease using of fossil fuels and try to use the sustainable energy. As a matter of fact, reliability in power grid, controlling part and distribution grid management is a main criterion. Increased reliance on renewable improve reliability in associated unwanted disasters.

As the technology develops, dependency on the secure electricity supplies, transmission and distribution part is increased. Grid monitoring and surveillances due to its characteristics has a significant role on SG security. Outages and blackouts avoidance as the result of high consumption or any unprecedented faults in the power grid should be considered as an important goal of SG. User cooperation is considered as the users' assistance to increase power grid functionality on the demand side of the SG. It should be mentioned that power system status as the received information by CS changes demand responses based on its analysis. Automated maintenance is an intelligence system whose actions are started automatically at regular intervals to perform maintenance operations. To this aim, SG should monitor all critical components of the power grid. Decreasing the consumption cost in the SG platform helps users schedule electrical appliance issues, minimizing variance in power consumption. SG demand side nodes have high effects on it although; power grid status controlling (distributing part) has effects on decreasing consumption cost by detecting the fault over the power grid. Disaster avoidance is another important goal of SG which can be achieved through higher rates of survivability following a natural disaster. Besides, DGM by balancing the power distribution is helpful for disaster avoidances in power grid. SG`s demand side role (by communicating with CS) on disaster avoidance is so notable. There are various types of SG node types, each one with different function and communication requirements. In this part, the most important SG node types and their communication requirements are presented.

Advanced Metering Infrastructure (AMI) is a set of SMs, communications networks, and data managing systems, for facilitating and enabling SMs to have two-way communications with the CS.

The Wide Area Situational Awareness (WASA) nodes supervise the power system over a wide geographic area. Thus, WASA has the significant role in identifying SG status and surveillances issues.

Distributed Energy Resources (DERS) are used to make possible renewable energy resources as a main part of the future SG to integrate and unify them into the power grid infrastructure. Besides, DERS have the role as the power supply resources for urgent situation usage during outages and remarkable disasters.

The Plug in Electrical Vehicle (PHEV) is useful for reducing greenhouse gas emissions and fossil fuel consumption. It is because they present the useful information of the electrical device charger for electrical vehicles.

The Distributed Grid Management (DGM) entity allows utilities to distantly monitor and control the required power grid parameters in the SG distribution network.

Prioritization CF can be defined as (4.31).

$$WN_i = \sum_{g=1}^{N_{goal}} W_g . N_{i_g} \quad (4.31)$$

in which N_{goal} is the number of the goals of Smart Grid System, W_g is the weight of the SG g_{th} goal (The goal importance based on the literature information and motivation to use SG and N_{n_g} is the node nth normalized value (to fulfill the SG g_{th} goal). WN_i is the non-normalized value of the Cost Function of node n indicating degree of the importance of the node n to fulfill all SG nodes. The CF is normalized to one, $\mathrm{CFSG_i}$, which is obtained from formula 4.32 :

$\mathrm{CFSG_i} = \frac{\mathrm{WN_i}}{\mathrm{CFSG_{max}}}$ (4.32), in which $CFSG_{\boldsymbol{max}}$=$maximum$ $\{WN_1, \ldots, WN_i\}$, i=1,…,N [214, 216].

4.9 SG Matrix of User Assigning and Energy Cost Function

Consider $i \in \{1, \ldots, N\}$ and $j \in \{1, \ldots, F\}$ and an area in which N and F are the number of different types of the SG node types and different RATs respectively. Making a matrix, showing step by step generating process in an array based method is shown here.

The selection of the transmission parameters, e.g., spectral efficiency, could affect the energy unit per bit in the transmitter side. First, by using higher spectral efficiency in a certain RAT, the data rate is increased. Therefore, the data of a certain SG node type, which has been aggregated in an aggregator, is being sent faster. Consequently, as it was discussed there are plenty of trade-offs (such as allocating a low latency RAT to support the node with low delay sensitivity) that should be considered and respected to make an efficient heterogeneous network for SG. In other word, matching RAT`s communication characteristics and the SG node type communication request must be respected. The other fact is that the reliability of the system is increased by using more joules per bits. As it can be seen there is a trade-off among different communication KPIs such as data rate, delay, reliability and security requirement in one side and energy aspects in another side. Energy per transferred bit it is more closely tied to important issues and subjections such as the battery life of a wireless device.

The fundamental lower limit on energy per transmitted and received bit imposed by the channel capacity theorem set by Shannon. Based on this lower bound, energy efficiency metric for evaluating practical RF systems is derived.

The energy per information bit in the signal is Eb . N0 is the noise power spectral density in Watts/Hz. If the channel is thermal noise limited, then N0 = kT, where T is temperature and k is Boltzmann's constant as it was discussed in chapter 4. The ratio Eb/N0 is referred to as the SNR-per-bit and the ratio C/B is a measure of spectral efficiency in bps/Hz. Both quantities are important metrics for comparing digital modulation modes. It is important to consider the differences between SNR and Eb/N0. SNR is a ratio of powers, while Eb/N0 is a ratio of energies.

For the purposes of assessing a given scheme's energy per bit performance, Eb/N0 is more meaningful than SNR. Modulation mode directly impacts a communication system's bandwidth efficiency and minimum achievable energy per bit (Eb/N0). Also, Low Power Communication is the key to realization of a little power sensor node [162]. RATs with lower data rate are not efficient in sense of communication spectral efficiency. Since Shannon's law runs the limit on the energy efficiency of radio communication and link capacity, it makes sense to have a deeper look at it. To include energy issues in our proposed method, energy per bit to noise power spectral density ratio, E_b/N_0 for RAT_j is considered. Using a certain communication configuration for the RAT_j

cause to have different, $(\frac{Eb}{N_0})_j = \frac{Eb_j}{N_0}$values. If E_{bj} is in joule per bit unit, in can be written as Eb_j=$\frac{S_j}{C_j}$ Joules per bit (4-33) in which S_j = signal power [$\frac{joules}{\text{sec}}$] and

$$C_j = B_j.log_2(1+\frac{S_j}{N}) \text{ (4-34.1)}$$

is the Shannon formula expressing the capacity of a given link. $C_j = \eta_j \times B_j$, where η_j is the spectral efficiency, in bits/sec/Hz and B_j is bandwidth (Hz).

The spectral efficiency can be defined as $\eta_j = \frac{C_j}{B_j}$ where C_j is bit rate in bps (η_j: spectral efficiency, bits/sec/Hz) and B_j is bandwidth (Hz). $(\frac{E_b}{N_0})_j$ **in** dB is the Energy per bit to noise power spectral density ratio, $(\frac{E_b}{N_0})_j$for RAT_j Using certain communication configuration $RATj \text{ } in \text{ } which \text{ } j \in \{1, \ldots, F\}$.

Thus, the different signal (in RATs) with different spectral efficiency can be compared in terms of energy efficiency. To do so, an algorithm should be applied. It can be defined by using the defined formula as following.

$$\eta_j = \frac{C_j}{B_j} = log_2(1+\frac{S_j}{N_j})$$

$$S_j = Eb_j.C_j$$

$$N_j = N0.B_j$$

$$C_j = \eta_j.B_j \text{ (4-34.2)}.$$

$$\eta_j = log_2(1+\frac{Eb_j.C_j}{N0.B_j}) = log_2(1+\frac{Eb_j.\eta_j.B_j}{N0.B_j}) = log_2(1+\frac{Eb_j.\eta_j}{N0}) = log_2(1+\frac{Eb_j}{N0}.\eta_j) \quad \text{(4-34.3)}$$

$$2^{\eta_j}=1+\frac{Eb_j}{N0}.\eta_j \quad \text{(4-34.4)}$$

$$\frac{Eb_j}{N0} = \eta en_j = \frac{2^{\eta_j}-1}{\eta_j} \quad \text{(4-34.5)}$$

By using this definition, easily the different signal (in RATs) with different spectral efficiency can be compared in sense of energy efficiency.

$$\mathrm{Max}_{\beta_{\mathrm{er}\,j}} = \max_j\{(\frac{\mathrm{Eb}}{\mathrm{N0}})_{\mathrm{j}}\}$$

$$\frac{Eb_j}{N0} = \eta en_j = \frac{2^{\eta_j - 1}}{\eta_j} \qquad \textit{(4-34.6)}$$

$$\acute{\beta}_j = \frac{\eta en_j}{Max_{\beta_{er_j}} + \zeta_0}, 0 < NJpb_j < 1,\ \zeta_0 \ll 1 \ \textit{to avoid}\ \acute{\beta}_j = 1, \quad \textit{(4-34.7)}$$

(4-34.8) is considered as the Energy Cost Function, the user percentage assigning to each RAT based on the ECF value for energy part using (4-34.8).

$$\mathrm{E_j} = \frac{1 - \acute{\beta}_{\mathrm{j}}}{\sum_{\mathrm{j}=1}^{\mathrm{F}}(1 - \acute{\beta}_{\mathrm{j}})}, \quad (4 - 34.8)$$

By using this method, higher joule per bits used in a certain RAT has higher energy CF that is not desirable. To make a balance between energy CF and communication CF, they could be combined to make an efficient tradeoff for assigning the SG users to different RATs.

Finally, it should be mentioned that the energy part is not included in the communication CF part because it does not belongs to the SG KPIs and SG node types communication needs.

4.10 SG Node Types Assigning Strategy Using CCF and ECF

There are some rationales behind the model which are described. First of all, this is a method to share entire number of a certain type of the node efficiently among the all available RATs. It is obvious that it is useful when it is needed to use all RATs to support a certain type of the nodes communication requirements instead of one RAT.

Secondly, this method also defines the minimum number of a certain type of the nodes which should be supported by the better RATs (in sense on CCF and ECF) which is achieved by the defined model. Moreover this model defines the maximum number of a certain type of the nodes which should be supported by the worst RATs (in sense on CCF and ECF) which is achieved by the introduced model as well. Table 4- 7 shows the node type i-th assigning to the different RATs based on the achieved desirability value based on the communication and energy criteria by using the CFs formulas including CCF and ECF. RAT_{ipj} means RAT with **priority** of order F for the node type i. (4.35) and (4.36) show the percentage of node type i assigning to the different RATs based on communication issues and Energy issues respectively. (4.39) which has been achieved using CF s formula and $(4.35 - 38)$ indicates to the node type i assigning percentage to RATj based on the CCF and ECF and the communication and energy weights (based on designer perspective). w_β and w_η show the communication and energy (joule per bits) impacts respectively.

$$CCF = \begin{bmatrix} CF_{11} & \cdots & CF_{1j} \\ \vdots & \ddots & \vdots \\ CF_{i1} & \cdots & CF_{ij} \end{bmatrix} \quad (4-34.9)$$

By using (4-34.11), the CFs values is changing to its inverse concept.

$$CCF_{ij}^{des} = \begin{bmatrix} 1 - CF_{11} & \cdots & 1 - CF_{1j} \\ \vdots & \ddots & \vdots \\ 1 - CF_{N1} & \cdots & 1 - CF_{NF} \end{bmatrix} \qquad \text{(4-34.10)}$$

$$\beta_{ij} = \frac{1 - CF_{ij}}{\sum_{j=1}^{F}(1 - CF_{ij})} = \frac{CCF_{ij}^{des}}{\sum_{j=1}^{F}(1 - \alpha_{ij})} \ (4-34.11) \text{ in which } \quad \sum_{j=1}^{F} \beta_{ij} = 1, \qquad [216,218] \quad \text{(4-34.12)}$$

$$P_{ij} = 100 \times \frac{(w_\beta . \beta_{ij}) + (w_\eta . \mathrm{E_j})}{(w_\beta + w_\eta)} \quad \text{(4-35)}$$

$$HET = \begin{bmatrix} P_{11}\% N_1 & \cdots & P_{1j}\% N_1 \\ \vdots & \ddots & \vdots \\ P_{i1}\% N_i & \cdots & P_{ij}\% N_i \end{bmatrix} \quad \text{(4-36)}$$

In which HET_{ij} shows the Number of Node type i which should be supported by the RAT j.

$$HET_{ij} = 100 \times \frac{(w_\beta . \beta_{ij}) + (w_\eta . \mathrm{E_j})}{(w_\beta + w_\eta)} \%\ N_i \quad \text{(4-37)}$$

$$P_{ij} = 100 \times \frac{w_\beta . \frac{(1 - CF_{ij})}{\sum_{j=1}^{F}(1 - CF_{ij})} + w_\eta . \frac{(1 - \acute{\beta}_j)}{\sum_{j=1}^{F}(1 - \acute{\beta}_j)}}{(w_\beta + w_\eta)} \quad \text{(4-38)}$$

$$P_{ij} = \frac{w_\eta . \frac{\left(1-\frac{\sum_{q\in\{KPI\}}\left(W_{qi}\cdot N_{q_{ij}}\right)}{\sum_{q\in\{KPI\}}\left(W_{qi}\right)}\right)}{\sum_{j=1}^{F}\left(1-\frac{\sum_{q\in\{KPI\}}\left(W_{qi}\cdot N_{q_{ij}}\right)}{\sum_{q\in\{KPI\}}\left(W_{qi}\right)}\right)} + w_\beta . \frac{\left(1-\frac{\frac{2^{\eta_j}-1}{\eta_j}}{Max\,\beta_{er_j}+\zeta_0},\right)}{\sum_{j=1}^{F}\left(1-\frac{\frac{2^{\eta_j}-1}{\eta_j}}{Max\,\beta_{er_j}+\zeta_0},\right)}}{(w_\eta + w_\beta)} \quad (4.39)[220]$$

For a certain i, $\sum_{j=1}^{F}\beta_{ij} = \sum_{j=1}^{F}E_j = 1$ (4.37)

ConsideringN_{ij}: $N_i = \sum_{j=1}^{F} P_{ij}\% N_i = N_{i1} + N_{i2} + \cdots + N_{iF}$

Equation 4.39.2 is achieved using all CCF and ECF and assigning method formulas which are used in this chapter.

To have a fair node assignment to different RATs, the trade-offs are considered and respected between ECF and CCF.

Here, SAT^{ij} is the percentage of the node type i that is supported by eligible RAT j (F_a $number\ of\ RATs\ out\ of\ F$) in which the RATs which are not eligible to fulfill the SG node type i requirements (in sense of delay) are excluded. (4.40-4.43) shows its formulization based on the theory part of the methodology.

Table 4- 7 Node assigning to different RATs Table

	Communication Desirability %	***Energy (joule per bit) Desirability %***	***Average % to assignnode type i to RAT j***	***Average N_i number for each single RAT***
$\boldsymbol{RAT_{ip1}}$	β_{i1}	E_1	p_{i1}=100 $\times \frac{w_\beta.\beta_{i1}+w_\eta.E_1}{w_\beta+w_\eta}$	N_{i1}= $p_{i1}.N_i$
$\boldsymbol{RAT_{ip2}}$	β_{i2}	E_2	p_{i2}=100 $\times \frac{w_\beta.\beta_{i2}+w_\eta.E_2}{w_\beta+w_\eta}$	N_{i2}= $p_{i2}.N_i$
$\boldsymbol{RAT_{ip3}}$	β_{i3}	E_3	p_{i3}= 100 $\times \frac{w_\beta.\beta_{i3}+w_\eta.E_3}{w_\beta+w_\eta}$	N_{i3}= $p_{i3}.N_i$
…	…	…	…	…
$\boldsymbol{RAT_{ipj}}$	β_{ij}	E_j	p_{ij}= 100 $\times \frac{w_\beta.\beta_{ij}+w_\eta.E_j}{w_\beta+w_\eta}$	N_{ij}= $p_{ij}.N_i$

$$SAT^{ij} = 1 - \frac{|(P_{ij}\times N_i)-N_i|}{N_i} = 1 - \frac{|(P_{ij}-1)\times N_i|}{N_i} = 1 - \frac{|(P_{ij}-1)|\times N_i}{N_i} = 1 - |(P_{ij}-1)| \quad (4.40)$$

$$(P_{ij}-1) \le 0 \qquad \forall i\ and\ j \in \mathbb{N} \quad (4.41)$$

$$SAT^{ij} \coloneqq \begin{cases} P_{ij}, & \text{if } P_{ij} \neq 0 \\ 0, & if\ P_{ij} = 0 \end{cases} \qquad (4.42)$$

For a certain SG node type i, $F_a \coloneqq \begin{cases} F, & \text{if } \forall j \in \{1,\dots,F\} \& N_{delay_{ij}} > 0 \\ F-n, & if\ for\ n\ number\ of j, j \in \{1,\dots,F\}\ \& N_{delay_{ij}} < 0 \end{cases}$ (4.43)

In (4.44), $\hat{a}$ Shows the case in which all node types are assigned to different RAT number of F_a equally.

$$\hat{a} = \frac{100}{F_a} \qquad (4.44) \qquad VAR_{sat}^{ij} = \frac{(SAT^{i1}-\hat{a})^2+(SAT^{i2}-\hat{a})^2+\dots+(SAT^{iF}-\hat{a})^2}{F_a}$$

(4.45)

VAR_{sat}^{ij} is shown the non-equableness degree of node assigning to all eligible RATs that support a certain node types ,i, with N_i number of the nodes. If all the nodes equally being assigned to the different RATs, then VAR_{sat}^{ij}=0. It also indicates how LEACH user assigning [132] method in which all nodes are equally shared among the RATs, can be non-efficient comparing with the proposed method in this dissertation. Although it is assumed there is no BW shortage in the proposed work but, in case of BW shortage the higher priority nodes will be served earlier based on the node assigning strategy. In case of BW shortage for a lower priority node exist, the nodes are assigned to their RATs with higher priority. One important applications of the introduced method is described here. If all CF_{ij} for a certain node type values and different RATs are members of **:**

B = **{** $CF_{i1}, CF_{i2},\dots, CF_{iF}$**}.** $\boldsymbol{B_{MAX}}$=Maximum $CF_{ij} \in$ **B** **, then** $\hat{\alpha}_{ij} = \frac{CF_{ij}}{\boldsymbol{B_{MAX}}}$ (normalized to 1) **,** $\hat{\boldsymbol{B}}$=**{**$\hat{\alpha}_{i1}, \hat{\alpha}_{i2}, \dots, \hat{\alpha}_{iF}$ **}** and they are ordered from higher value to the lower, from $\hat{\alpha}_{ip1}\ to\ \hat{\alpha}_{ip5}$**.** Also $\acute{\beta}_j$ for different RATs being a member of set **E** = **{** $\acute{\beta}_1,\dots, \acute{\beta}_F$**}.** $\boldsymbol{E_{MAX}}$=Maximum $\acute{\beta}_j \in$ **E** **, then** **,** $\widehat{\beta_j} = \frac{\acute{\beta}_j}{\boldsymbol{E_{MAX}}}$ **,**$\hat{\boldsymbol{E}}$=**{**$\widehat{\beta_1}, \widehat{\beta_2}, \dots, \widehat{\beta_F}$ **}** and they are ordered from higher value to the lower, from $\hat{\alpha}_{ip1}\ to\ \hat{\alpha}_{ip5}$**.**This is a special case of facing both situation(A5&B5) together as following.

Table 4- 8 Node assigning to different RATs Table, The bolded columns are related to the last example of this chapter						
	CCFp		ECFp		Percentage%	
RAT1	$\hat{\alpha}_{ip1}$	$\boldsymbol{a_1}$	$\widehat{\acute{\beta}_{p1}}$	$\boldsymbol{b_1}$	p_{i1}	$\boldsymbol{N_1^i}$
RAT2	$\hat{\alpha}_{ip2}$	$\boldsymbol{a_2}$	$\widehat{\acute{\beta}_{p2}}$	$\boldsymbol{b_2}$	p_{i2}	$\boldsymbol{N_2^i}$
RAT3	$\hat{\alpha}_{ip3}$	$\boldsymbol{a_3}$	$\widehat{\acute{\beta}_{p3}}$	$\boldsymbol{b_3}$	p_{i3}	$\boldsymbol{N_3^i}$
RAT4	$\hat{\alpha}_{ip4}$	$\boldsymbol{a_4}$	$\widehat{\acute{\beta}_{p4}}$	$\boldsymbol{b_4}$	p_{i4}	$\boldsymbol{N_4^i}$
RAT5	$\hat{\alpha}_{ip5}$	$\boldsymbol{a_5}$	$\widehat{\acute{\beta}_{p5}}$	$\boldsymbol{b_5}$	p_{i5}	$\boldsymbol{N_5^i}$

In which: $1 > \hat{\alpha}_{ip1} > \hat{\alpha}_{ip2} > \hat{\alpha}_{ip3} > \hat{\alpha}_{ip4} > \hat{\alpha}_{ip5} > 0$ (A5) [Special case]

$0 < \widehat{\acute{\beta}_{p1}} < \widehat{\acute{\beta}_{p2}} < \widehat{\acute{\beta}_{p3}} < \widehat{\acute{\beta}_{p4}} < \widehat{\acute{\beta}_{p5}} < 1$ (B5) [Special case]

Table 4- 9 Node assigning combination with SG node prioritization				
RAT priority / Node Priority	***First priority RAT and defined assigning%***	***Second priority RAT and defined assigning%***	...	***F th priority RAT and defined assigning%***
Node type p1	$\boldsymbol{RAT_{1p1}\%}$	$\boldsymbol{RAT_{1p2}\%}$	...	$\boldsymbol{RAT_{1pF}\%}$
Node type p2	$\boldsymbol{RAT_{2p1}\%}$	$\boldsymbol{RAT_{2p2}\%}$	...	$\boldsymbol{RAT_{2pF}\%}$
Node type pi	$\boldsymbol{RAT_{ip1}\%}$	$\boldsymbol{RAT_{ip2}\%}$	...	$\boldsymbol{RAT_{ipF}\%}$
…	…	…	...	…
Node type pN	$\boldsymbol{RAT_{Np1}\%}$	$\boldsymbol{RAT_{Np2}\%}$	...	$\boldsymbol{RAT_{NpF}\%}$

In Table 4.9, the percentage of the node type i, assigning to different RATs j, p_{ij}, which were achieved and explained completely. Combining the introduced methods, with the SG node type prioritization based on SG goals is another strategy can be used to have a more reliable and efficient communication network for SG. In case of data rate of a certain RAT j or any communication aspects subject to a certain value, the priority table helps to assign the spectrum to the higher priority nodes. Moreover, the unprecedented additional offload can be assigned to the different RATs based on this method. In the last part, the $f^{NT_{ij}}$, the node type i assigning percentage to RAT j as the function of different variable and functions can be re-driven and rewritten as following (4.46).

$$\boldsymbol{f}^{NT_{ij}}_{\left(\left(KPI_{1ij},KPI_{2ij},\ldots,KPI_{4ij},\left(\frac{Eb}{N0}\right)_j\right)\right)} = \frac{1}{(w_\beta + w_\eta)} \times \left(w_\beta . \frac{\left(1 - \frac{\sum_{q\in\{KPI\}}\left(W_{qi}\cdot Nq_{ij}\right)}{\sum_{q\in\{KPI\}}\left(W_{qi}\right)}\right)}{\sum_{j=1}^{F}\left(1 - \frac{\sum_{q\in\{KPI\}}\left(W_{qi}\cdot Nq_{ij}\right)}{\sum_{q\in\{KPI\}}\left(W_{qi}\right)}\right)} + w_\eta . \frac{\left(1 - \frac{\frac{2^{\eta_{j-1}}}{\eta_j}}{Max_{\beta er_j} + \zeta_0}\right)}{\sum_{j=1}^{F}\left(1 - \frac{\frac{2^{\eta_{j-1}}}{\eta_j}}{Max_{\beta er_j} + \zeta_0}\right)} \right) \quad (4.46)$$

$$KPI_{1ij} = \boldsymbol{f}_{((\mathrm{R_{Ni}}, \mathrm{M}, S, Co_S, BW_j, k_j, n_j, \eta_j, \ldots, KPI_{qij}, Eb/N0_j))}, \; KPI_{2ij} = \boldsymbol{f}_{((Buf_{ij}, \alpha_{ij}, proc_{ij}, prop_{ij}, frame_j, D_i, D^{max}, \ldots, \epsilon))}$$

$$KPI_{3ij} = \boldsymbol{f}_{\left(\left(NRE_{ij}, NMAX_{ij}, \lambda_i, \mu_j, K_j, \ldots, \chi_{ij}^{mmPr}\right)\right)}, \; KPI_{4ij} = \boldsymbol{f}_{((WSE_i, \propto_{EN}, \mathrm{ENP}_j, \propto_{COM}, \mathrm{COMC}_j, \propto_{RST}, \mathrm{RST}_j, SEC, \ldots, Nsec_{max}))} \quad (4.47\text{-}50)$$

All the variables of the functions are even as a function of the different variables. At the end of this chapter, combinations of this method with SG node type's prioritization are explained but before it is needed to bring a part as the assumptions. Eq. (4.51) and (4.52) indicates on total goodput capacity of all available RATs and total data rate required by a SG system including all node types traffic respectively.

$$DR^{Ft} = \sum_{j=1}^{F} DR_j^g = \sum_{j=1}^{F}\left(\prod_{s=1}^{S}\left[(1 - Co_s) \times BW_j \times \frac{k_j}{n_j} \times \eta e_j\right]\right), \; (4.51) \qquad DR^{Nt} = \sum_{i=1}^{N} DR_i \; (4.52)$$

Prerequisite that all generated data being supported by the F number of RATs is:

$$DR_{Nt} \leq DR_{Ft}$$

Sufficient condition would be when ∀ Node type i, with delay sensitivity of D_i there if exist at least one RAT in which its latency is lower than any SG node types whose delay tolerance are higher than RAT latency and the total required data by these specific node types should be less than the data rate that the mentioned RAT can support. Another Sufficient condition would be when ∀ q out of N different Node types i while there are F-p RATs in which p RATs can fulfill q different type of SG node types delay sensitivity and the other F-p RATs can fulfill th other N-q different type of SG node types delay sensitivity as well.

Thus, if $\sum_{i=1}^{q} DR_i \leq \sum_{j=1}^{p} DR_j$ and also $\sum_{i=q+1}^{N} DR_i \leq \sum_{j=p+1}^{F} DR_j$ the whole network can fulfill the SG node communication requirements. In case of $\sum_{i=q+1}^{N} DR_i > \sum_{j=p+1}^{F} DR_j$ or (and) $\sum_{i=1}^{q} DR_i > \sum_{j=1}^{p} DR_j$, the BW shortage is happened. Although investigation this problem is out of scope of this work, but using SG node type prioritizations allows to decrease the disadvantages of BW shortage (during disasters, outages and unexpected events).

The general algorithm in this case is given as follows. It should be mentioned in this method, if any RATs cannot fulfill the certain node type communication requirements, the assigning the nodes based of the ECF done after excluding the mentioned RATs that cannot support the node type requirements.

PRIORITY BASED ALGORITHM
1. Start
2. Elaborate the priority table (different node type, different RATs, assigning percentage, SG node types ordered based on their priority
3. p=i=1, n=j=1, Define N and F, Ip: node i with priority p, p=1,…, N; Pn: RAT with priority n, n=1,…, F
4. Assign node Ip to Pn, its n-th RAT priority (Ip, Pn)
5. if RAT n support all node type Ip%, then n=n+1, goto6, else goto8
6. if n>F, p=p+1, goto 4
7. if p> N, goto END
8. If RAT n can NOT support all node type Ip%, then n=n+1
9. Compute the extra traffic, assign to the other RATs based on the desirability values
10. Save the value of non-supported p node type value, (DRs)p in Matrix A, A (1, p) = DRs, if p> N, goto 12
11. if n>F , p=p+1 , goto 4
12. Call the matrixes from 10, allocate more BW to support them
13. Finish

Chapter 5

RESULTS AND DISCUSSIONS

5.1 An overview of the conducted simulations

By using the average number of nodes and collectors per branch of the network domain that is defined by UTC, the primary numerical results based on the first proposed method are achieved. The results show that respect to the number of KPIs which are used in the main CF, the best RATs for each type of SG nodes can be selected. In consequence, all the SG node communication requirements are fulfilled while the resource allocation is done in an efficient. The first parts of the results based on the UTC information are given in the next section.

Moreover, priority table is achieved by using the SG node type prioritization methods. Combination of SG node type prioritization with the primary results help designer to allocate RAT spectrum to the different SG node types based on the aforementioned priority table. Furthermore, based on the CFs values, the desirability value of each RAT for a certain node types are defined and the user get assigned to different RATs based on these values.

Rather than it, the energy per information of bit as an important characteristic of RAT transmitter is considered to make a trade of between communication CF, CCF and energy CF, ECF. It should be notified that higher spectral efficiency has a non-predictable effect on CCF value. It is because of having several variables as the KPIs. Additionally, using the combination of two CFs namely CCF and ECF helps to make an efficient heterogeneous network to support the different node types communication requirements based on the information are prepared by UTC. MATLAB simulation is used to implement the method in order to obtain the results.

Using SG node prioritization methods in combination with these two CFs gives a developed method of SG node type assigning over all RATs while priority of SG node types are considered in case of critical situations such as BW shortage.

In the second and main part of the results, the all node types densities, details and characteristics are given. Besides, several RATs characteristics are considered in the introduced methods as well. Some outcomes of defined methods are shown in different figures in section 5.3 in order to have a clear idea of functions of the proposed methods. Different SG scenarios in sense of RATs parameters and node densities are considered. MATLAB codes including several functions are used to implement the method in order to simulate the proposed methods.

The impact of this thesis results can change the policy of designing heterogeneous communication network that supports different M2M type nodes with different communication requirements. This method helps to assign billions of M2M devices amongst different RATs in which the spectrum efficiency can be the high in sense of communication and transmitters Eb/N0 aspects. Moreover, tradeoffs between spectral efficiency, RATs latency, reliability and security issues are respected in an efficient way. Furthermore, the results of the proposed CFs gives a significant insight to network designers in sense of marketing, operator and installation cost. It should be notified that there are m numbers of RATs among N RATs that their CCF for a certain node type increases from lower to higher while the corresponding ECFs decrease from higher to lower. Therefore an efficient way can be defined to support the node communication requirements by using the CCF and ECF as the main criteria to assign the certain node types to different RATs. Thus, the method would be both energy and communication efficient. The results shows that sharing the certain SG node type depends on many parameters. Moreover the assigning method is sensitive to node's density and node type communication requirements. Node type with higher density needs more data rate to be supported. High data rate RATs are facing with many tradeoffs when supporting a certain node type communication requirements. All of these tradeoffs should be considered and respected in order to design a high efficient heterogeneous communication network.

The results which have been published in several journals and conferences are given as the references in the result part.

5.2 Prioritization Method and Results based on the UTC Standard per branch of the network

Figure 5-1 shows normalized value as the function of RAT latency and SG node types delay sensitivity; using (4.8). It is clear to see that the normalized delay is higher if the latency and SG node delay difference is higher and vice versa. This helps to define the KPI in a way that allocating RATs spectrum with higher latency to SG node having a lower delay requirement is done. Whenever the latency of a certain RAT is higher than the SG node required delay, its normalized value is negative so, it is excluded from the available RATs to support the selected node types.

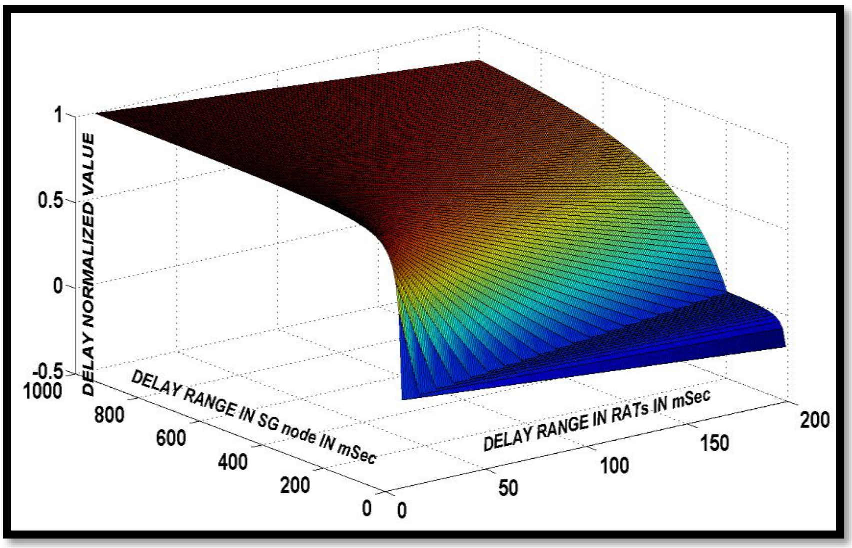


Figure 5-1 Normalized value for delay

Tab 5.1 summarizes the requirements of the SG node types in terms of data rate and latency, where in the first two columns the values as defined by the Utilities Telecom Council (UTC) are reported, while in the other two the values used in this section study are reported.

Table 5.1. Communication requirements of SG nodes (UTC) [2]

	Reference Data Rate [kb/s]	*Reference Latency [s]*	*Selected Data Rate [kb/s]*	*Selected Latency[s]*
AMI	500	2-15	**500**	**2**
WASA	600-1500	0.02-0.2	**1000**	**0.03**
DERS	9.6-56	0.02-15	**40**	**1**
PHEV	100	2-300	**100**	**5**
DGM	9.6-100	0.1-2	**70**	**0.5**

By using the first defined method, the elements of CF namely KPIs values are defined. LTE modulation mode is chosen 64QAM, reference BW 1.4 MHz and RTT 10-20 msec. For GSM, GMSK modulation mode is chosen considering the latency 100-200 msec. LEO uses 8PSK modulation mode having 100-150 ms RTT. The primary results are achieved [214,215].

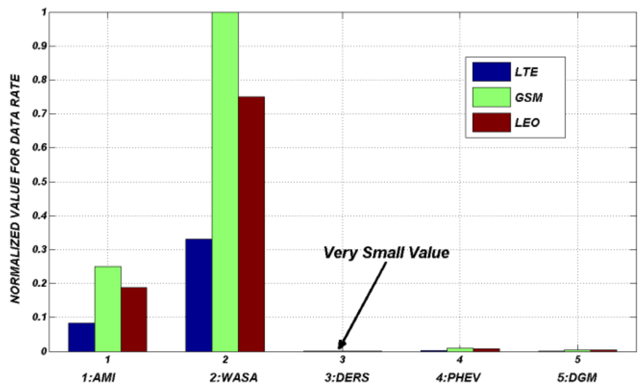


Figure **5.2** Data Rate Normalized value

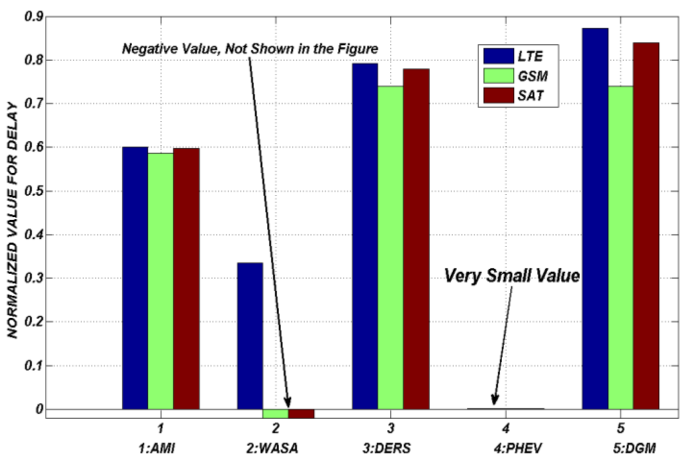


Figure 5.3 Delay Normalized value

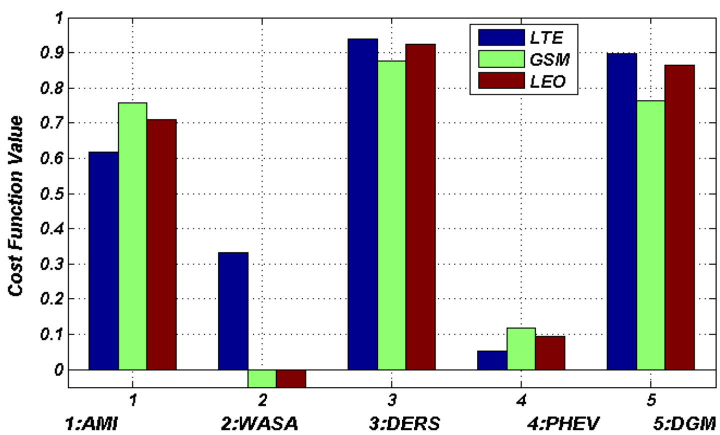


Figure 5.4 CF value

The negative part is not shown fully in Fig.5.3 but, its negative value by using the proper CF can be seen at the final value for the CF at Fig.5.4. Fig 5.2 and Fig5.3 show the data rate and delay normalized value respectively for different type of the SG node over three different RATs. WASA CF values are negative using configuration correspond to LEO and GSM since their delay is higher than WASA delay tolerance. As it is can be seen the nodes like PHEV with lower delay sensitivity have lower delay weight than the other high delay sensitive nodes. The SG nodes in the first column of the Tab 5.2 have been ordered from up to down based on their priority of respecting the SG goals.

Table 5.2 Priority table

	First Priority	*Second Priority*	*Third Priority*
WASA	*LTE*	-	-
AMI	*LTE*	*LEO*	*GSM*
DGM	*GSM*	*LEO*	*LTE*
DERS	*GSM*	*LEO*	*LTE*
PHEV	*LTE*	*LEO*	*GSM*

Although LTE is the first priority for WASA, AMI and PHEV but at the first step, this resource is allocated to the SG node with higher priority. This is because may a certain RAT is not able to support all the nodes, hence, the highest priority nodes should be served earlier.

Table 5.3 – Different Configurations (Config. j) corresponding to the CTs [214,215]

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5
SE bits/Hz	4	1.35	1.8	1.2	1.07
Modulation mode	64 QAM	GMSK	8PSK	DVB-S2,Extensions APSK	4PSK OR PSK
PD,msec	5	5	25	150	350
PT,msec	5	5	5	5	5
Corresponds .to Configuration, C.Con	LTE	GSM	LEO	MEO	GEO

The next part of the results is achieved to find the CFs as a function of SMs density. For 4000 SMs in AMI, a collector receives data from 200 numbers of SMs in average in a second. Referring to literature, for 4000 SMs, 500 Kbps data rate of a single aggregator can supports these amounts of SMs. Moreover, it is shown for a certain number of SMs, the buffered size data, Buf_{SM} , in a collector can be calculated by using (5.1) [20, 214,215].

$$Buf_{SM} = s \times N_{sm} \ (5.1)$$

where Buf_{SM}, s and N_{sm} are, respectively, the buffered data in aggregator in 1 Sec $(Kbits)$, the line slip and the number of SMs. Based on the literature, s, can be easily calculated as following: $\mathrm{s} = \frac{500 \text{ Kbps}}{4000} = 0.125 \text{ Kbps}$, thus: $\mathrm{Buf_{SM}} = 0.125 \times \mathrm{N_{sm}}$ Kbps [214,215]. Using (5.2) and (5.3) the delay normalized value can be achieved by highlighting the propagation delay effect. Thus by considering the highest propagation delay corresponding to GEO, maximum $\alpha \approx 30$ is considered (30 times more than propagation delay using GEO satellite and data transferring time will be approximately near 15 seconds that is the SM delay sensitivity). Therefore, $1 < \alpha < 30$ and in the mentioned design, it is considered $\alpha = 10$ [214,215]. The policy of equal weights is used in this part.

$$\mathrm{TotLat_{sj}} = \left(\frac{Buf_{SM}}{DRconfig_j}\right) + \left(\alpha.Pdl_j + Pros_j\right) \ (5.2) \quad , NDE_{sj} = 1 - \frac{\mathrm{TotLat_{sj}}}{\mathrm{DL_s}} \quad (5.3)$$

Figure 5.5 shows the delay normalized value for SMs when $\alpha = 1$ and $\alpha = 10$. As it can be seen, the normalize values are decreasing by increasing the network delay in both cases.

Moreover, by considering α =10, the effect of the propagation delay is more significant and the lower value for the normalized value than situation that α =1 for the same network delay is achieved which results in having lower CF in which the network delay effect has been highlighted more.

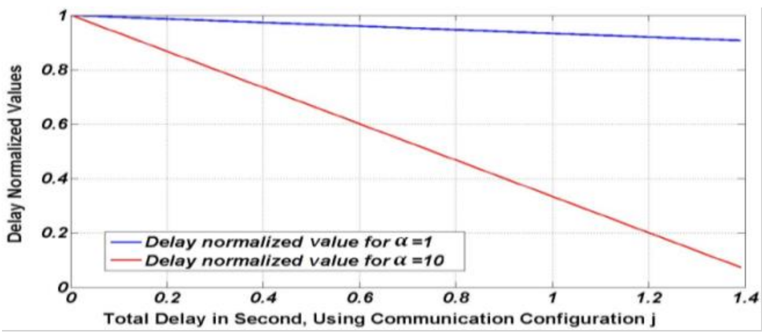


Figure. 5.5 Normalized value [214,215].

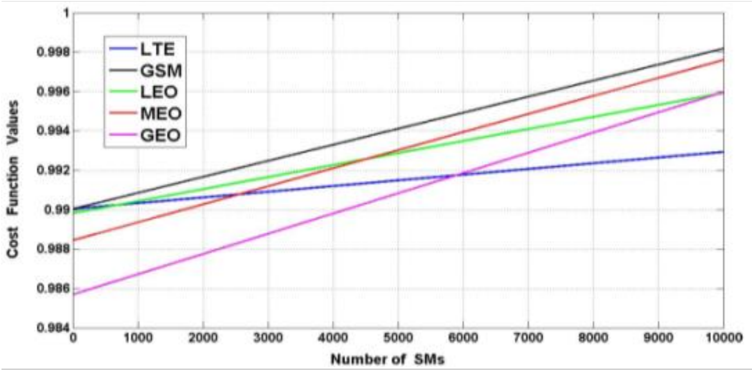


Figure. 5.6 CF vs #SMs

The results are shown in Figure 5.6. For an AMI infrastructure with 4000 SMs, as it is seen in satellite communication using orbit GEO satellites is the best choice due to its lowest CF value for 4000 SMs.

When the SMs numbers increases, the data rate normalized value increase as well. Moreover, the delay normalizes value decrease because the more buffered data needs more time to be transferred to the CS. The LTE can be the best choice for the $N_{sm} > 6000$ because higher buffered data by SMs have a significant effect in both data rate and delay normalized value. GSM has the highest CF value among the others and does not have any advantages over the others in case of using the proposed part in this section which all the weights have been considered equal. For $N_{sm} > 10000$ the configuration 3 (Co.to LEO) due to its higher Spectral Efficiency, SE, shows the better functionality than the configuration 5 (Co.to GEO). The configuration 4 (Co.to MEO) shows the better functionality than configuration 3 (Co.to LEO) due to its higher propagation delay but, for $N_{sm} > 5000$ their functionality got inversed due to higher SE in configuration 3 (Co.to LEO) than configuration 4 (Co.to MEO). For 8000 SMs (each AMI,4000 SM) the priorities from 1th to 5th are Co.to LTE,GEO,LEO,MEO and GSM respectively. The SG node types prioritization formula based on the policy which are described in methodology part using (4.31) and (4.32) are given here in Fig 5.7 and Tab.5.4 [214,215].

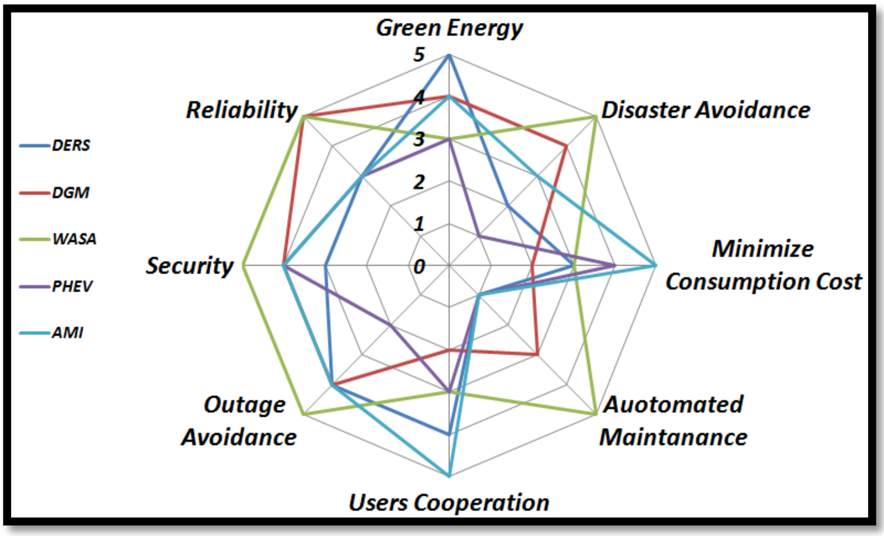


Figure 5.7- The role of each node type on satisfying smart grid goals

Table 5.4 SG node prioritization based on the SG goals [216]

	(W_g)	*AMI*	*PHEV*	*WASA*	*DGM*	*DERS*
Green Energy	5	4	3	3	4	5
Reliability	4	3	3	5	5	3
Security	3.5	4	4	5	4	3
Outage Avoidance	4.5	4	2	5	4	4
Users Cooperation	3	5	3	3	2	4
Automated Maintenance	3.5	1	1	5	3	1
Minimize Consumption Cost	4	5	4	3	2	3
Disaster Avoidance	4.5	3	1	5	4	2
WN_n	-	116	83	136	114	102
$CFSG_{max}$	-	0.85	0.61	1	0.84	0.75

The bandwidth has been supposed to be equal to 5 MHz for all the RATs, for fairness purposes, while the data rate of each RAT is different based on the spectrum efficiency. The weight of data rate and delay for the different SG node types are defined based on the proposed method and just ε used in (5.4) and (5.5) which is a very small value (close to 0) which avoids delay weight and normalized values to be equal to 0 (without ε may have value of 1 which results in 0% user assignment).

The worst-case scenario is studied here using the highest delay sensitivity of the SG node types and high data reported for them. Figs. 5.8 and 5.9 show the normalized data rate and delay for different types of SG nodes. Thus, the nodes allocation to the different RATs is defined and the percentage calculated. For all the SG node types, the nodes allocation percentages for each RAT are evaluated.

$$N_{D_{ij}} = 1 - \frac{D_i}{D_j + \epsilon} \quad (5.4), \qquad W_{D_{ij}} = 1 - \frac{D_i}{D^{max} + \epsilon} \quad (5.5)$$

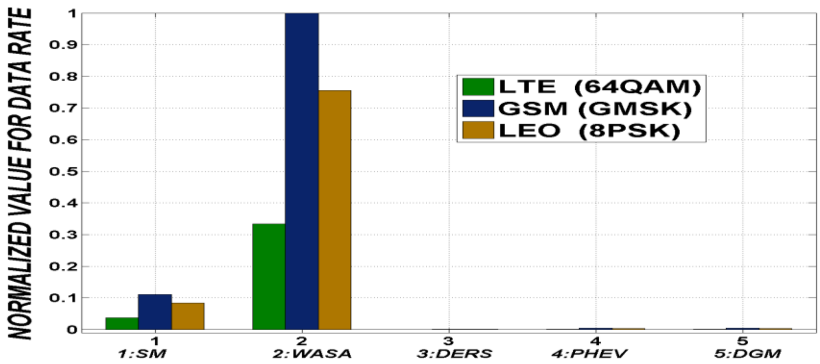


Fig. 5.8. Data Rate Normalized value

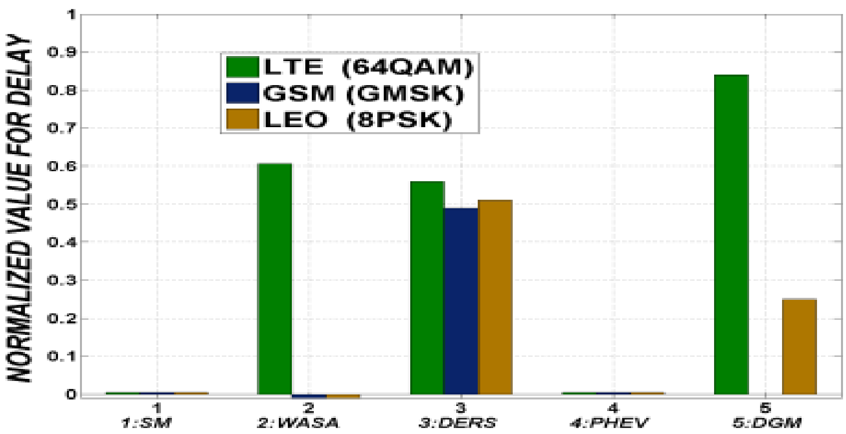


Fig. 5.9. Delay Normalized value

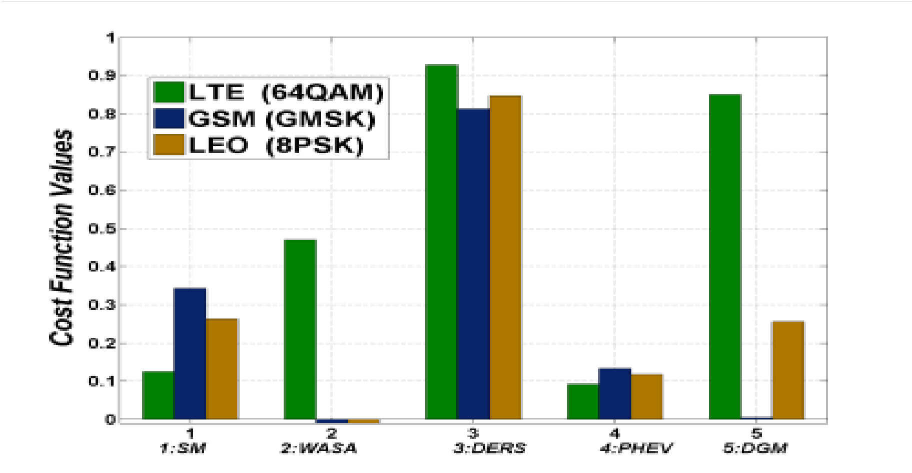


Fig.5.10 CF value

CF numerical values for each type of SG node and RATs considered in aforementioned study for worst case scenario, represented in Fig.5.10.Based on the proposed node assigning method, the percentage of each type of SG nodes which should be shared among the available RATs are evaluated. Fig. 5.11 and Tab. 5.5 show the results reached by using node assigning method. The SG node types are prioritized in Tab. 5.5.

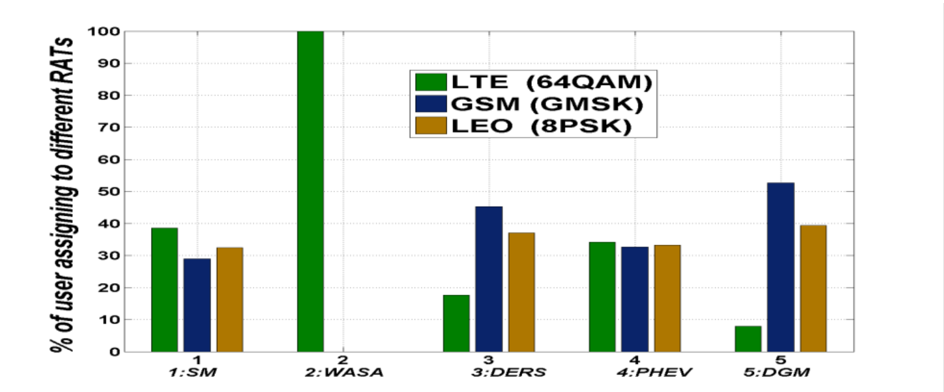


Fig.5.11 Node assigning %

Table 5.5. Allocation percentage of SG nodes

Assigning percentage	**LTE%**	**GSM%**	**LEO %**
WASA	100%	0%	0%
SM	38.6%	28.9%	32.5%
DGM	7.97%	52.7%	39.33%
DERS	17.6%	45.3%	37.1%
PHEV	34.2%	32.6%	33.2%

Figure 5.11 and 5.12 shows the MMPR as a function of packet loss probability (PLP) for the SMs and PHEV in one Figure and for WASA, DERS and DGM on the other one using the Tab 5.1 data.

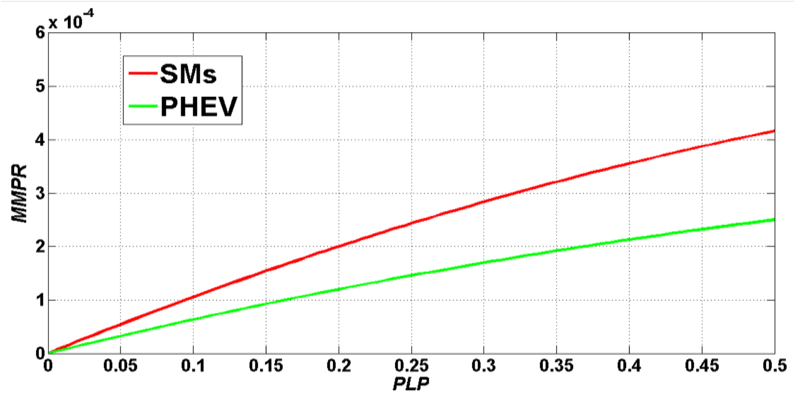


Figure 5.11 MMPR vs PLP

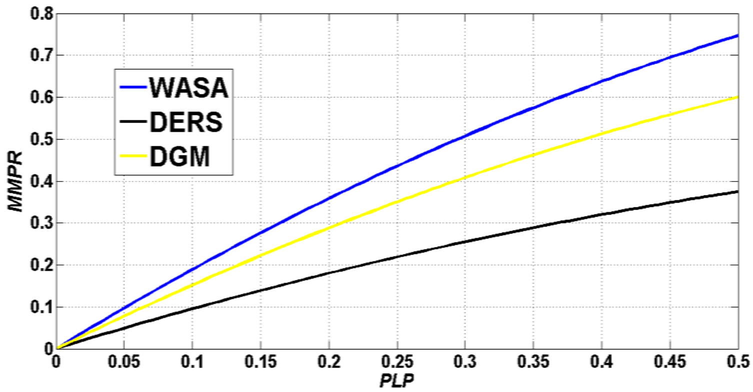


Figure 5.12 MMPR vs PLP

Higher MMPR allows having higher normalized value for reliability that results in a high value of the CF. Higher delay sensitivity of these nodes leads to higher MMPR in comparison with SMs and PHEV. It should be mentioned that mesh network and routing delay can be used in the delay KPI, thus the CFs are useful to make the communication network in an efficient way in this case. PLP as a function of service rate and receiver buffer size is shown in Figure 5.13. Based on the service rate and buffer size the PLP can be defined to be used as one elements of MMPR formula.

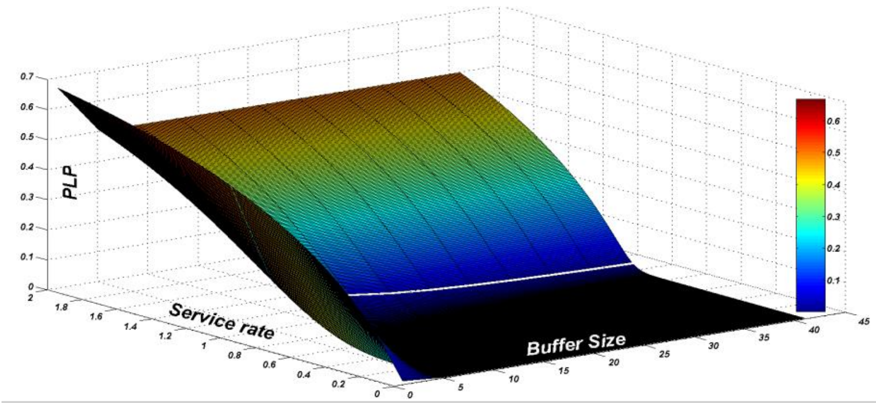


Figure 5.13 PLP as a function of Buffer Size and service rate [218]

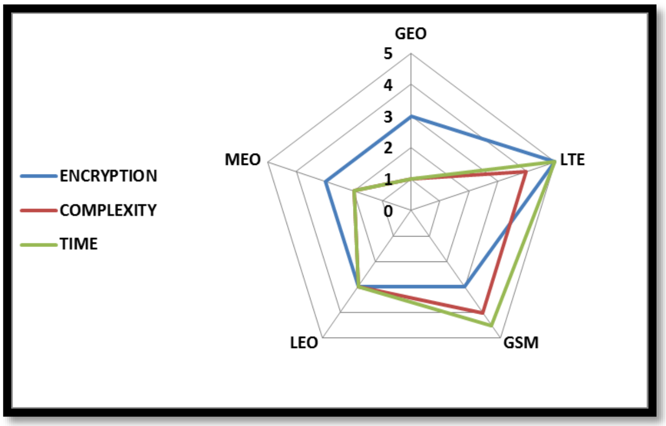


Figure 5.14 Satisfaction of each security

Here based on the first part of the proposed methodology results, the method to evaluate security elements those are introduced in methodology part are given at Fig. 5.14. By considering the Eb/N0, as it was discussed in the methodology part, primary results in order to elaborate a Het-Net, are combined with energy CFs of RATs and desirability values are achieved. Each RAT support certain traffic percentage of a certain SG node type as a result of achieved desirability values. Fig.5.15 and Fig.5.16 show the data rate and delay normalized (the communication CF) value for different type of the SG node over three different RATs.

Table 5.6. Communication requirements of the SG nodes

	Reference Data Rate [kb/s]	*Reference Latency [s]*	*Reliability*	*Security*	*Selected Data Rate [kb/s]*	*Selected Latency [s]*
AMI	500	2-15	99-99.99%	High	500	2
WASA	600-1500	.02-.2	99.999-99.9999%	High	1000	.05
DERS	9.6-56	.02-15	99-99.99%	High	40	1
PHEV	100	2-300	99-99.99%	Relatively high	100	5
DGM	9.6-100	0.1-2	99-99.999%	High	70	0.5

Some figures references values are shown in Tab. 6.5. CCF is shown in Fig 5.17.

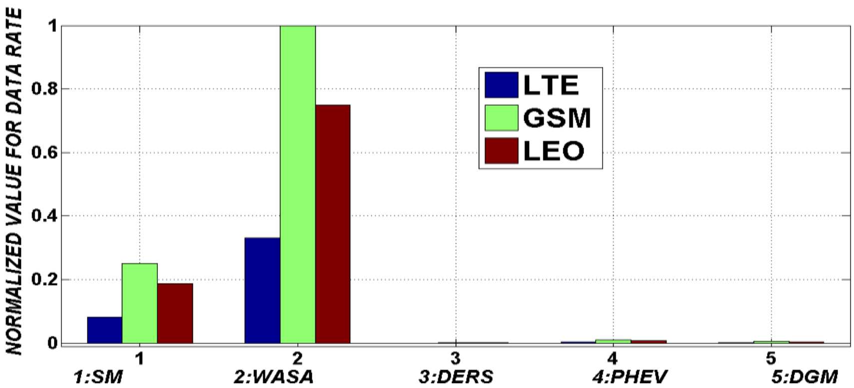


Fig 5.15 Data Rate Normalized value

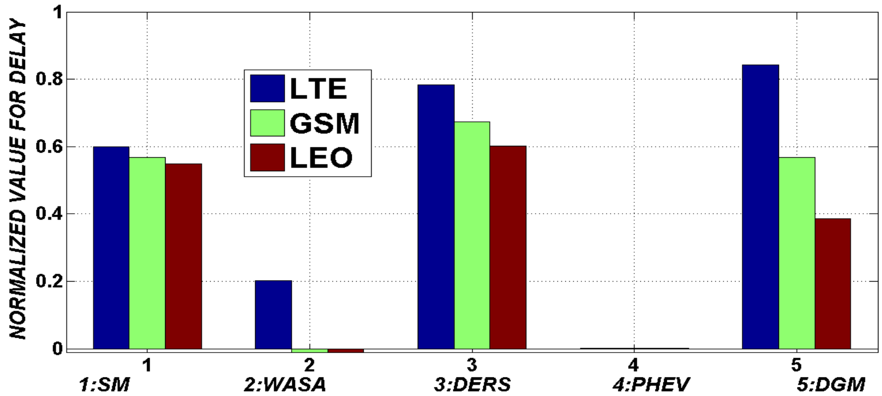


Fig. 5.16 Delay Normalized value

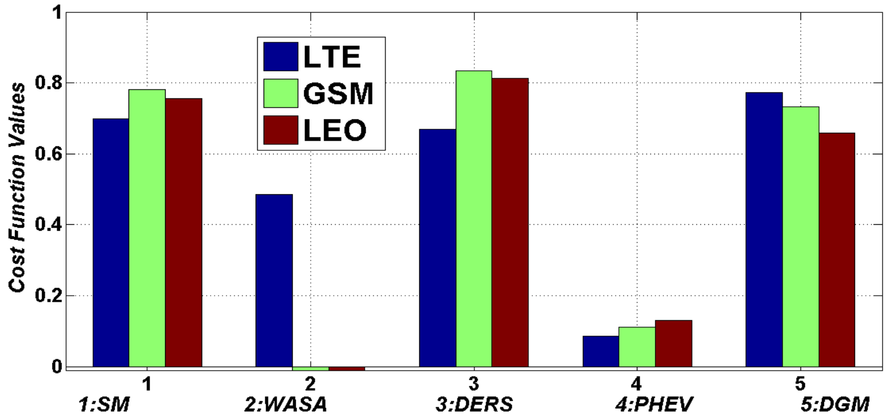


Fig. 5.17 CF value

The RATs resource can be allocated to the SG node based on the desirability value (which is achieved by using CF) in terms of communication aspects or even in terms of both energy and communication aspects. Based on the communication CF values which results to have the desirability values, the user assigning percentage to different RATs table can be made as it can be seen in Fig.5.18. UTC standard inputs are used in this section to evaluate the proposed method.

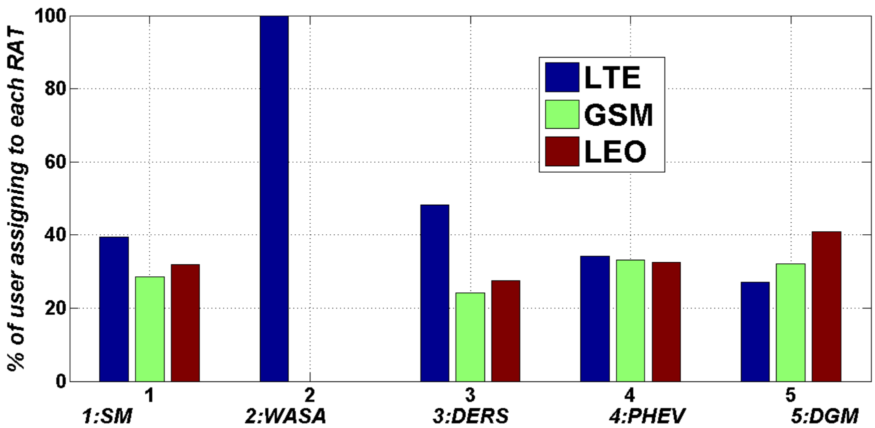


Fig. 5.18 Percentage of different type of the SG nodes assigning over RATs [218]

Satellite access technology using DVB-S2 protocol in which the direct end to end communication has been established between terrestrial station and satellite has much lower spectral efficiency comparing with LTE (using Shannon , refering to methodology part) but since its intrinsic latency is higher than LTE, the user assigning percentage difference between two mentioned RATs is not too considerable. Furthermore, the higher data rate requirement for AMI is among the highest data rate of the different node types, thus the data rate of each RAT plays a main function in terms of assigning percentage.

Due to high data rate requirements of AMI and GSM lower spectral efficiency (1.35 bits/Sec/Hz coding rate 5/6) the lowest user assigning percentages is assigned to GSM. User assigning percentage of satellite accesses technology (LEO constellation) is the lowest when the SMs are assigned to the RATs based on the communication KPIs desirability values.

Lower modulation mode has the potential for lowest energy per bit and a complex modulation scheme that packs many bits of data into each signal transition has the potential for higher energy per bits. But, there is a tradeoff; more complex schemes achieve higher information rates and as a part of one parameter of the proposed CCF has a great (not directly) effect on lowering or increasing the CCF value.

If system link margin is dynamic, then the combination of the complex CCF proposed and the ECF, both bandwidth and energy and many other communication parameters are considered. Schemes with lower Eb/N0 deliver more data for a fixed amount of energy, while those with higher Eb/N0 deliver highest transmission rate for a fixed amount of bandwidth.

After considering the energy desirability value in terms of joules per bits of information in combination of communication desirability values, due to LTE`s higher spectral efficiency, its assigning percentage decreases. The results can be seen in Fig.5.19 and Table. 5.7. For WASA, just LTE intrinsic latency can respect its delay requirements among the other available RATs because WASA delay sensitivity is very high. Accordingly, WASA nodes should be assigned to the LTE even if the energy desirability value is not high for it. In DERS and DGM both types of the nodes have similar communication requirements in terms of data rate, although DGM data rate is a bit higher. In terms of delay sensitivity because both types of nodes are partially low delay sensitive, GSM sounds to be a good option for them. DGM higher required data rate makes it more appropriate for LEO and LTE.

Its higher delay sensitivity makes it more apposite for GSM. GSM has lower reliability normalized value to support DGM comparing with LEO. Also, in sense of security KPI, GSM is better option rather than LEO.

For AMI, energy desirability value of LTE decreases the SG node assigning percentage to LTE. DERS has lower delay sensitivity which makes GSM more suitable for it but, its lower data rate comparing with DGM, occupy lower percentage spectrum in RATs with higher spectral efficiency such as LTE and LEO. Besides, reliability of LEO is better for DERS though security KPIs for DERS is better in case of using GSM. PHEV nodes due to its particular communication necessities such as data rate that equals 100 kbps which is high and also its delay sensitivity, 5 seconds, that is the highest delay requirements among the other SG node types, it has been somehow equally assigned to the different available RATs by considering the reliability and security KPIs in the proposed CF, regardless of considering energy desirability values.

For assigning PHEV nodes to different RATs there is a tradeoff between delay sensitivity which is the lowest here and its data rate that is somehow high. RATs with higher spectral efficiency make them as the better choice for PHEV. PHEV lower delay sensitivity makes the RATs with higher latency more suitable based on the defined CF.

After combining the communication desirability values and energy desirability values, Fig.5.19 shows the percentage of the users assigning to different RATs based on the finalized CF values for both energy and communication issues.

Tab. 5.7 shows node assigning percentages to different RATs based on Eb/N0 of each RAT [217].

Table.5.7 Assigning percentage of SG nodes over RATs (CE & EE) [218]

ϱ_j , Desirability%	**LTE: 19.67%**	**GSM: 41.07%**	**LEO: 39.27%**

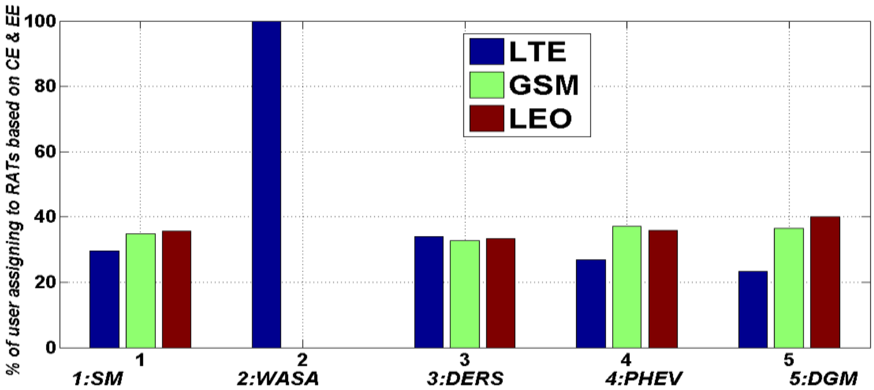


Fig. 5.19 Percentage (CE & EE) [217]

Table.5.8 Assigning percentage of SG nodes over RATs (CE & EE) [217]	LTE%	GSM%	LEO%
WASA	100%	0%	0%
SM	29.6%	34.8%	35.6%
DGM	23.4%	36.6%	40%
DERS	34%	32.7%	33.3%
PHEV	26.9%	37.1%	35.9%

At the next section the comprehensive results are given which are obtained after tradeoffs using several RATs communication characteristics and SG node types communication requirements.

5.3 Comprehensive Results Using All RAT`s Characteristics and SG Node Details

Different parameters in both node and RATs part are needed to be evaluated and their inputs are used in the defined CFs including the sub CFs and the main CFs. These parameters and communication configurations (C.Con) are shown in Tab.5.9. First, an overview of the conducted simulations is presented. Respect to the defined densities for different SG node types, the required data rate are measured based on the system model. Then the weights of each KPI are computed. At the next step different RATs with different communication characteristics are defined. Then the normalized value of each KPI for a certain node type which is supported by different RATs are computed. Moreover, the ECF for different RATs are computed. By simulating the implemented formulas in MATLAB, the node assigning percentage to different RATs as a result of computing desirability value of each RAT are achieved.

Tab.5.9 The parameters used to defined CFs

BER	PLL	SE	FEC	LATENCY	Service rate	Buffer Size	Response time	Encryption	SYSTEM complexity	Eb/N0	Frame size	Goodput	Access method	Modulation mode

Data size	**Generating rate**	Delay sensitivity	Security requirement	Reliability requirement	**Node density**	Node priority	**Buffering time**	**Sync nodes**	Collector buffer size	Geographical locations	Ack #

The different SG node types characteristics are shown in Chapter3 and are given in Tab. 5.10. It should be mentioned that for simplicity and doing an efficient network design, some same nodes among the different types of the SG node are considered as a unified node. For example, Wide Area Protection includes Adaptive islanding, Predictive under frequency load shedding and wide area control has Wide area power oscillation damping control which all of these nodes type have the same communication requirements and work in the same power domain , can be unified. Thus, based on the Table 3- 2,considering these three types of the node generate $(3 \times 200) Bytes$ (adding some more bit as the headers and the other issues to have the worst case) approximately 5000 bits every 100 milliseconds is generated and the calculation is based on this approach. Just for being clearer these unified nodes is called WASA1 in this work. Also two different node types with same average communication requirements, Wide area voltage stability control and Local voltage stability monitoring which can be unified. Thus approximately 300 Bytes are generated by both these nodes considering every 1 second.

Table. 5.10 The SG node communication requirements

Node	*Data Rate, bps*	*Delay sensitivity, Second*	*Generating period sec*	*Security*	*Reliability*
WASA1	5000	0.1	0.1	*High*	99.999-99.9999%
WASA2	8000	2.5	2.5	*High*	99.999-99.9999%
WASA3	3200	120	60	*High*	99.999-99.9999%
WASA4	5000	0.05	0.1	*High*	99.999-99.9999%
WASA5	1250	0.05	0.1	*High*	99.999-99.9999%
WASA6	1000	120	60	*High*	99.999-99.9999%
WASA7	2500	2.5	2.5	*High*	99.999-99.9999%
WASA8	15000	15	15	*High*	99.999-99.9999%
WASA9	75000	15	15	*High*	99.999-99.9999%
DGM1	10000	0.1	1	*High*	99-99.999%
DGM2	5000	0.025	1	*High*	99-99.999%
DGM3	5000	0.1	1	*High*	99-99.999%
DGM4	250000	0.15	1	*High*	99-99.999%
DERS	2400	3	4×3600	*High*	99-99.99%
PHEV	800	5	6×3600	*Relatively High*	99-99.99%
AMI	1000	2	15×60	*High*	99-99.99%

The summary of some figures which are useful to compute the CFs values are given in this section. Figures of two different node types one very high delay sensitive, WASA1 and another very low delay sensitive node type, DERS are chosen to be shown (just for one scenario and as a complementary description). Reference BW is 5MHz. The RATs that supports DERS have certain C.Con come as follows. Modulation mode 16QAM, coding rate 0.95, framing and propagation times 0.002 sec are some of main communication character for LTE. For GSM, GMSK modulation, coding rate 2/3 is chosen. In LEO, DVB-S2 protocol is used. Modulation mode is 8PSK and coding rate 2/3 is used. In MEO DVB-S2 protocol is used. The modulation mode 4PSK and coding rate 2/3 is chosen. In GEO DVB-S2 protocol, the modulation mode 4PSK and coding rate 2/3 are chosen.

The delays are given in Tab. 5.3. PLL equals to 0.01and processing time 0.005 msec are chosen for all RATs C.Con. RATs that support WASA1 node types have the same communication characteristics as above except modulation mode in LTE is 64QAM for these RATs. Figure 5-20 shows the effect of node number on the total delay (DERS). The policy was described in the system model but, as a reminder, after obtaining the total needed data rate to support a certain number of the nodes, here DERS, using 4.2, 4.3 and 4.6 show the time is needed to transfer the accumulated data in an aggregator to the CS.

The nodes have been synchronized and the results for DERS nodes are shown in Figure 5-.20-23. Here, the nodes have been synchronized.

As it was described in the communication characteristics and requirements part, each DERS generate 2400 Bits every 4 hours.

DERS delay sensitivity is 3 seconds. 800 bps data rate (i.e., one or two RB in LTE) can support the data is generated by 4800 DERS nodes connected to a collector.

The different synchronization policy can be implemented. As a simple example 4800 DERS data can be accumulated in the buffer of the connected collector and just by allocating a RB of LTE per seconds, all the data can be sent to the CS by around 3 seconds. It should be mentioned the density of DERS depends on the geographical area and can be reached to 2500 number per square kilometer. In case of having high node dense, the first DERS collected data in buffer is sent first.

It should be mentioned that assigning percentage of a certain node type to different RATs is sensitive to the density and number of the certain node types as well as the other parameters such as SG communication requirements and RATs communication characteristics.

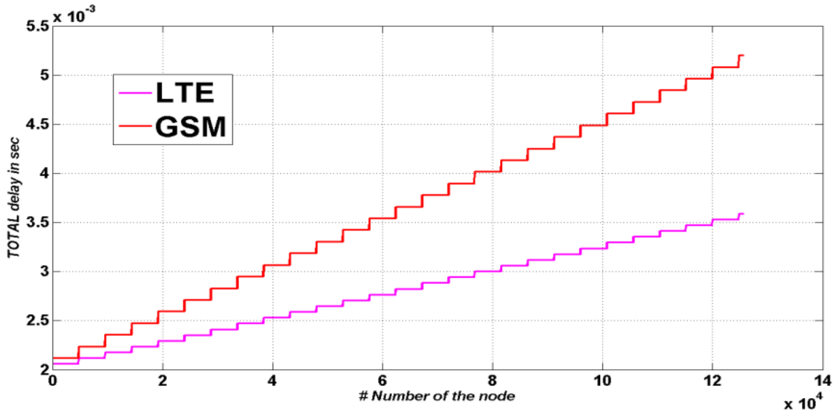


Fig. 5.20 Delay vs # DERS, For LTE &GSM [221]

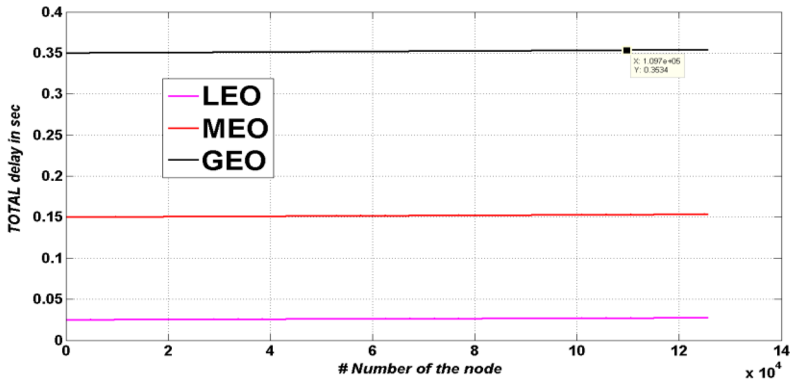


Fig. 5.21 Delay vs # DERS, For DVB-S&S2 different constelation

Fig. 5.20 and 5.22 and 5.23 show the nature of the synchronization methods. The certain number of nodes data is gathered in collectors for a certain period of time and then are transfres in the same time duration to the CS.

Therefore for the certain amount of the nodes data transfering time is same. The effects of propagation delay while using satellite communication is obvious in Fig.21. Fig.5.22 and 5.23 shows the data tansfering delay as the function of coverage radius and nodes density for two different types of RATs using the given protocols and C.Con.

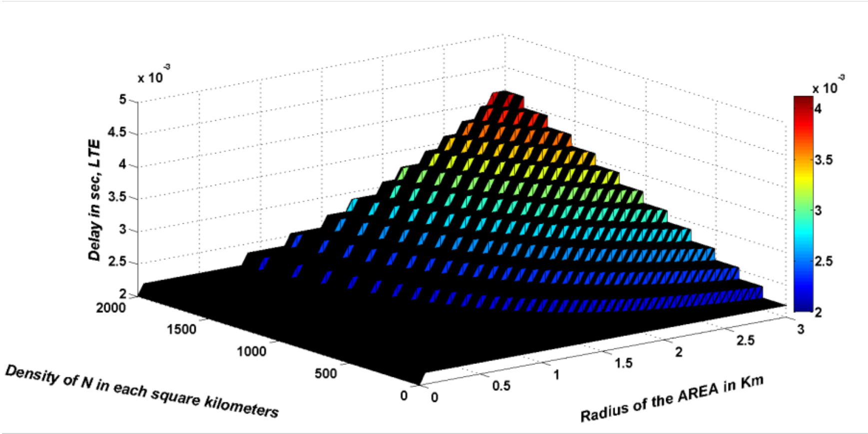


Fig. 5.22 Contour Delay vs # DERS, For LTE

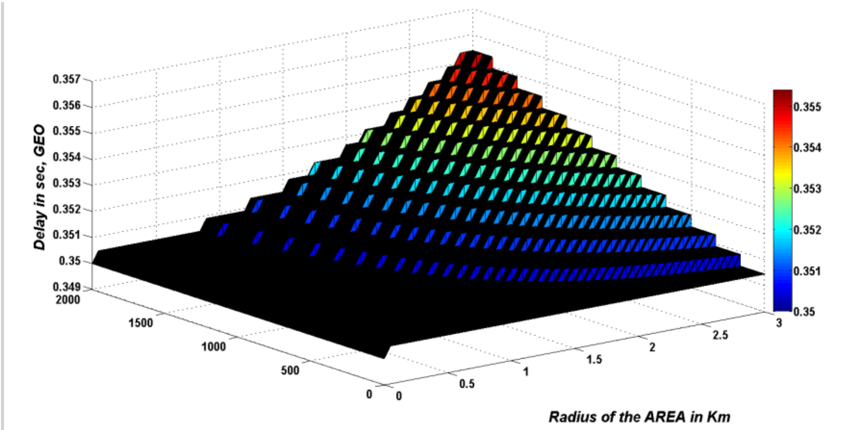


Fig. 5.23 Contour Delay vs # DERS, For DVB- S2 GEO constelation

As an example of synchronization, considering SMs generating 1000 bits data every 15 minutes and its delay sensitivity is 2 seconds.

Thus (as a rough assumption regardless the issues are discussed in Chapter 5) if 450 SMs generate data in order, each two seconds after previous one, then 500 bps is needed to support these amount of data (450×1000/15×60) bps [216, 221].

Figure 5- 24.1 and 5.24.2 shows the MMPR as a function of number of DERS nodes considering in both LTE and GSM respectively.

The synchronization methods have been used for all DERS nodes. Tab.5.3 shows some communication configuration and RAT characteristics which are used to obtain these figures. Maximum three acknowledgment messages has been used in satellite communications and based on the methodology part, using 5.9.2 and 5.11, and as it is obvious the MMPRs values for satellite communications are significantly high.

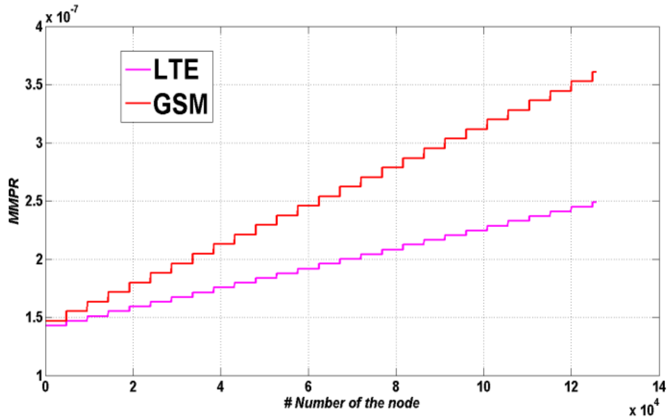


Fig. 5.24.1 MMPR vs number of DERS

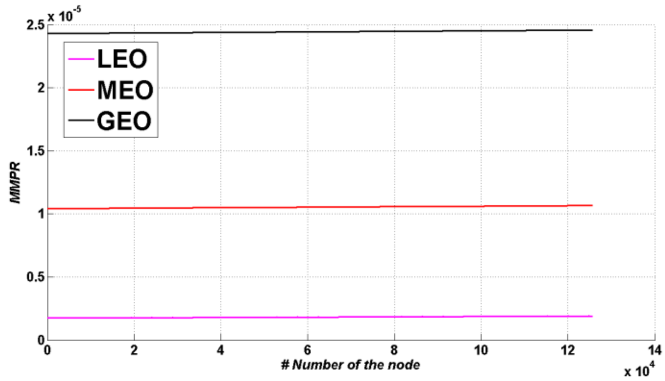


Fig. 5.24.2 MMPR vs number of DERS

Just a very important point should be reminded. For delay sensitive nodes that their generating rate is higher than their delay tolerance, more synchronized node can be supported (DGM4). The MMPR values for these types of the nodes with high required data rate and delay sensitivity, the exponentially behavior as a function of number of nodes are seen easily, Fig. 5.25.1 and 5.25.2. But for low delay sensitive, with low average data rate and very high generation time, the MMPR although still is exponentially, but its effect cannot be seen in the certain defined scale and defined node number, Fig. 5.24.1-2. Its effects are shown later in the node assigning to the different RATs.

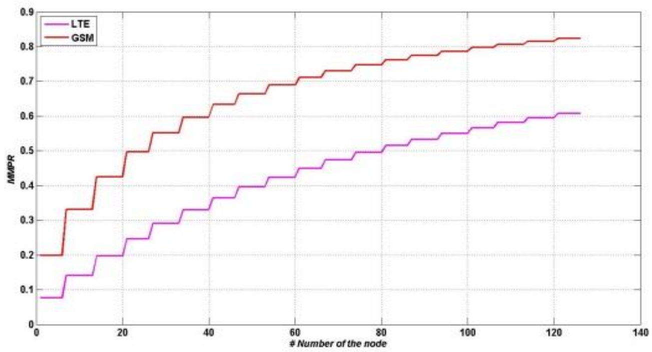


Fig. 5.25.1 MMPR vs number of DGM4 [220]

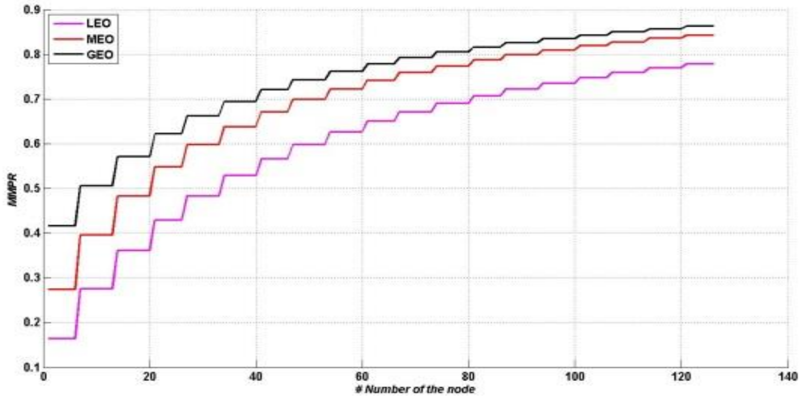


Fig. 5.25.2 MMPR vs number of DGM4 [220]

Figure 5.26 and 5.7 shows the MMPR as function of PLP and delay respectively. It seems Fig. 5.7 is linear but in fact it is not linear and due to high difference values between generating time period and delay sensitivity, this behavior is seen.

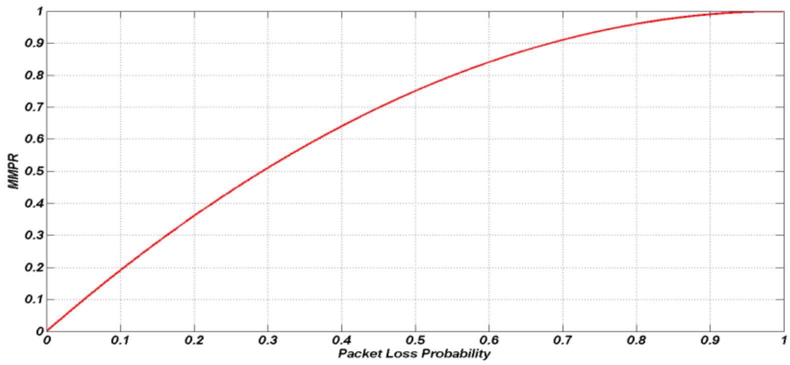


Fig. 5.26 MMPR vs PLP (DERS)

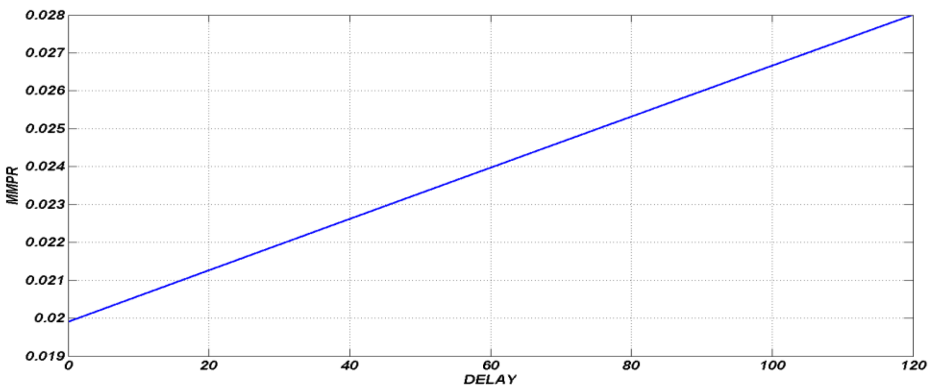


Fig. 5.27 MMPR vs Delay (DERS)

Fig 5.28 shows the 3D diagram of total needed bit rate as a function of area radius and node density for WASA1 node types. It discussed in detail in chapter 5 how data rate is calculated.

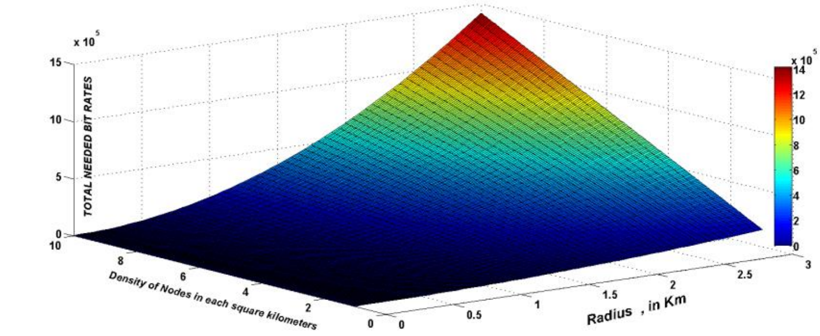


Fig. 5.28 WASA1 Bps as a function of radius(R) and nodes density(D)

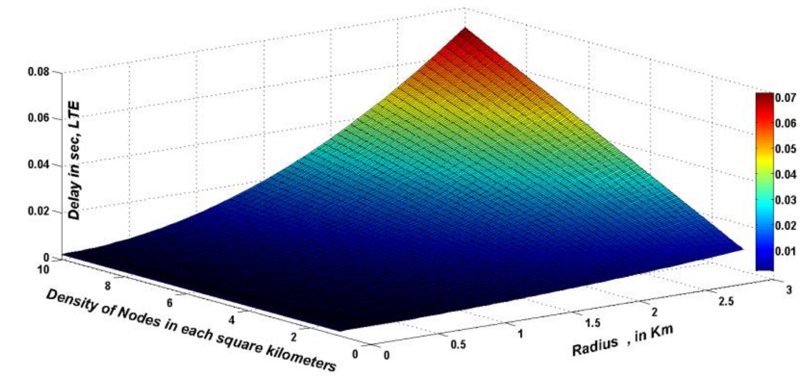


Fig. 5.29 WASA1 transferring delay as a function of R &D using LTE

Figure 5- 29 and 5.30 shows the delay as a function of density and radius in transferring data from collectors to CS by using LTE and satellite communication technology respectively with the certain C.Con which was described in this chapter. The propagation delay (GEO) is clear in Fig. 5.30.

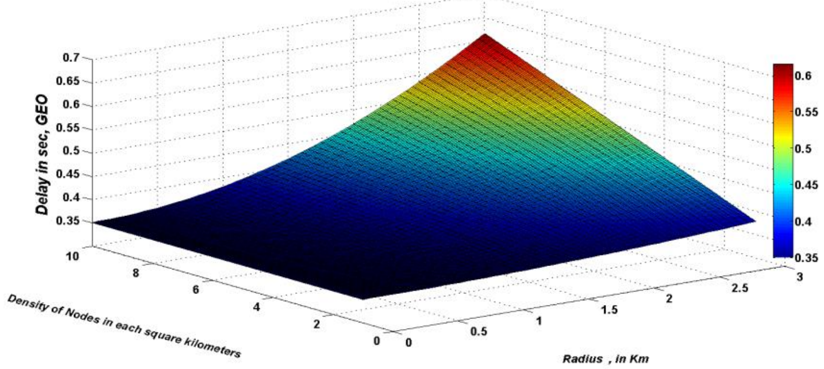


Fig. 5.30 WASA1 transferring delay as a function of radius and nodes density

Fig 5.31 shows the MMPR for WASA1 as a function of latency and PLP. Because its generating rate is high, MMPR effects grow fast.

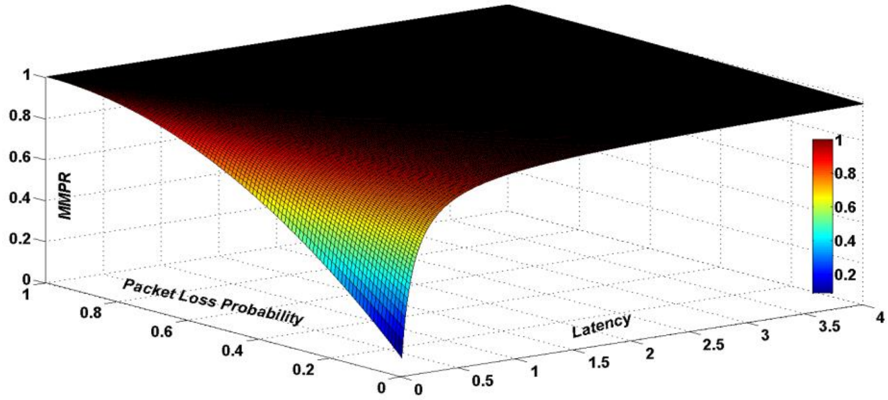


Fig. 5.31 MMPR as a function of latency and PLP for WASA1, generating rate equals to 10 mses

Fig. 5.32 and 5.33 shows MMPR as a function of number of nodes (WASA1) for different RATs which their C.Con are given in Tab.5.3.

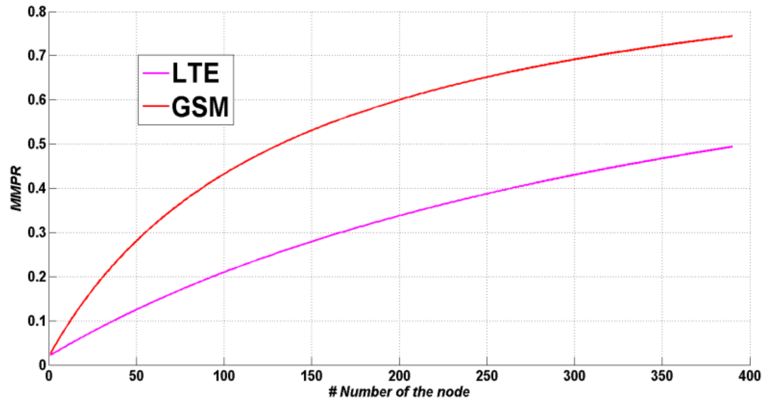


Fig. 5.32 MMPR as a function of number of nodes (LTE, GSM)

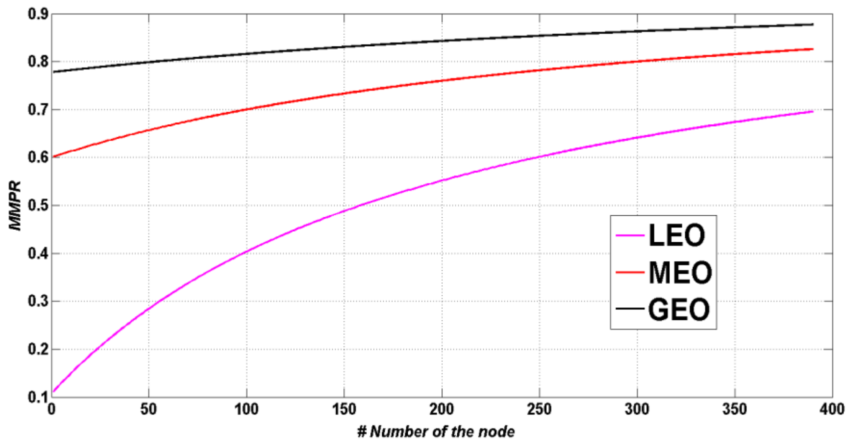


Fig. 5.33 MMPR as a function of number of nodes

Fig 5.34 shows the MMPR as function of delay for WASA1. Due to its feature and higher delay sensitivity and generating rate it is obviously different from Fig.5.27.

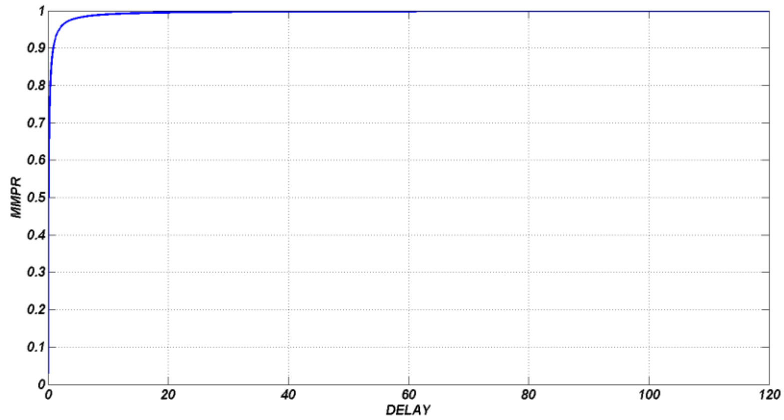


Fig. 5.34 MMPR vs Delay (WASA1)

These are just the tiny part of figures which are needed as the inputs to compute the KPIs for the main CCF. As it is shown in figurative way, a certain MMPR value for a certain node type can be desirable and for the other node with different characteristics can be totally unacceptable.

As it is discussed in depth in chapter 5, the ECF is achieved using 5.34.1-8. Fig. 5.35 shows EB/N0 as a functional spectral efficiency and Fig.5.36 shows the ECF for a certain spectral efficiency.

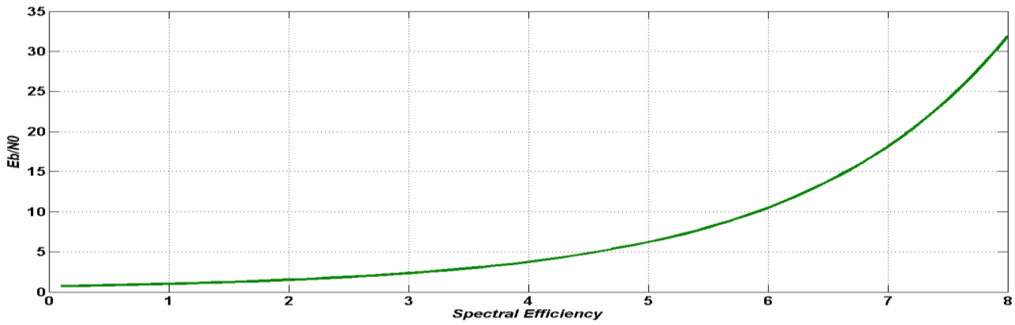


Fig. 5.35 MMPR as a function of number of nodes (LTE,GSM)

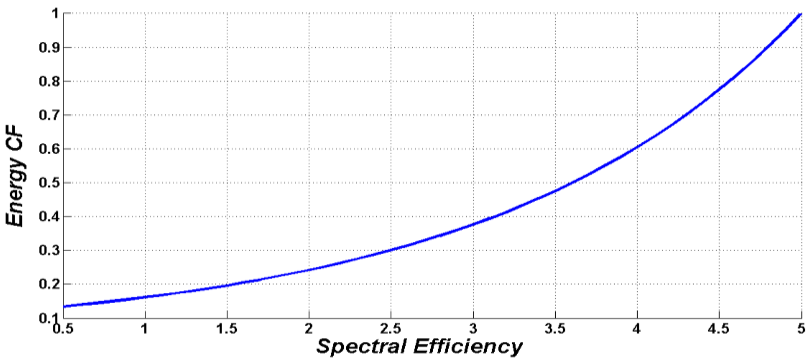


Fig. 5.36 MMPR as a function of number of nodes

Before going to see and analyze the other results which are more important, it should be mentioned for a certain PLL, i.e., 0.001 (in [135] considered 0.005) the MMPR as the function of latency and node generating rate is shown in Fig.5.37. PLL depends on the buffer size and the link efficiency, another two parameters which are needed to be used in the CCF.

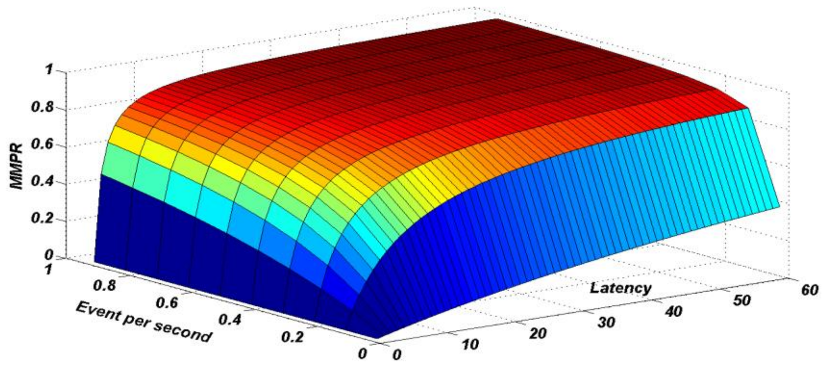


Fig. 5.37 MMPR as a function of generating rate and latency for PLL=0.001[216]

Table 5.11 and 5.12 are shown the RAT C.Con, node geographically information namely density and area size respectively for 10 different scenarios in sense of RAT and node numbers.

For example scenario one uses 5 different RATs each with different characteristics and C.Con. Goodput, Spectral efficiency, SE, coding rate and forward error correction, FEC, Packet Loss Probability, PLP, which also is a function of buffer size and link efficiency, Round Trip Time mostly including the propagation delay and Processing time, Process, in each RAT are given. Security evaluation of the system already is evaluated in the both chapter 5 (mainly) and this chapter.

The encryption method and algorithm which got used are given as well. There is no specific defined standard to choose a certain node density for a scenario but there can be found plenty of references which shows the node types numbers in some special area [134-144, 157] and [145, chapters 5,6,7 and 8]. The node densities vary based on many factors such as geographical are, sustainable energy resources availability and so on.

Table. 5.11 The Scenarios RAT communications characteristics and configurations [220]

SCENARIO 1						SCENARIO 6					
	LTE	GSM	LEO	MEO	GEO		LTE	GSM	LEO	MEO	GEO
SE	5.4	1.35	1.87	1.25	1.87	SE	3	1.9	2.5	1.7	3.2
Modulation	64QAM	GMSK	4PSK	4PSK	8PSK	Modulation	8QAM	PSK	8PSK	4PSK	16PSK
FEC rate	0.9	7/8	5/6	3/4	2/3	FEC rate	1	8/9	7/8	5/6	2/3
PLP	0.001	0.007	0.009	0.01	0.015	PLL	0.001	0.004	0.004	0.05	0.009
RTT	0.001	0.009	0.025	0.150	0.350	RTT	0.005	0.005	0.025	0.150	0.350
PROCESS	0.001	0.002	0.003	0.004	0.005	PROCESS	0.001	0.001	0.002	0.003	0.004
Encryption	AES	DES	3DES	AES	AES	Encryption	3DES	RAS	AES	3DES	3DES
SCENARIO 2						SCENARIO 7					
SE	4.8,5	1.35	2.9	3.2	3,9	SE	2	2	2.8	3.2	2.8
Modulation	32QAM	7/8	8PSK	16PSK	32PSK	Modulation	4QAM	4QPSK	8QPSK	16PSK	16PSK
FEC rate	1	0.95	8/9	7/8	5/6	FEC rate	1	8/9	2/3	3/4	2/3
PLP	0.01	0.01	0.03	0.01	0.1	PLP	0.002	0.001	0.003	0.01	0.005
RTT	0.005	0.009	0.025	0.150	0.350	RTT	0.005	0.005	0.025	0.150	0.350
PROCESS	0.001	0.002	0.003	0.003	0.003	PROCESS	0.001	0.002	0.003	0.004	0.005
Encryption	AES	RSA	DES	3DES	AES	Encryption	AES	DES	AES	3DES	AES
SCENARIO 3						SCENARIO 8					
SE	2.9	2.4	2.07	3.1	1.87	SE	6	3.8	2.8	1.6	1.6
Modulation	8QAM	8PSK	8PSK	16PSK	4PSK	Modulation	64QAM	16GMSK	8PSK	4PSK	4PSK
FEC rate	1	8/9	2/3	4/5	7/8	FEC rate	1	8/9	7/8	3/4	3/4
PLP	0.001	0.02	0.02	0.04	0.05	PLP	0.001	0.001	0.001	0.002	0.002
RTT	0.008	0.009	0.025	0.150	0.350	RTT	0.005	0.007	0.025	0.150	0.350
PROCESS	0.001	0.004	0.003	0.002	0.003	PROCESS	0.005	0.002	0.002	0.003	0.005
Encryption	DES	DES	RSA	3DES	AES	Encryption	3DES	DES	RSA	3DES	AES
SCENARIO 4						SCENARIO 9					
SE	4	1.5	1.60	2	3	SE	5.8	2	1.9	1.8	3.8
Modulation	16QAM	4PSK	PSK	4PSK	8PSK	Modulation	64QAM	GMSK	4PSK	4PSK	16PSK
FEC rate	1	8/9	7/8	3/4	2/3	FEC rate	0.9	2/3	7/8	7/8	5/6
PLL	0.001	0.001	0.02	0.03	0.04	PLL	0.007	0.003	0.007	0.008	0.01
RTT	0.005	0.008	0.025	0.150	0.350	RTT	0.005	0.005	0.025	0.150	0.350
PROCESS	0.005	0.005	0.005	0.005	0.005	PROCESS	0.002	0.002	0.002	0.002	0.002
Encryption	AES	3DES	AES	AES	AES	Encryption	3DES	3DES	3DES	AES	3DES
SCENARIO 5						SCENARIO 10					
SE	4	4	4	4	4	SE	4.9	1.7	3.8	2.9	1.87
Modulation	16PSK	16PSK	16PSK	16PSK	16PSK	Modulation	32QAM	GMSK	16PSK	8PSK	4PSK
FEC rate	1	8/9	3/4	3/4	3/4	FEC rate	1	9/10	2/3	3/4	7/8
PLL	0.01	0.01	0.01	0.01	0.01	PLL	0.004	0.001	0.007	0.006	0.005
RTT	0.005	0.005	0.025	0.150	0.350	RTT	0.005	0.005	0.025	0.150	0.350
PROCESS	0.001	0.001	0.001	0.001	0.001	PORCESS	0.001	0.001	0.001	0.001	0.001
Encryption	AES	3DES	DES	AES	3DES	Encryption	AES	3DES	AES	AES	AES

Table. 5.12 The different Scenarios, for different node types, Coverage area radius (R) and Node Densities (D)

Scenarios R,D / Node types	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6		Scenario 7		Scenario 8		Scenario 9		Scenario 10	
	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D
1 AMI	3	500	5	50	4	300	2	3000	3	1000	3	400	4	300	3	100	4	8	1	2000
2 PHEV	40	3000	30	2000	30	1000	30	3000	40	200	30	3000	10	800	2	900	50	40	2	4000
3 DERS	40	3000	40	2500	20	4000	40	2000	20	300	40	800	32	3000	40	2000	10	30	30	400
4 DGM1	1	4	1	5	2	1	1	4	1	2	2	1	1	1	2	1	1	1	2	2
5 DGM2	1	100	2	20	2	20	2	15	1	18	1	120	1	30	1	14	1	11	2	7
6 DGM3	1	100	2	15	2	25	6	6	3	5	3	9	1	15	3	7	1	2	2	26
7 DGM4	1	5	1	3	2	1	1	4	1	2	1	2	1	3	2	1	2	1	1	3
8 WASA1	3	10	2	12	3	2	5	1	4	2	2	2	3	3	3	2	1	1	1	1
9 WASA2	1	40	1	25	1	80	2	13	1	6	2	6	2	2	2	5	2	4	1	3
10 WASA3	1	2000	3	300	2	700	3	250	2	800	3	100	1	600	3	200	2	55	2	33
11 WASA4	1	8	2	2	1	10	2	3	2	3	1	4	1	9	2	1	1	3	1	2
12 WASA5	1	4	2	2	2	2	1	3	2	10	1	1	1	3	1	2	1	1	2	2
13 WASA6	3	200	1	300	2	250	2	150	4	100	1	20	3	80	2	250	1	400	3	25
14 WASA7	2	1	3	1	1	3	2	2	1	30	2	2	2	1	1	2	1	3	2	1
15 WASA8	5	10	4	8	3	7	3	9	4	60	4	8	3	7	3	3	1	15	2	10
16 WASA9	5	10	6	3	3	8	4	15	2	8	3	25	2	18	3	15	4	10	8	2

By using (4.15-2) and tables and formula in chapter5, normalized values of security, NSE_{ij} for different RATs are achieved and normalized to 1. As an example he mentioned values for just one scenario (described before) come as following; {0.357143, 0.5, 0.642857, 0.821429, 1} [216].

At first scenario,S1, as it can be seen from Tab.5.11the highest and lowest SE belongs to LTE and GSM respectively. It should be mentioned that the numbers of X axis indicates to the type of the nodes and it can be seen in the first column of the Tab.5.12. Because the samples and nodes are so many, thus some of them are explained on the same discussion and policy can be extended to the other different scenarios.

Although using 64QAM due to its high SE difference comparing with the other RATs cause to have the lowest CF for all SMs node types among the other RATs, but in general, due to modest dense of SMs, its very high SE causes it to be the best in this scenario, Fig.5.38. The priorities of RATs for different node types are different with each other due to many tradeoffs. The node types 2 and 3 although have the different CCF values but in sense of their RATs priority behaves in the same manner. But node type 4 behaves in different manners. Its delay tolerant is less than GEO orbit satellite propagation latency, thus GEO (when it is said GEO, MEO or LEO, for simplicity it indicates satellite communications with DVB-S or DVB-S2 protocols having the diverse communication configuration which are given in Tab.5.11) may not able to support it and also the LEO choice has lower CCF comparing with GSM and the tradeoffs such better SE, better encryption method and more fitness in delay sense and the other matched issues achieved by using the node details and RAT characteristics in this table makes it more suitable. For node 5 and 6 the same behavior are shown in sense of their RATs priority. But, the CCF for LEO lowers for node 6 (DGM3) because of delay fitness is closer to LEO rather than LTE. Node7 has the best fattening in sense of delay with LEO and although LEO is better choice than GSM but nodes required higher data rate in tradeoffs with transferring time, has a good effect on the reliability part of the CCF.

The same discussion can be done for node 8, 12 and 7 but because the node 7 requires higher data rate, its CFs values are higher than node 7 but the priority are the same and the values are achieved based on all of these tradeoffs. The same discussion can be done for node 9 and 2 although the tradeoffs are not straightforward to be known just by the figures and tables of CCF details. For node 10 and 13 which almost have the same manner, the behavior comparing with other nodes are somehow different.

High generating rate and high delay tolerance and using high level encryption in GEO and MEO causes delay KPIs and reliability effects on CFs values being highlighted. For the nodes 14, 15 and 16 the same behavior are seen, although the values of CFs are different. As MEO has the lowest SE and nodes generating rate and delay tolerant are high , thus the nodes have been assigned based on the CCF in which the SE effect have been bolded. Fig.39 shows the ECF and the node assigning percentage just based on the ECF using equations 4.34.5-10. Fig.5.40 shows the node assigning percentage to different RATs based on the CCF using equations4.34.12, 13. As it can be seen in Fig.5.41, the nodes have been assigned to different RATs by using combination of both CCF and ECF using equations 4.34.15-17 and as it can be seen percentage of allocation for high level modulation RATs has been decreased. The key results such as assigning different node types as a function of their density, communication requirements and RATs communication characteristics are done. Matching a certain node type communication requirements with RATs communication characteristics includes several tradeoffs. The node with low delay sensitivity requirement should be supported by high latency RATs. This latency decreases the system reliability. Moreover, the RAT transmitter SE results in increasing the data rate and Eb/N0, the desirable and non desirable criteria respectively. Each KPI is a function of several parameters and optimized node assignments are done based on these parameters. They are used in the CFs in order to do efficient tradeoffs in sense of communication and energy CFs parameter. By using this method , the entire spectrum or high percentage of a RAT spectrum are not allocated to just a certain node type in order to have an efficiency in network designing to avoid facing with spectrum scarcity.

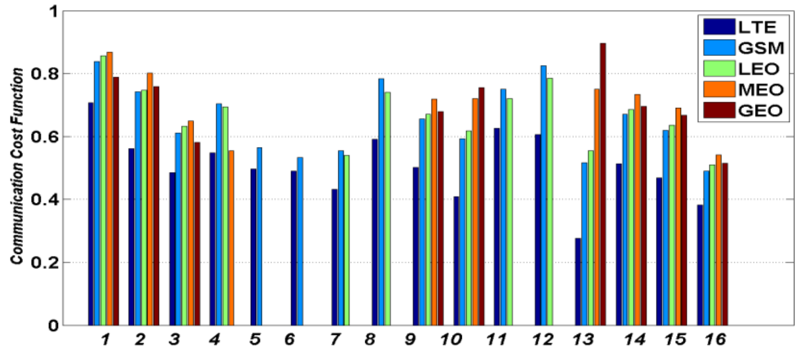


Fig. 5.38 CCF (S1 means scenario 1, Sn: Scenario n)

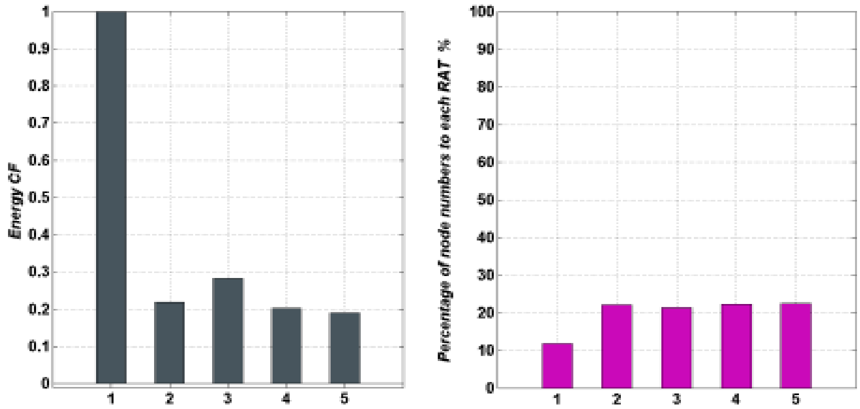


Fig. 5.39 Percentage, ECF (S1)

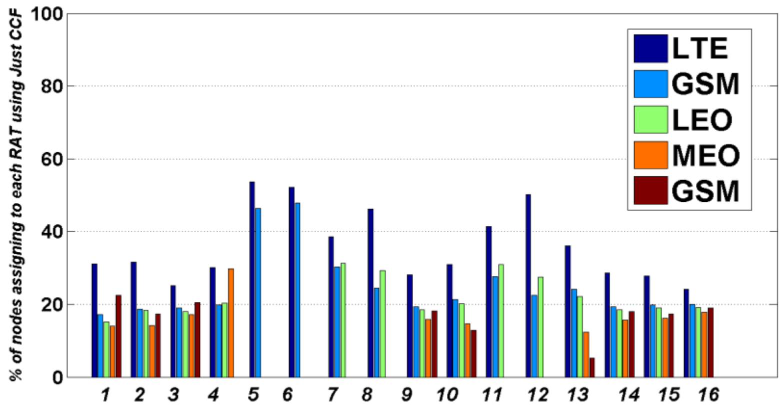


Fig. 5.40 Node assigning based on CCF (S1) [221]

As it is mentioned the defined method for assigining the certani node type traffic to different RATs is sensitive to the node type densities and is changed by changing the node types densities.

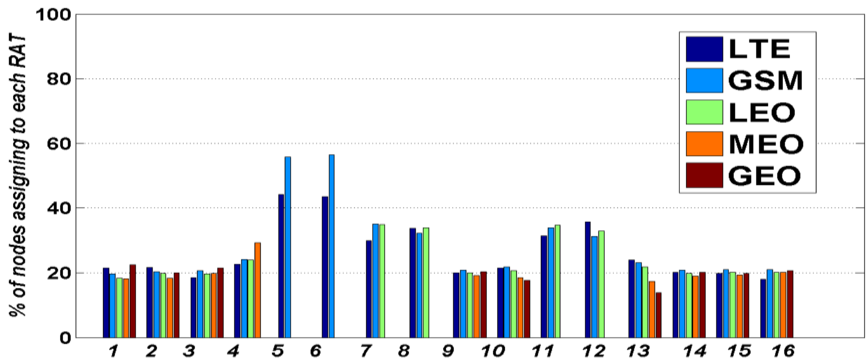


Fig. 5.41 Node assigning based on CCF and ECF (S1)

In S2, Fig 5.42-45, the area is a low node dense area. For node 1, rather than LTE, MEO and GEO CF values show a better performance. They high SE makes them better RATs than GSM and LEO. Although the higher SE of LTE comparing with GEO should make the CCF lower but GEO characteristics such as high delay fitness with SMs, its coding rate and the other characteristics makes it the best choice for SMs. Comparing SMs in S2 with SMs in S1, in S2 the MEO has been better option comparing with LEO and GSM. Its high SE in tradeoffs with higher matched delay with SMs makes MEO slightly better than GSM and LEO. The same behavior can be explained as it shown in S2 for node type 2, 3 and 9.

For the node type 4 in S2, different behaviors are shown. The MEO is the best RAT in sense of CCF but GSM shows lower CCF comparing with the same node in S1.

MEO`s higher SE in combination with its higher delay fitness makes it better choice even than LTE. For the nodes 5 and 6 in S2, although still LTE SE is higher than GSM SE, but GSM higher defined delay in both RTT and processing time, makes GSM better in sense of CCF. Although in node 7 in S2 can be seen some changes in CCF values comparing with the same node at S1 but, even with lower LTE SE in S2, due to density of the nodes and changing the CCF, it shows the better performance in S2 comparing with S1.

For node8 in S2 the same description as node 7 can be done. For node 10 and 13, they do not have the same manner as S1. the behavior comparing with other nodes are somehow different. For node 10, S2, GEO CCF is lower than GSM, LEO and MEO but in node 13, GEO CCF is just lower than MEO. By taking a look at the node densities in these two scenarios, node 13 has lower numbers. Higher density in node 10 increases the CFs for RATs with lower SE.

Nodes 11 and 12 in S2 has the same description as S1.The RATs priorities for NODES 14, 15 and 16 are same but are different comparing with S1due to different node densities using different C.Con in S2.The same ECF approach, node assigning based on the CCF and based on the both CCF and ECF are shown for S2 in Fig.5.43-45.

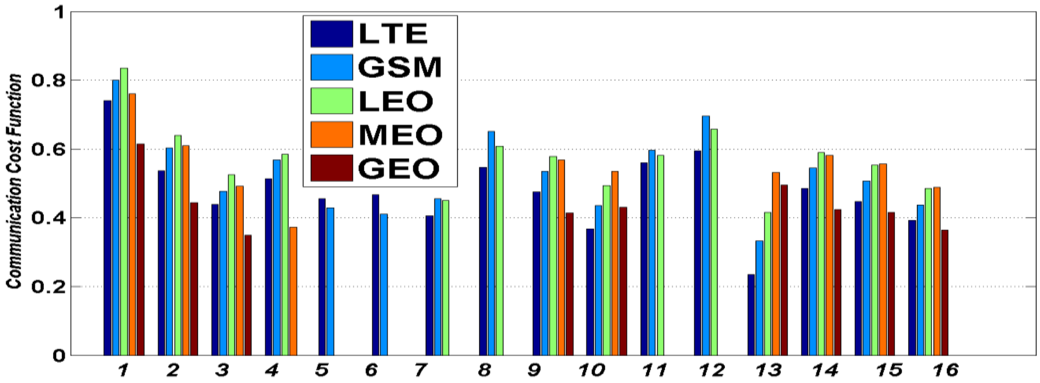


Fig. 5.42 CCF (S2)

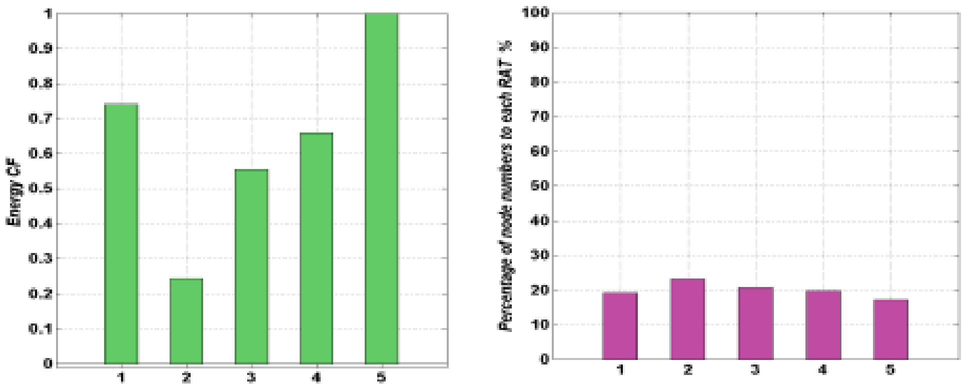


Fig. 5.43 Percentage, ECF (S2)

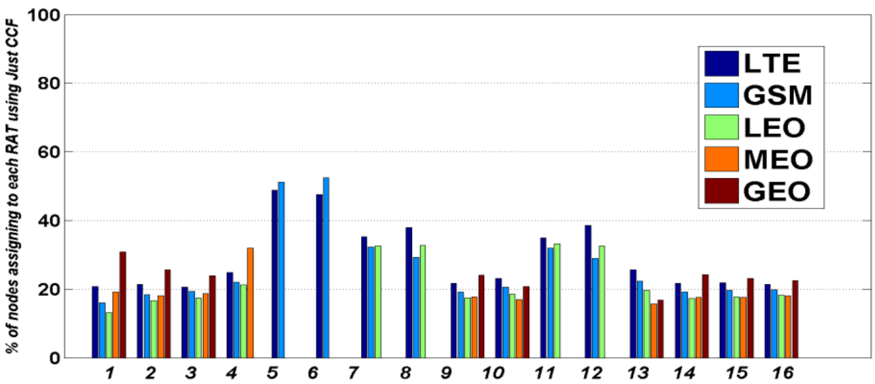


Fig. 5.44 Node assigning based on CCF (S2)

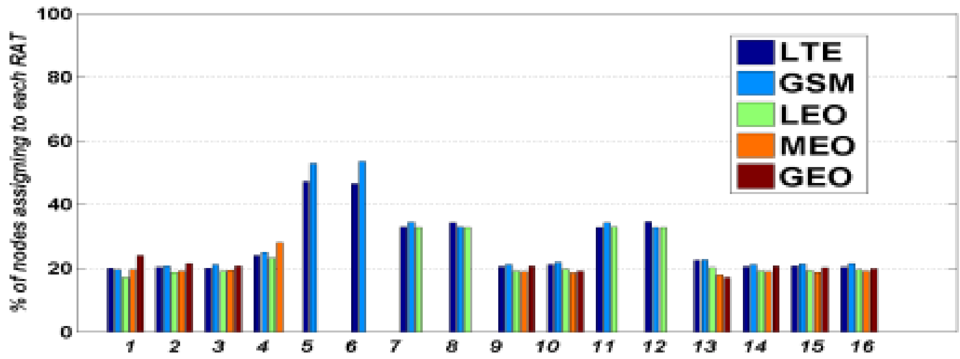


Fig. 5.45 Node assigning based on CCF and ECF (S2)

At S3, node 7 due to having high number of nodes whose data requirement are high, the effect of SE is bolded and even LTE has the lower PLP. The other tradeoffs such as security and reliability cause to have these values for CCF.

The other description of S3 is like the S2 and S3. The lower modulation mode used in S3 is obviously clear in the CCF differences and also in node 16 CCFs. As it can be seen, none of C.Con cannot affect the CCFs meaningfully values without considering the other node effects to calculate the CFs values and RATs characteristics and other C.con.

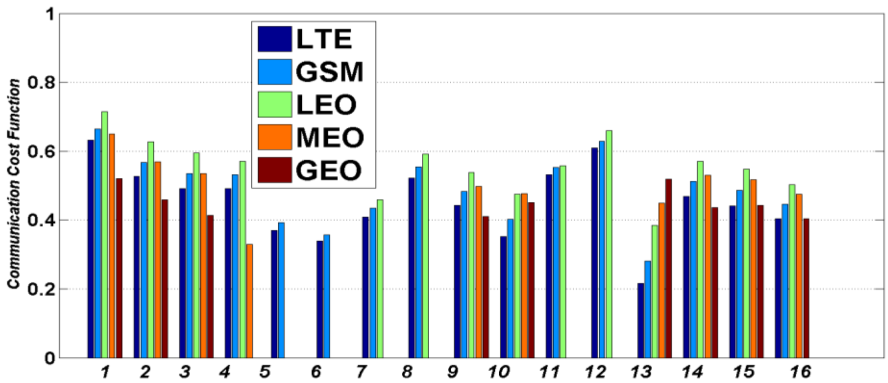


Fig. 5.46 CCF (S3)

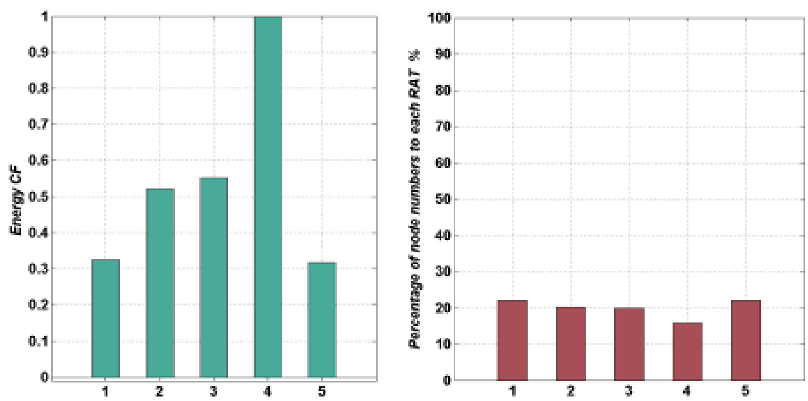


Fig. 5.47 Percentage, ECF (S3)

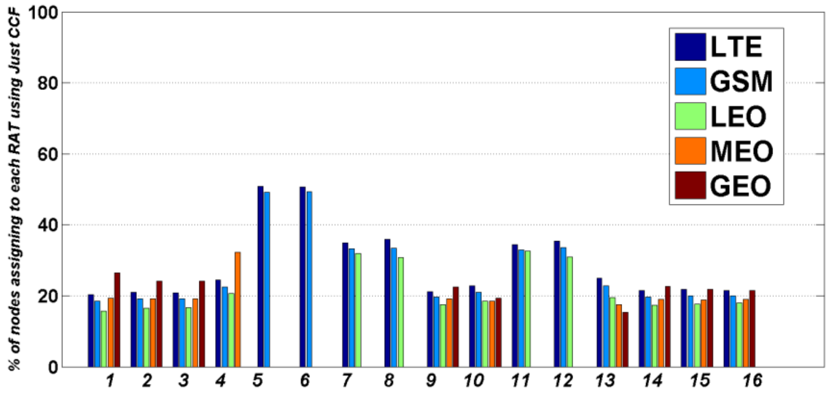


Fig. 5.48 Node assigning based on CCF (S3)

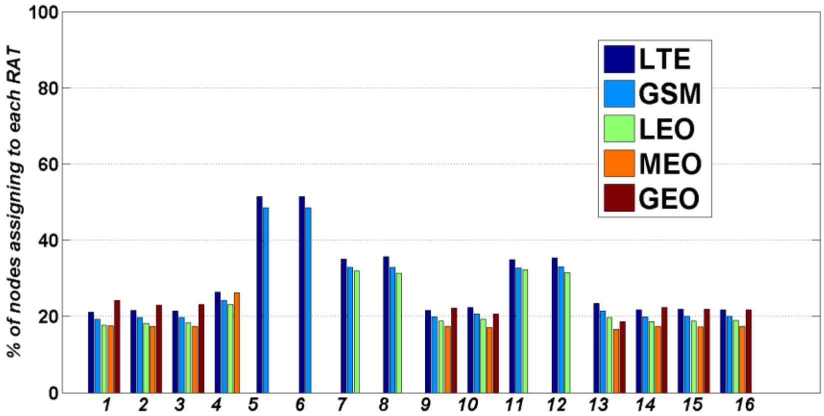


Fig. 5.49 Node assigning based on CCF and ECF (S3)

At S4, S5 and S8 in general the same behavior are seen, Fig 5.50-53, Fig.5.52-55, Fig.5.66-69. Although the same RATs in these three different scenarios have used different C.Con and even the defined node densities and numbers are totally different and has been considered high, medium and low dense area, still some behaviors in sense of RATs priority for different node types in these 3 scenarios exist although some significant differences can be seen in sense of RATs priority for some node types. At S4 and S5, node types 1,2,3,4,5,6,9,11,12,13,14 and 16 shows the same behavior in sense of RATs priorities used by proposed CCF for each same node in S4 and S5.

For node 1-3 LTE is the best choice in sense of CCF value but at node 4, MEO is the best choice. Node 4, DGM1, due to its high data rate requirement and high delay sensitivity cannot be supported by GEO. As MEO has the highest degree of delay matching with MEO, although it does not have the high SE but, considering its high level of encryption, it is the best choice for DGM1, even better than LTE, regarding to the tradeoffs are discussed in chapter 5. Even in S5 that all SE are considered equal or in S8, MEO has the lowest SE but still is the best choice for DGM1.

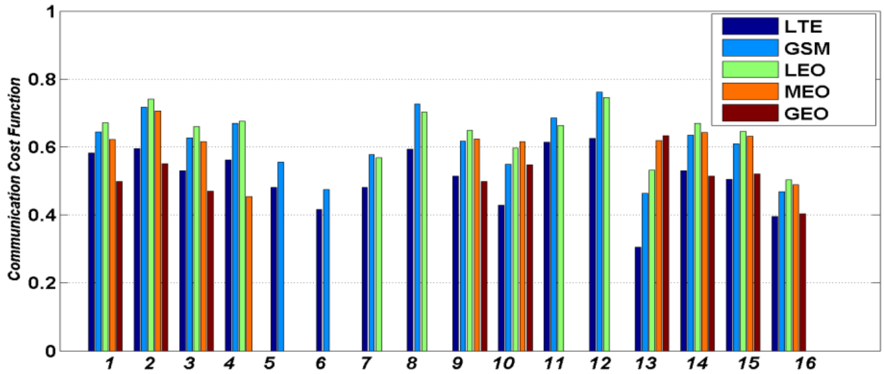


Fig. 5.50 CCF (S4)

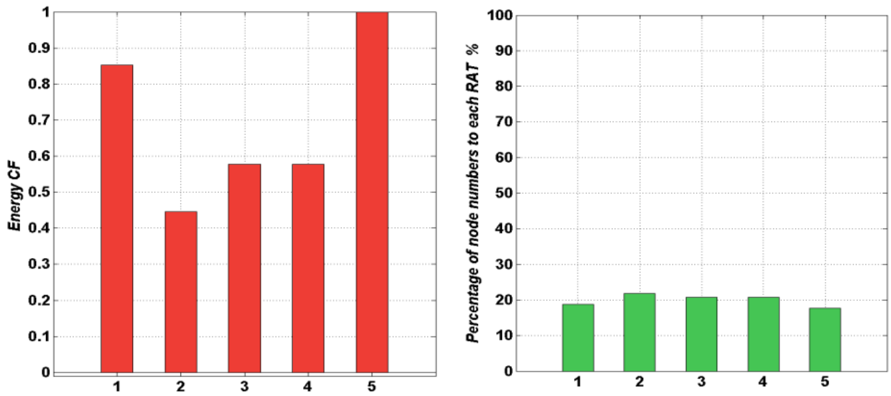


Fig. 5.51 Percentage , ECF (S4)

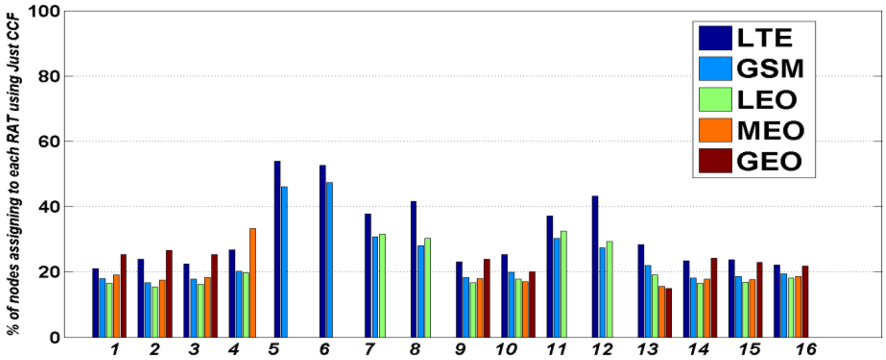


Fig. 5.52 Node assigning based on CCF (S4)

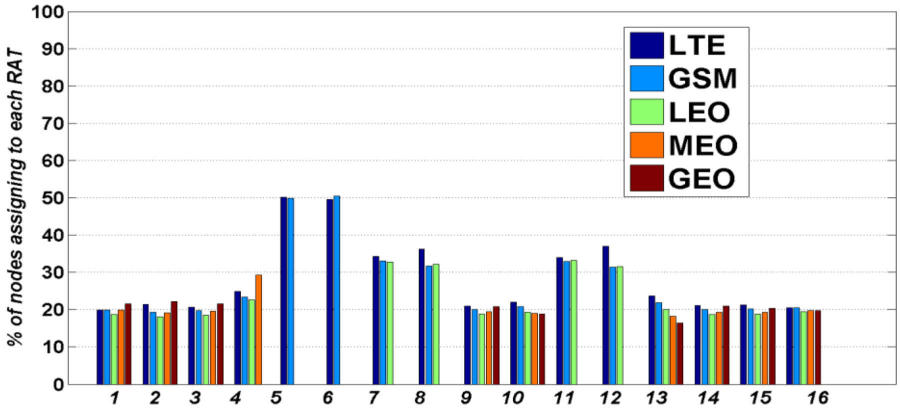


Fig. 5.53 Node assigning based on CCF and ECF (S4)

In S4 , the high PLP in GEO causes its reliability is being low and lower PLP in MEO causes the required data rate such as node 13, having lower CCF and its effects is highlighted. Due to high amount of data rate required by node 5 and 6, and as somehow same latency which in GSM and LTE have been considered, respecting to the all considered configurations, LTE is slightly better than GSM for node 5 and 6.

Then the node assigning process is done using both CCF and ECF. Any different node assigning to the RATs causes on higher CCF or higher ECF. At S4, S5 and S8 node types 4,5,6,9, 13, 14 and 16 shows the same behavior in sense of RATs priorities used by proposed CCF for each same node in S4, S5 and S8.

The level of encryption which is used as a part of security KPIs, is another criteria changing the node assigning policy. In S5 , Node 8 , GSM has lowers CCF than LEO and because its encryption algorithm and coding rate is somehow better than LEO and even delay fitting of LEO is better but due to the mentioned reasons GSM has lower CCF.

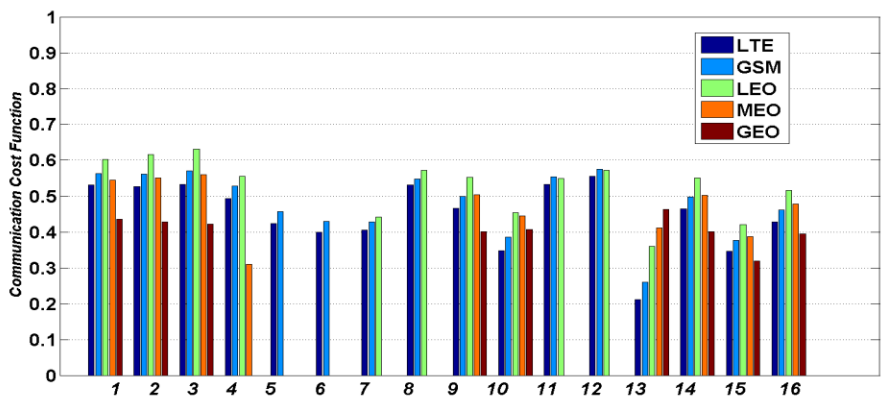


Fig. 5.54 CCF (S5)

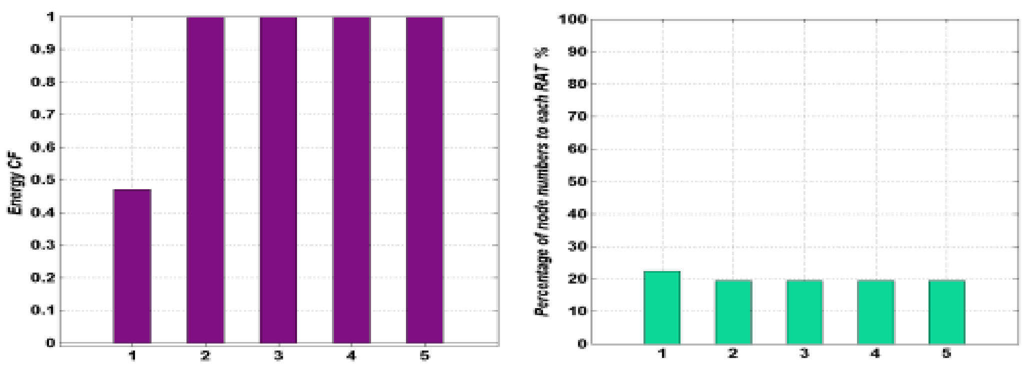


Fig. 5.55 Percentage, ECF (S5)

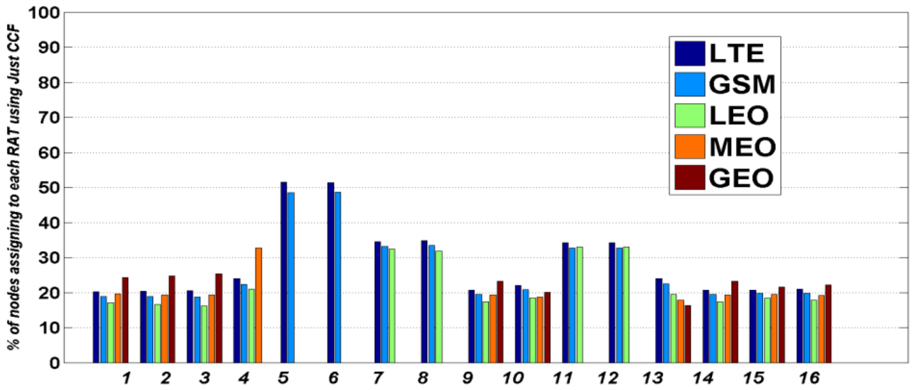


Fig. 5.56 Node assigning based on CCF (S5)

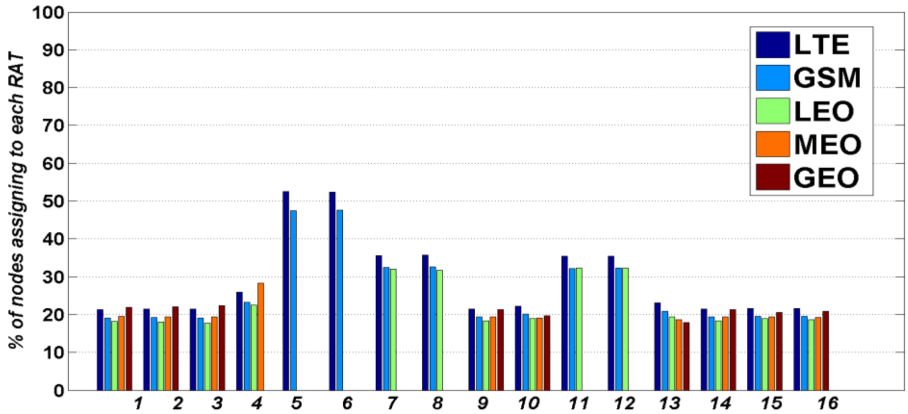


Fig. 5.57 Node assigning based on CCF and ECF (S5)

At S6 and S2 in general the same behavior are seen, Fig 5.58-61 and Fig.5.42-45. S6 is a scenario in which nodes densities are slightly low.

High value of PLP for nodes with lower density and lower required data rate causes PLP role in reliability being bolded and as it can be seen in S6 details, for example, GSM for node9 has lower CCF comparing with MEO due to its lower PLP.

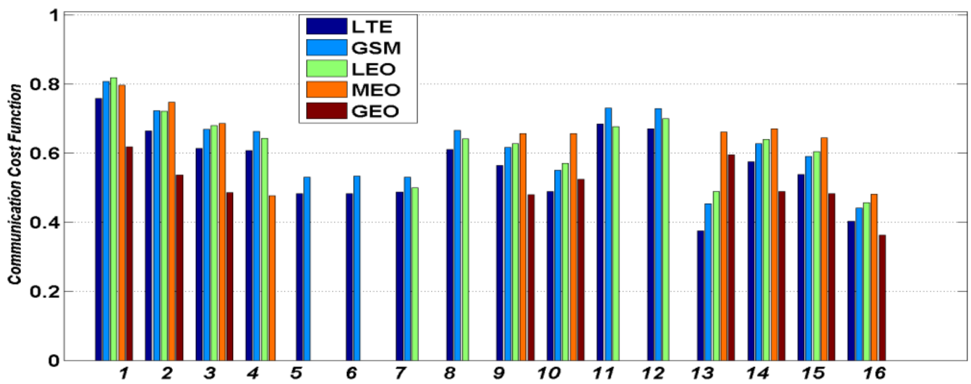


Fig. 5.58 CCF (S6)

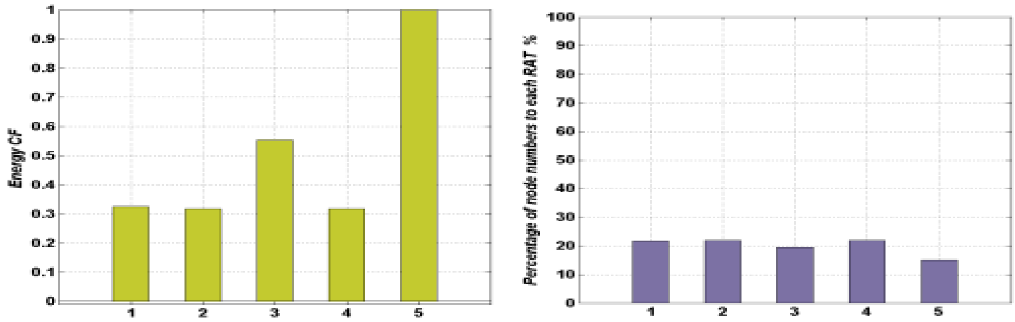


Fig. 5.59 Percentage, ECF (S6)

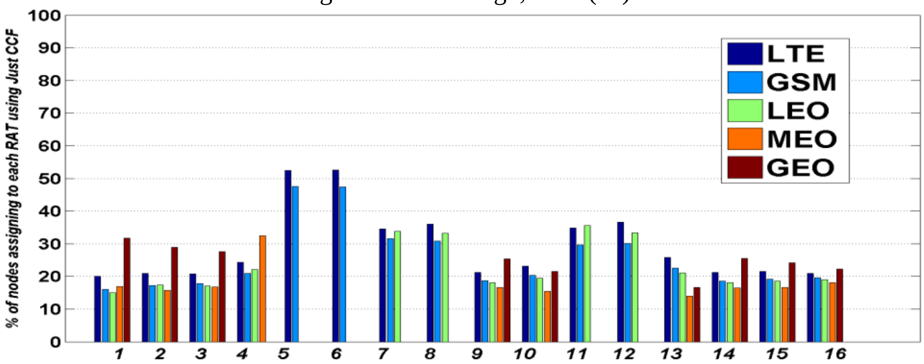


Fig. 5.60 Node assigning based on CCF (S6)

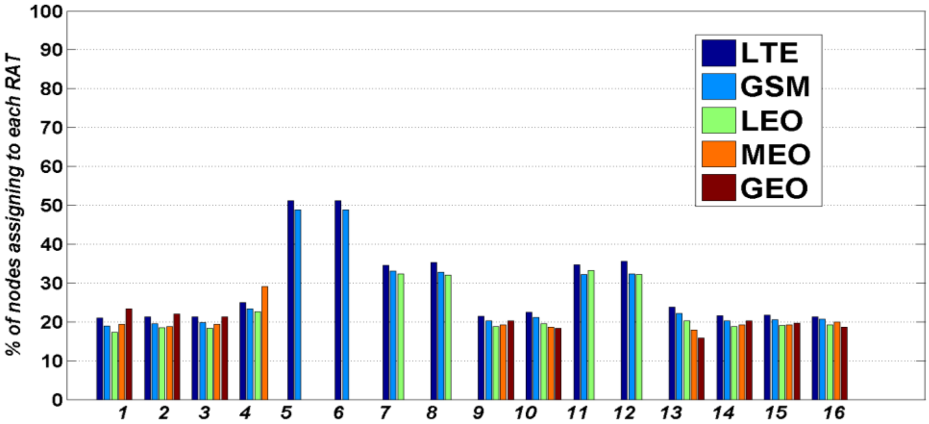


Fig. 5.61 Node assigning based on CCF and ECF (S6)

At S7, S9 and S10 in general the same behavior are seen, Fig 5.62-65, Fig.5.70-73, Fig.5.74-77 For the different scenario, the priority of different SG node types are changed based on the node type numbers and the given communication configurations for different RATs.

Node 9, lower generating data rate in average has the best match with GSM among GSM and MEO. Higher PLP in MEO increases the reliability KPI values.

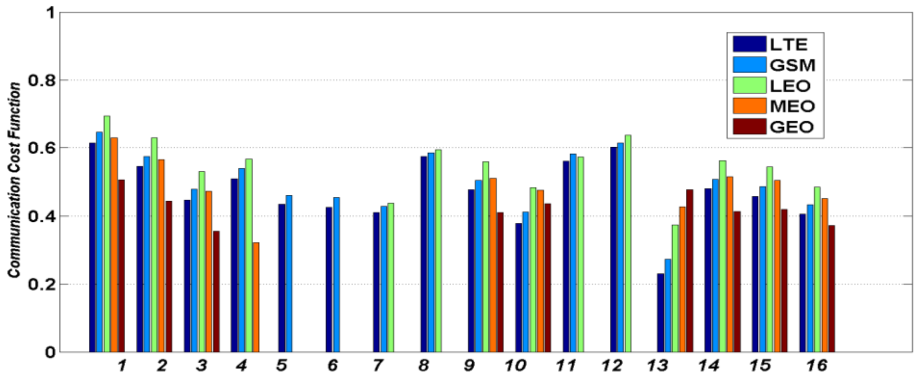


Fig. 5.62 CCF (S7)

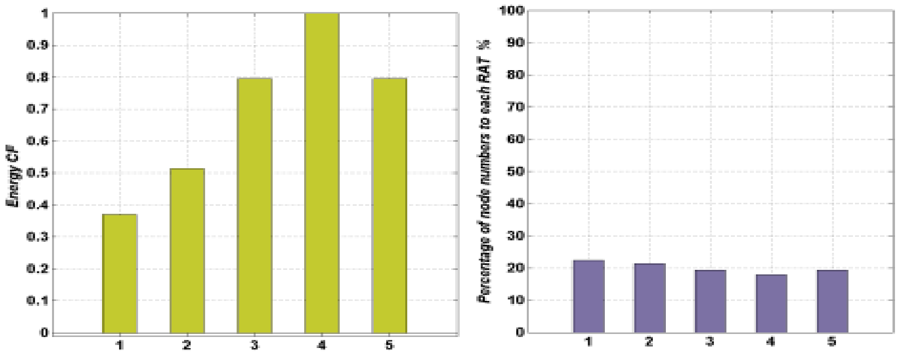


Fig. 5.63 Percentage, ECF (S7)

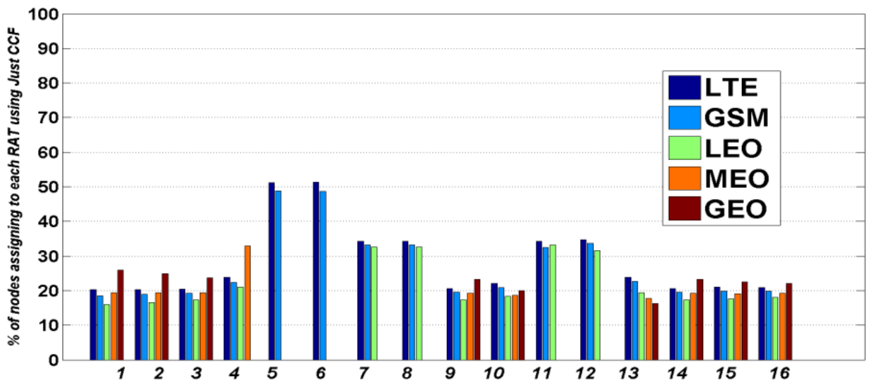


Fig. 5.64 Node assigning based on CCF (S7)

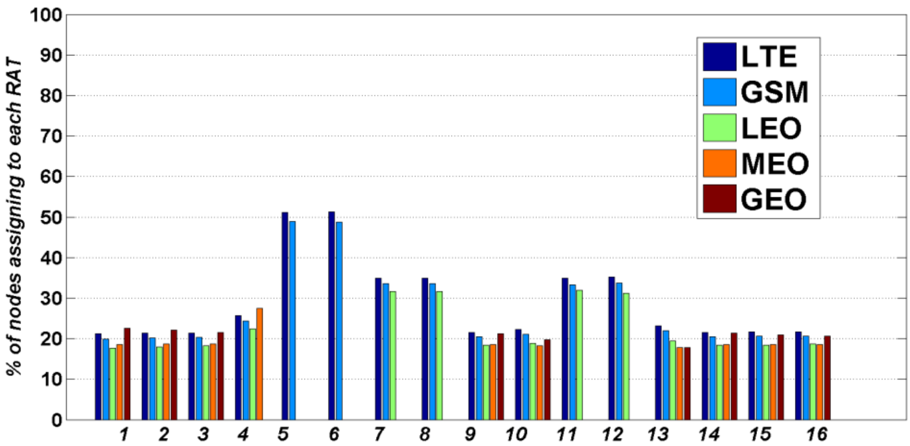


Fig. 5.65 Node assigning based on CCF and ECF (S7)

At S8 nodes 1,2,3,10,11 and 12 in general shows the different behavior for the corresponded nodes in each scenario comparing with S4 and S5, high delay sensitive nodes, Fig.5.66-69. Although at S4, S5 and S8 in general the same behavior are seen, Fig 5.50-53, Fig.5.52-55, Fig.5.66-69. S4 is a high dense scenario and S8 is a low dense one. MEO CCF for node 1,2 and 3 is higher than GSM in S8 and are lower than GSM in S4 and S5 due to these reasons. At S7, S9 and S10 in general the same behavior are seen, Fig 5.62-65, Fig.5.70-73, Fig.5.74-77.

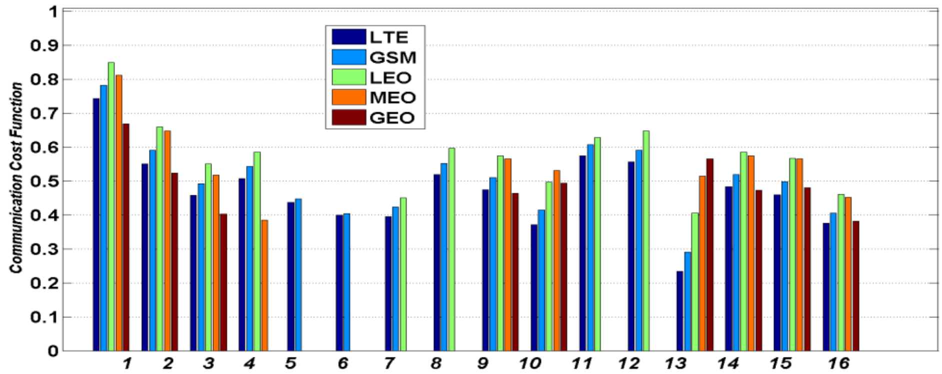


Fig. 5.66 CCF (S8)

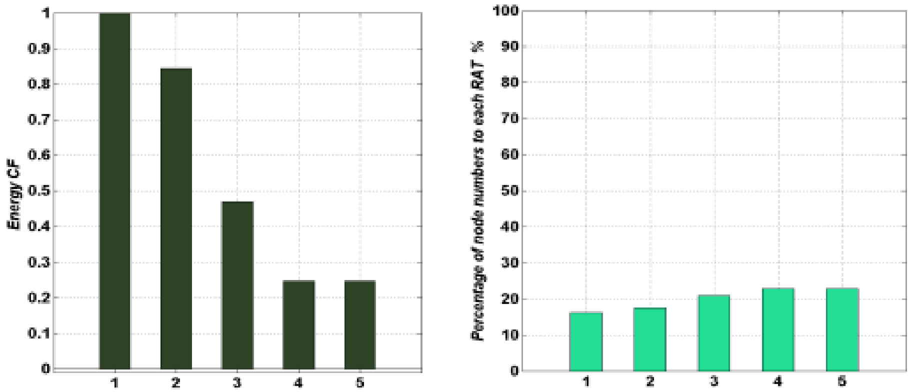


Fig. 5.67 Percentage , ECF (S8)

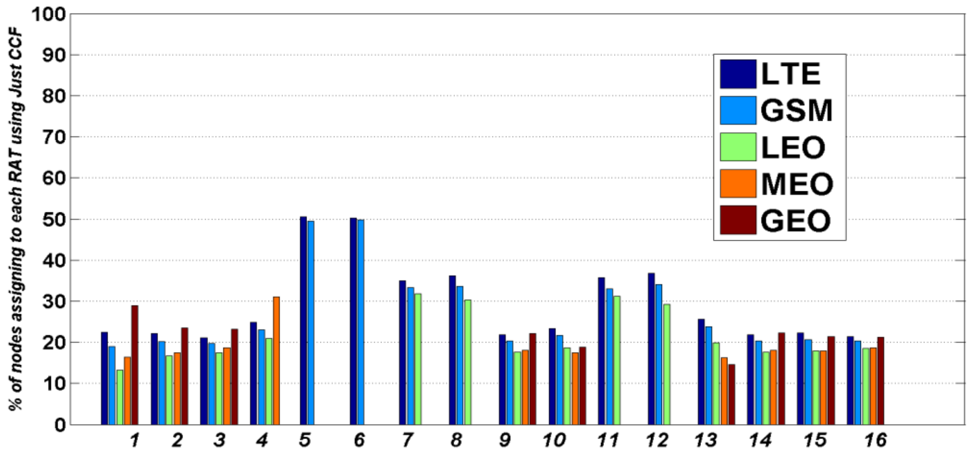


Fig. 5.68 Node assigning based on CCF (S8)

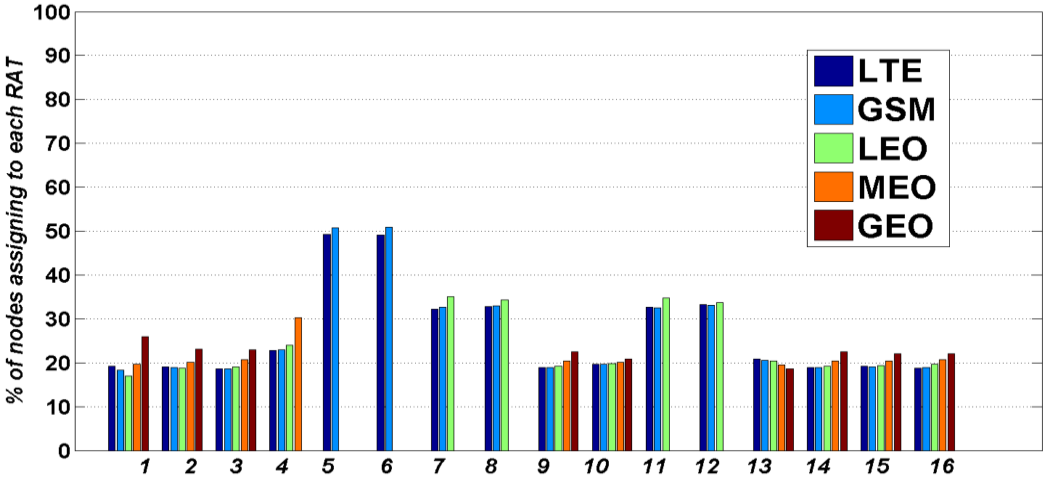


Fig. 5.69 Node assigning based on CCF and ECF (S8)

Also GEO should have much better performance comparing with MEO, but its high PLP comparing with MEO makes it just slightly better than MEO for node type 13 in S9. In S9 although RAT GEO has the higher fitting value in many senses, but its higher PLP and node low data rate characteristics causes it would be slightly better than MEO.

The slight difference between CCF of RAT LEO and RAT MEO for Node type 10 in S7, S9 and S10 shows that the RAT communication characteristics fitness with the node type 10 is close. Although SE is high for RAT GEO in S7 but its higher PLP comparing with LEO makes LEO CCF as somehow equal (slightly higher) tan GEO.

As a very clear example of specific case at S9, node 13, (A5 and B5). In other word, CCF of RAT 1-4 increases from RAT1 to RAT4. The ECF behaves inversely, Fig 5.70&5.71.

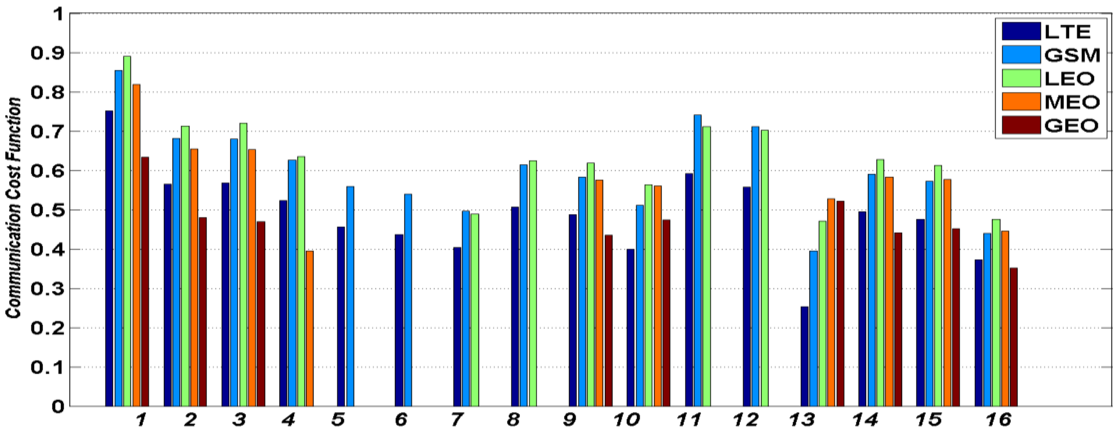


Fig. 5.70 CCF (S9)

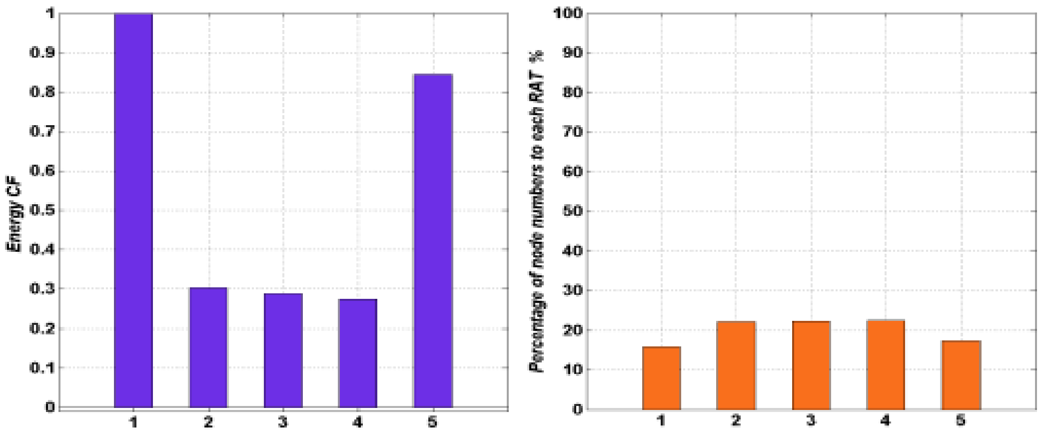


Fig. 5.71 Percentage , ECF (S9)

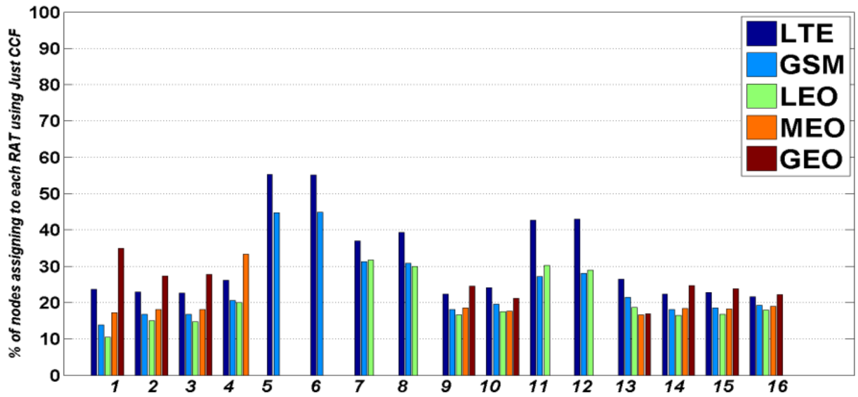


Fig. 5.72 Node assigning based on CCF (S9)

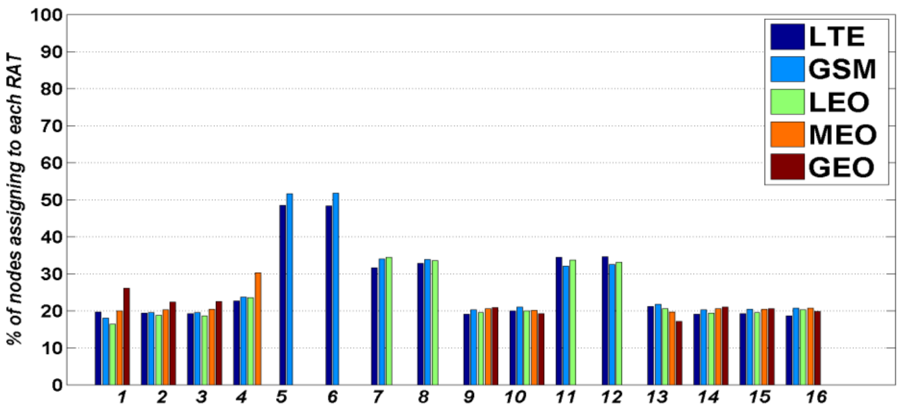


Fig. 5.73 Node assigning based on CCF and ECF (S9)

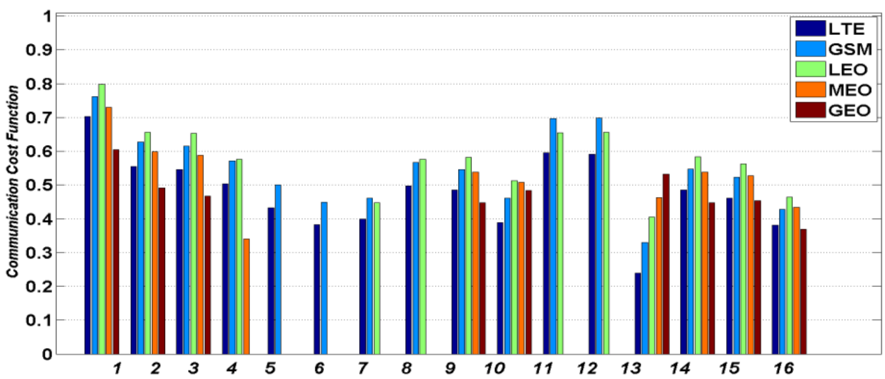


Fig. 5.74 CCF (S10)

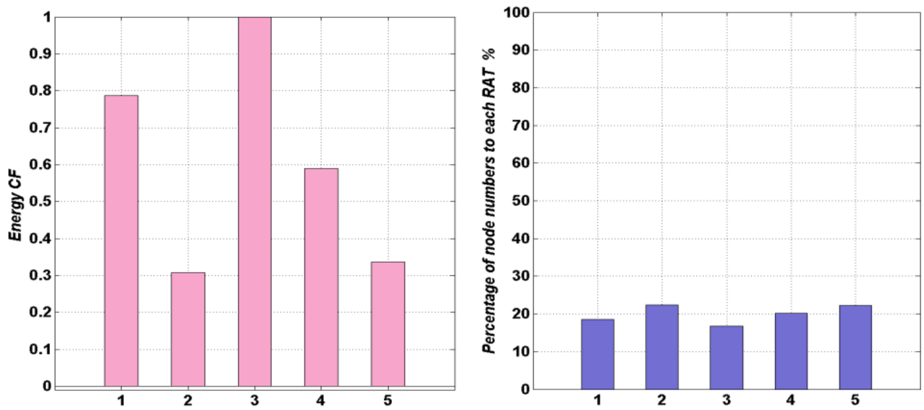


Fig. 5.75 Percentage , ECF (S10)

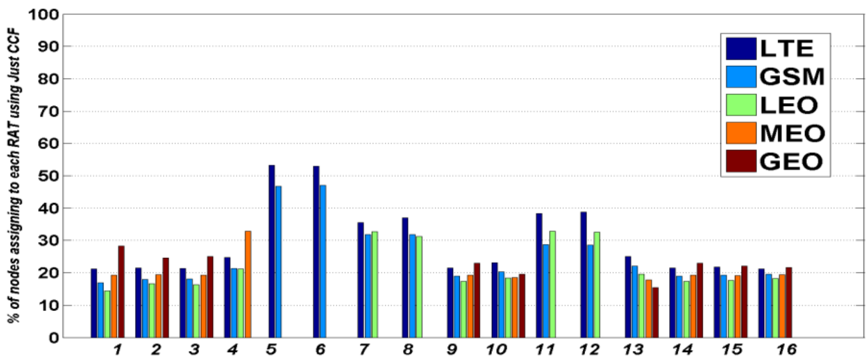


Fig. 5.76 Node assigning, CCF (S10)

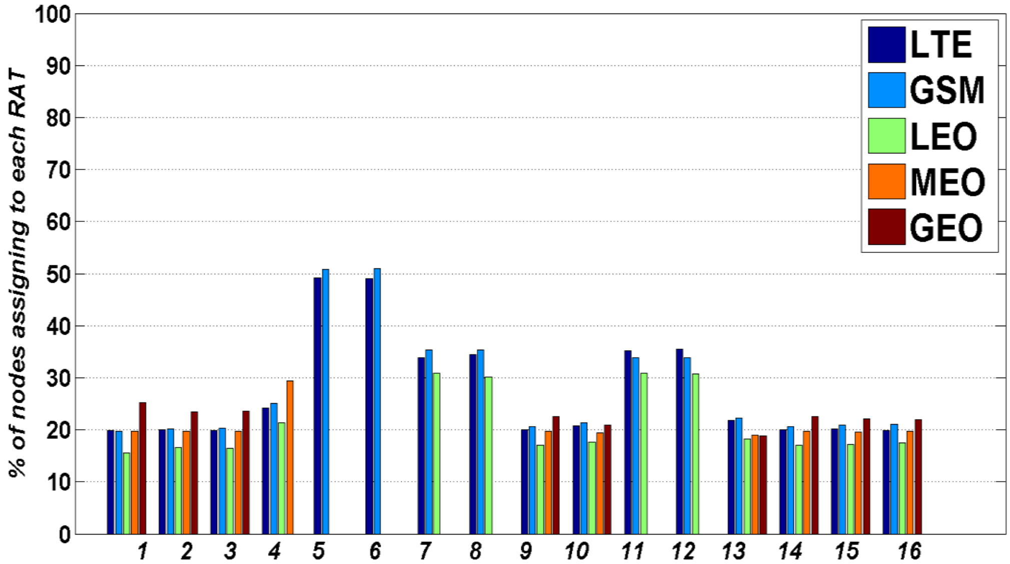


Fig. 5.77 Node assigning (S10)

As it was seen, changing the RATs parameter and configuration results in changing the assigning percentage of the nodes to different RATs.

For example in the many defined scenarios can be seen the high level modulation using in a certain RAT does not make the RAT as the first priority of the certain node types. In other words, lots of defined criteria as the input of CCF determine the desirability value of RATs for a certain node in a certain scenario.

As the last analysis of this part, if the weight of power efficiency in the comprehensive CFs $w_\eta = 0.3$, then the effect of the CCF is highlighted and just as an example the node assigning using comprehensive CFs with new amount of ECF weight, cause to lower the effect of ECF as it is seen in Fig.5-79 which recalculated for S10.

As it was seen the introduced method is sensitive to the different node types densities in order to have an efficient node assignment to different RATs as a function of several communication configuration aspects.

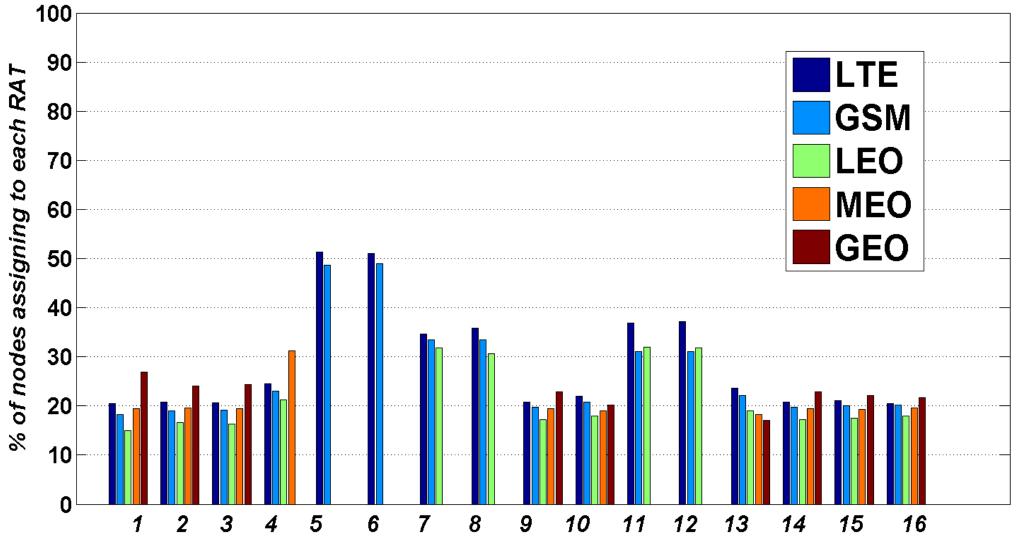


Fig. 5.79 Node assigning when $w_\eta = 0.3$ (S10)

In Fig. 5.77 (Scenario 10) the ECF for GSM is the lowest and in sense of energy efficiency, when it is combined with the comprehensive CCF with $w_\eta = 1$, its higher assigning to GSM is obvious for node type 1, AMI (SMs). If $w_\eta = 0$, the assigning is just based on the CCF and vice versa, (4.46).

Table. 5.13 The different Scenarios, for different node types assigning percentage to different RATs [220]

Scenario 1	LTE	GSM	LEO	MEO	GEO	Scenario 6	LTE	GSM	LEO	MEO	GEO
AMI	21.4764	19.6464	18.2479	18.1326	22.4967	AMI	20.9356	18.9520	17.2935	19.4053	23.4136
PHEV	21.6856	20.3687	19.7564	18.2758	19.9134	PHEV	21.3193	19.5400	18.4279	18.7595	21.9533
DERS	18.5058	20.5840	19.6372	19.7792	21.4938	DERS	21.2412	19.7995	18.3268	19.3239	21.3086
DGM1	22.6912	24.1465	23.8937	29.2687	0	DGM1	25.0052	23.3321	22.5664	29.0963	0
DGM2	44.1994	55.8006	0	0	0	DGM2	51.1907	48.8093	0	0	0
DGM3	43.4810	56.5190	0	0	0	DGM3	51.2424	48.7576	0	0	0
DGM4	29.9676	35.1416	34.8908	0	0	DGM4	34.5441	33.1254	32.3305	0	0
WASA1	33.8013	32.2919	33.9068	0	0	WASA1	35.2458	32.7203	32.0340	0	0
WASA2	19.9565	20.7450	19.9076	19.1009	20.2900	WASA2	21.4696	20.2460	18.8327	19.2636	20.1881
WASA3	21.4073	21.7485	20.6710	18.5004	17.6728	WASA3	22.4627	21.1003	19.4716	18.6799	18.2855
WASA4	31.4201	33.8588	34.7211	0	0	WASA4	34.6358	32.1373	33.2269	0	0
WASA5	35.7931	31.2581	32.9488	0	0	WASA5	35.5276	32.3175	32.1549	0	0
WASA6	23.9623	23.1211	21.7249	17.3709	13.8208	WASA6	23.7687	22.1855	20.2822	17.8792	15.8844
WASA7	20.2115	20.7500	19.8606	18.9720	20.2058	WASA7	21.5053	20.2228	18.7867	19.1777	20.3074
WASA8	19.7562	21.0031	20.1015	19.2395	19.8997	WASA8	21.6696	20.4828	19.0153	19.2189	19.6133
WASA9	17.9652	21.0176	20.1860	20.1111	20.7202	WASA9	21.3382	20.6983	19.2798	19.9958	18.6879
Scenario 2	LTE	GSM	LEO	MEO	GEO	Scenario 7	LTE	GSM	LEO	MEO	GEO
AMI	19.9820	19.5461	16.9193	19.5402	24.0124	AMI	21.2732	19.9052	17.6472	18.5962	22.5783
PHEV	20.3005	20.7033	18.6623	18.9152	21.4188	PHEV	21.2883	20.1317	17.9032	18.6054	22.0715
DERS	19.9302	21.1780	19.0633	19.2616	20.5668	DERS	21.3514	20.2409	18.2847	18.6064	21.5166
DGM1	24.0089	24.9533	23.0622	27.9756	0	DGM1	25.7283	24.3593	22.4417	27.4707	0
DGM2	47.1182	52.8818	0	0	0	DGM2	51.1745	48.8255	0	0	0
DGM3	46.4609	53.5391	0	0	0	DGM3	51.2231	48.7769	0	0	0
DGM4	32.8579	34.4555	32.6866	0	0	DGM4	34.8558	33.5016	31.6426	0	0
WASA1	34.2385	32.9666	32.7949	0	0	WASA1	34.8392	33.5625	31.5983	0	0
WASA2	20.4114	21.1145	19.0261	18.8045	20.6434	WASA2	21.4748	20.4051	18.3242	18.5301	21.2658
WASA3	21.1681	21.8479	19.5738	18.4250	18.9853	WASA3	22.2169	21.1059	18.8167	18.2133	19.6472
WASA4	32.6998	34.3118	32.9884	0	0	WASA4	34.8699	33.1902	31.9399	0	0
WASA5	34.5286	32.7740	32.6975	0	0	WASA5	35.1199	33.7432	31.1369	0	0
WASA6	22.3967	22.7039	20.1134	17.7588	17.0272	WASA6	23.1182	21.9486	19.3718	17.8090	17.7524
WASA7	20.4462	21.1156	18.9666	18.7432	20.7284	WASA7	21.4827	20.4032	18.3073	18.5227	21.2840
WASA8	20.5658	21.3507	19.1962	18.7122	20.1751	WASA8	21.6541	20.5726	18.4483	18.4628	20.8622
WASA9	20.3223	21.4700	19.4253	18.9634	19.8191	WASA9	21.5965	20.5871	18.6597	18.5182	20.6385

Scenario 3	LTE	GSM	LEO	MEO	GEO	Scenario 8	LTE	GSM	LEO	MEO	
AMI	21.1330	19.3290	17.7898	17.5221	24.2261	AMI	19.2749	18.2496	16.9814	19.6141	25.8799
PHEV	21.5234	19.7068	18.2364	17.4705	23.0628	PHEV	19.1159	18.8351	18.7900	20.1035	23.1556
DERS	21.4495	19.6759	18.3078	17.4707	23.0959	DERS	18.5524	18.5862	19.1148	20.7543	22.9922
DGM1	26.3763	24.2227	23.1281	26.2729	0	DGM1	22.8564	22.8717	23.9640	30.3079	0
DGM2	51.5194	48.4806	0	0	0	DGM2	49.2022	50.7978	0	0	0
DGM3	51.4124	48.5876	0	0	0	DGM3	49.0562	50.9438	0	0	0
DGM4	35.1357	32.9097	31.9545	0	0	DGM4	32.2614	32.7310	35.0075	0	0
WASA1	35.6362	32.9706	31.3932	0	0	WASA1	32.8581	32.8991	34.2428	0	0
WASA2	21.6026	19.9401	18.7406	17.4627	22.2540	WASA2	18.9486	18.9013	19.2312	20.4186	22.5003
WASA3	22.3984	20.6147	19.1965	17.1077	20.6828	WASA3	19.7145	19.6124	19.7600	20.1041	20.8089
WASA4	34.9580	32.7318	32.3103	0	0	WASA4	32.6857	32.5755	34.7388	0	0
WASA5	35.4426	33.0574	31.5000	0	0	WASA5	33.1896	33.0701	33.7403	0	0
WASA6	23.4442	21.5041	19.7222	16.6463	18.6832	WASA6	20.8591	20.6082	20.3530	19.5197	18.6600
WASA7	21.7077	19.9258	18.6002	17.3855	22.3808	WASA7	18.9795	18.9047	19.1853	20.3883	22.5422
WASA8	21.8809	20.1113	18.7809	17.3266	21.9003	WASA8	19.1598	19.0756	19.3304	20.3346	22.0997
WASA9	21.7610	20.0982	18.9550	17.3850	21.8008	WASA9	18.7239	18.9002	19.6321	20.7651	21.9787
Scenario 4	LTE	GSM	LEO	MEO	GEO	Scenario 9	LTE	GSM	LEO	MEO	GEO
AMI	19.9294	19.8806	18.6996	19.9430	21.5474	AMI	19.6861	18.0210	16.3778	19.8606	26.0545
PHEV	21.3830	19.2305	18.0908	19.1217	22.1740	PHEV	19.3114	19.4525	18.6903	20.2814	22.2644
DERS	20.6102	19.7934	18.5262	19.5615	21.5088	DERS	19.1909	19.4849	18.5085	20.3117	22.5040
DGM1	24.8147	23.3239	22.5518	29.3096	0	DGM1	22.6006	23.6706	23.5182	30.2106	0
DGM2	50.1125	49.8875	0	0	0	DGM2	48.3927	51.6073	0	0	0
DGM3	49.5079	50.4921	0	0	0	DGM3	48.3013	51.6987	0	0	0
DGM4	34.2214	33.0860	32.6925	0	0	DGM4	31.5894	34.0255	34.3851	0	0
WASA1	36.1682	31.7066	32.1251	0	0	WASA1	32.7330	33.7798	33.4872	0	0
WASA2	20.9860	20.0077	18.7709	19.3764	20.8590	WASA2	19.0158	20.1749	19.4457	20.4741	20.8896
WASA3	22.0395	20.8422	19.3348	18.9169	18.8666	WASA3	19.9561	20.9044	19.9211	20.0633	19.1550
WASA4	33.9275	32.8891	33.1835	0	0	WASA4	34.4206	31.9480	33.6315	0	0
WASA5	36.9403	31.4518	31.6078	0	0	WASA5	34.5647	32.4300	33.0053	0	0
WASA6	23.6090	21.8438	19.9805	18.1898	16.3770	WASA6	21.0772	21.7896	20.5215	19.5597	17.0520
WASA7	21.1044	19.9758	18.6509	19.2905	20.9784	WASA7	19.0467	20.1555	19.3941	20.4497	20.9540
WASA8	21.2849	20.2279	18.8740	19.2466	20.3667	WASA8	19.2494	20.3429	19.5379	20.3796	20.4901
WASA9	20.4455	20.5738	19.4657	19.7535	19.7615	WASA9	18.6503	20.7073	20.1725	20.7426	19.7273
Scenario 5	LTE	GSM	LEO	MEO	GEO	Scenario 10	LTE	GSM	LEO	MEO	GEO
AMI	21.2807	19.1049	18.2559	19.5020	21.8564	AMI	19.8108	19.6929	15.5869	19.6926	25.2169
PHEV	21.4015	19.1762	18.0017	19.3806	22.0401	PHEV	19.9877	20.2308	16.6461	19.7396	23.3958

DERS	21.4161	19.0995	17.7905	19.3478	22.3461	DERS	19.8933	20.2638	16.4992	19.7181	23.6256
DGM1	25.8638	23.2074	22.5672	28.3616	0	DGM1	24.2326	25.1117	21.3142	29.3415	0
DGM2	52.5064	47.4936	0	0	0	DGM2	49.1754	50.8246	0	0	0
DGM3	52.4349	47.5651	0	0	0	DGM3	49.0291	50.9709	0	0	0
DGM4	35.5134	32.4335	32.0531	0	0	DGM4	33.7799	35.3943	30.8258	0	0
WASA1	35.6619	32.5978	31.7403	0	0	WASA1	34.5149	35.3834	30.1016	0	0
WASA2	21.5429	19.4242	18.3784	19.3382	21.3163	WASA2	19.9664	20.6802	17.0542	19.6866	22.6125
WASA3	22.2009	20.0814	18.9261	19.0802	19.7114	WASA3	20.7958	21.4094	17.5714	19.3482	20.8752
WASA4	35.3883	32.2226	32.3891	0	0	WASA4	35.2271	33.8570	30.9159	0	0
WASA5	35.4096	32.2454	32.3450	0	0	WASA5	35.4276	33.7860	30.7865	0	0
WASA6	23.1548	20.9292	19.4118	18.6416	17.8625	WASA6	21.7889	22.2736	18.1797	18.9245	18.8333
WASA7	21.5404	19.4256	18.3851	19.3403	21.3086	WASA7	19.9689	20.6793	17.0492	19.6850	22.6177
WASA8	21.5548	19.6079	18.9045	19.4213	20.5116	WASA8	20.1366	20.8661	17.2031	19.6278	22.1663
WASA9	21.6860	19.5935	18.5837	19.3061	20.8308	WASA9	19.8206	21.0188	17.5160	19.7483	21.8963

Tab.5.13 shows the different SG node types assigning percentage to different RATs whose communication configuration and characteristics are given in Tab.5.11 and the nodes number as a function of density and area radius are given in Tab.5.12 as 10 different scenarios. The SG node type characteristics are given in Table 5.10 (were elaborated and achieved).

Fig.5.78 shows the variance of 5 different node types to different RATs in 10 different Scenarios.

As an example, DGM1 has high delay sensitivity, thus DGM1 nodes in S8 has a variance of near 7 when it was assigned to different RATs based on the proposed assigning method and it indicates a non-equal but efficient node assigning among all acceptable RATs with different communication configurations.

In consequence, node type whose delay tolerance is closer to the RATs latency, its assigning percentage among different RATs changes more significant in different scenarios.

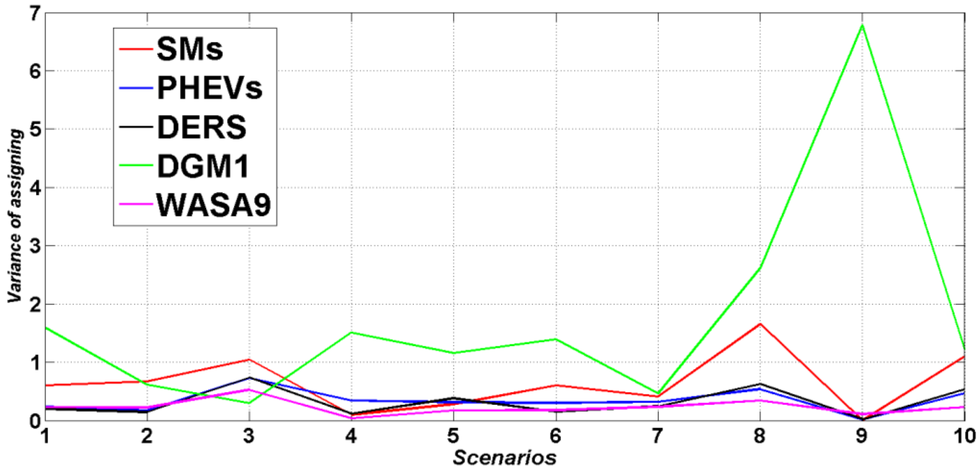


Fig. 5.78 Five different node types assigning variances over 10 Scenarios [220]

Thus based on the defined strategy, the CCF for different RATs supporting a certain node types are calculated and based on the CCF value a communication of the node assignment is done.

Then by using the ECF, another type of the node assignment is done. By using the weights for ECF and CCF the finalized assigning is done. In case of a RAT has the highest CCF and ECF, either the RAT can be excluded and the nodes can be shared among the other RATs or either the lowest assigning node can be done for the mentioned RAT.

The designer based on the defined perspectives can manage the weights for CCF and ECF which results in different node assigning % for a certain node among all available RATs. As an example in S10, the LEO scenario has the highest CCF and ECF among the other RATs for node type 1, SMs, thus it can be neglected and the nodes which has been assigned to it can be shared among the different RATs based on their desirability value or even, the lowest node% is assigned, Fig,5.74-77,to it based on the rational described in chapter1&5.

Chapter 6

CONCLUSIONS

The different node types in SG have to communicate several type of information with different requirements to the Control Stations. The SG node types are identified and their communication requirements were described.

There are many RATs, with different characteristics such as modulation mode, spectral efficiency, latency, service rate, buffer size, and response time, security elements like encryption algorithm, system complexity, and joule per information of bits, frame size, goodput access method, and coding rate. These RATs support the SG node type's with different characteristics such as data generating period and size, nodes density , node priority, aggregator buffering size and time, synchronized nodes which having different communication requirements such as required data rate, delay sensitivity, required reliability and security.

To make such heterogeneous RATs covering all SG nodes cause to support all SG communication requirements efficiently. Besides, Because of spectrum scarcity, efficient spectrum allocation methods should be elaborated. Rather than this different node types should be prioritized based on the SG goals fulfillment. As a result, it is needed that different methods being defined to have the high level of fitness between RATs communication characteristics and SG node types communication requirements. Thus, communication requirements of the SG (KPIs) node types are defined. Then different types of CFs are introduced to evaluate the desirability value of a certain RAT that supports a certain SG node types traffic requirements. Based on the Eb/N0 in RAT transmitter an energy CF is defined as well. By combination of these two different CFs (the CCF is very comprehensive and complicated) the percentage of the SG node types which should be assigned to different RATs is achieved. In a different SG node assigning method by using the SG nodes prioritization and the proposed CF, a priority table is defined in which the nodes and the

RATs are put in order. The primary numerical results show that the proposed method allows selecting the best RATs for each type of SG nodes in a way that all the SG node communication requirements were fulfilled while the resource allocation done in an efficient way.

The results give insights to the network designer for solving the problems on resource management. An elaborated method was introduced and investigated to properly choose the best RATs considering their communication characteristics for SG different branch of the node types or give the node`s density; to define the required traffic requirement of them; with different communication requirements while all SG node types type meet their communication necessities in an efficient way in combination with SG node prioritization.

These methods were explained based on two different types of input data. At first one, the given SG node types the values has been defined by the Utilities Telecom Council (UTC) by considering an average number of nodes and collectors per branch of the network users. At the second one based on the SG node types densities, data generating rate and generated data size, the data rate and traffic rate of the nodes were calculated and the proposed methods are applied.

Both satellite and terrestrial communication network with different communication configurations are considered in this work. Obtained results are evolutionary approaches in load balancing, resource allocation and elaborating the heterogeneous network for heterogeneous node types different methods. The outcome show that dividing the certain node type depends on many parameters. Furthermore the assigning method is sensitive to node's density and node type communication requirements. Node type with higher density needs more data rate to be supported. High data rate RATs are facing with many tradeoffs when supporting a certain node type communication requirements. All of these tradeoffs should be considered and respected in order to have a high efficient heterogeneous communication network.

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