Chapter

Density-Aware Smart Grid Node Allocation in Heterogeneous Radio Access Technology Environments

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Abstract

Smart grid (SG) is an intelligent enhancement of the conventional energy grid allowing a smarter management. In order to be implemented, SG needs to rely on a communication network connecting different node types, implementing the SG services, with different communication and energy requirements. Heterogeneous network (Het-Net) solutions are very attractive, gaining from the allocation of different radio access technologies (RATs) to the different SG node types; however, due to the heterogeneity of the system, an efficient radio resource optimization and energy management are a complex task. Through the exploitation of the most significant key performance indicators (KPIs) of the SG node types and the key features of the RATs, a joint communication and energy cost function are here defined. Through this approach it is possible to optimally assign the nodes to the RATs while respecting their requirements. In particular, we show the effect of different nodes' density scenarios on the proposed allocation algorithm.

Keywords: smart grid, wireless communications, heterogeneous networks, heuristic optimization

1. Introduction

Smart grid (SG) systems are characterized by the presence of several applications aiming at efficiently managing the energy grid. In order to do this, a smart grid communication network (SGCN) is implemented strictly coupled with the energy grid, which is able to interconnect the different nodes managing the energy grid applications. A typical SGCN scenario is characterized by the presence of different radio access technologies (RATs), with different communication configurations and characteristics able to support the SG communication requirements. However, wireless communications are now deployed for supporting different applications; hence an efficient resource allocation to support different types of SG nodes should be performed in order to maximize the resource efficiency while respecting to the different SG node type communication requirements, with a particular attention to data rate, delay, reliability, and security. For associating the nodes to the considered RATs, we propose to measure the suitability of the assignment toward a certain RAT of a given node type based on its communication requirements and RAT communication characteristics. To this aim, an appropriate communication cost function (CCF) is defined based on some KPIs as a function of node types and densities and RAT characteristics. At the same time, low-power communication is the key for the realization of reduced form factor SG nodes; to this aim a suitable energy cost function (ECF) is also defined for minimizing energy per transferred data bit. A novel approach to assign the node to different RATs based on jointly exploiting the CCF and the ECF is here proposed resulting in a heterogeneous network that is efficient in both energy and communication aspects. Cost function (CF), based on node communication requirements, node type densities, and RAT features, defines the percentage of each node type which should be allocated to each RAT. The numerical results show the advantage of the proposed node allocation approach to different RATs with respect to the separate CFs. Moreover, a variable number of nodes are considered for understanding the impact of the nodes' density in terms of allocation efficiency.

2. Literature review

In the literature there are several papers dealing with SGCN, the node type communication requirements, and RAT selection. The summary of some of the most important papers is given in this section. In [1] a complete research on advanced metering infrastructure (AMI) exploring how to link consumer data gathered by utilities and managing insufficient communication network resources is considered. As an outcome of [1], it is clear that several data relay nodes and aggregators are needed to collect data produced by smart meters (SMs). Moreover, the SM message gathering problem is considered, and a method to collect multiple SM information incoming at the data collector nodes in order to reduce protocol overhead is considered. In [2] the capacity of a backhaul network to support the distribution grid in SG is considered. Several communication technologies are taken into consideration for coping with the SG communication requirements for the backhaul, connecting customer data collection points to the CS. A multi-hop wireless communication architecture is proposed, and its capability in meeting the requirements of the backhaul link is assessed by simulations. Despite introducing several RATs that have been suggested to fulfill the communication requirements at the distribution level, it is still lacking a method to assign SMs to the RATs. A method showing the suitability of a given RAT with respect to the other can be useful in assigning the nodes to the different RATs. In [3] the distribution network implemented through WiMAX is considered, by taking into account the communication characteristics of different SG. An analysis of the communication requirements of SG specifically to the power grid distribution domain and the consumer domain is also performed. In [3], the authors measure the smart metering aggregator data rate and the quality of service (QoS) performance; WiMAX is used as the backhaul from aggregators to the control station. In [4], the exploitation of wireless communications for SG applications has been discussed; however the node type communication requirements have not been considered. Moreover, the resource allocation efficiency has not been considered in this work, and the scalability and performance analysis on LTE networks have been left as future work.

There are other general surveys on the communication architecture in SG. In [5] the network implementation challenges in the power system settings have been deeply studied. Another survey on the communication architecture in SG is [6] focusing on communication network requirements for the main SG applications in home area network (HAN), neighborhood area network (NAN), and wide-area network (WAN). For different communication standards and SG use cases, in [6], the authors propose to collect the information about different communication requirements for diverse SG applications, in the three different fields, i.e., HAN, NAN, and WAN. Hence, a method to support the usage of different SG implementations is considered. The US Department of Energy discusses the main issues in SG by presenting the most significant goals of the different node types [7]. Furthermore, the communication requirements of different SG node types (i.e., data rate, delay sensitivity, reliability, and security) are explained [8]. Although there is no unique solution for elaborating a certain RAT for SG, the SG node communication requirements give a high-level vision to SG communication network designer in order to design the optimized RAT [9].

With the aim of designing a reliable and secure heterogeneous network, load balancing methods have been introduced [10]. Round-robin method, which distributes the traffic evenly among all the available base stations, regardless of existing load and performance, is proposed in [11]. As it is obvious, this type of balancing, regardless of RAT characteristics and SG node communication requirements and their adoptability, results in an inefficient heterogeneous network [12]. Load balancing is implemented in a way that the new user load is assigned to the base station with the lower traffic. Another network balancing method is named predictive node method where all the available base stations are observed over time and the trends are analyzed. The load balance works by assigning the traffic to the base stations with the best performance in terms of energy and spectral efficiency. Managing such type of balancing is very complex in both hardware and software aspects. Moreover, this type of observation needs a cognitive process and sensing and finding that results in having higher delay [13].

Several studies have been also performed related to different communication network infrastructures and their performance. In [14] the authors focused on LTE uplink transmission scheme. Single-carrier frequency-division multiple access (SC-FDMA) is the multiple access technique adopted in the LTE uplink transmission scheme. Compared with orthogonal frequency-division multiple access (OFDMA), used in the LTE downlink transmission and WiMAX, 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 [14], an overview of LTE and LTE uplink transmission is done. The technology behind the uplink transmission (i.e., SC-FDMA) is analyzed in depth. In [15, 16] the authors studied a SG test-bed based on GSM capable of load management [15], fault detection, and self-healing [16]. This test-bed allows the implementation of various protocols and methodologies, which can be used for investigating the problems in SG.

Assessing the different communication network reliabilities is an important issue which has not been studied a lot. Wireless sensor networks for smart grid applications using a case study on link reliability and node lifetime evaluations in power distribution systems are described in [17]. The authors introduce the main scenarios and design challenges of wireless sensor networks for SG applications. SG node reliability in wireless sensor networks for SG applications is assessed through specific studies based on field tests in power system. Moreover, the authors in [17] discuss the challenges due to the RATs and SG channel conditions. One of the most used approaches for defining the reliability of a RAT for different node types is described in [18, 19]. In this technique, by means of the most important RAT reliability criteria, such as buffer size, link usefulness, latency, node generating rate, system status changing, and packet loss probability, the reliability of different network types for a certain node type is done.

3. System model

In order to support the communication requirements of the SG node types by using different RATs, we aim at defining a method where the percentage allocation of each SG node type to the considered RATs is optimized. By a suitable cost function (CF), defined in terms of the communication requirements of all the SG node types and the RAT communication characteristics, it is possible to evaluate the suitability of RATs for the selected SG node types [20].

In this model it is assumed that the SG node data are buffered in aggregators, each one considering a specific type of node; the aggregators are then connected with a control station. The data generated by the nodes are gathered to the aggregators and the collectors using different short- and medium-range RATs. In the proposed model, we aim at maximizing the allocation efficiency to the different RATs. The radio resource allocation is done based on the node densities and RAT communication characteristics and features. The allocation is performed by using a suitable CF, defining a matching score between RAT features and node communication characteristics. Moreover, the node traffic changes as a function of node density. This is also considered giving interesting insights in the numerical results related to the effect of the densities of the different node types.

The proposed CF is based on a joint approach between a CCF, defined in terms of the communication requirements and characteristics, and an ECF defined in terms of energy consumption per bit. By noticing that the energy efficiency expressed in energy spent per bit is trading off with respect to the spectral efficiency, by using the CCF in combination of ECF, an efficient method is introduced to make a heterogeneous network for heterogeneous SG nodes in an efficient way in which a trade-off between communication requirements and energy savings is considered. In order to have a scalar output for mapping different types of RATs to support different SG node type communication requirements a desirability value is defined. The node allocation is performed with the aim of maximizing the desirability of the RATs with respect to the node characteristics. Smaller values of the CF stand for a higher importance of a given RAT for a given node type. In the proposed approach, the RATs not qualified to achieve the communication requirements of the nodes are omitted.

A SG environment is characterized by several types of nodes, having different characteristics and requirements. In this section a brief description of the main SG node types and their characteristics is given.

Advanced metering infrastructure (AMI) is considered as the backbone of the SG. It is composed by smart meter (SM) nodes that cooperate on the power demand controlling with the goal of optimizing the energy consumption. Besides, AMI utilizes the power distribution management indirectly as it reports the consumption to the control center in order to optimize the power consumption. Meter reading allows a utility to collect data from electric, gas, and water meters and transfer data to a CS for billing and analysis.

Plug-in hybrid electric vehicles (PHEVs) are a node type used in electric transportation applications for managing both electricity flows from vehicles to the power grid (vehicle to grid (V2G)) and from the power grid to the vehicles (grid to vehicle (G2V)). Electric transportation applications allow to receive information of vehicle battery state of charge and inform vehicles about electricity prices [7, 21].

Wide-area situational awareness (WASA) is used for implementing the awareness of the SG, in order to get information and react with respect to unwanted and unbalanced situations that may cause some problems to the electrical grid [7, 8, 22, 23].

Distributed grid management (DGM) allows to implement a smart management of the power distribution network. Within this context cyber-attacks or risky weather conditions are considered. These bi-directional communications are vital to accomplish power distribution. The real-time procedure of grid structure, automation control, and information communication and information management to monitor and control the distribution grid is possible by using DGM [5–7, 17].

Distributed energy resources (DERs) are used for managing the distributed electrical sources with an impact on the user generation plants and distributed energy storage sites [7, 22, 24].

The communication requirements of the considered node types are reported in **Table 1**.

(a) Smart meter parameters					
Smart meters	**Reporting time period**	**Packet size**			
	Every 15 min	125 bytes (i.e., 1000 bits)			
(b) SG node characteristics [6, 25]					
SG node type	**Average data size (bytes)**	**Reporting time period [S]**	**Latency [S]**	**Reliability (%)**	***Security***
AMI					
SMs infrastructure	125	900 min	15		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	

(b) SG node characteristics [6, 25]					
SG node type	**Average data size (bytes)**	**Reporting time period [S]**	**Latency [S]**	**Reliability (%)**	***Security***
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	>25	2–6 per dispatch period per day	<5 S	>99.5	High
Storage (charge/discharge command from DAC to the storage)		(discharge: 5 am–9 am or 3 pm–7 pm; charge: 10 pm–5 am)			

Table 1.
SG node communication requirements.

As different RATs are supposed to be used in a Het-Net, in this study, LTE, GSM, and three different satellite-based communication systems have been considered, where the three main constellation types have been used (i.e., low Earth orbit, medium Earth orbit, and geostationary Earth orbit), while the reference communication system has been considered to be the DVB-S2/DVB-RCS2 for the downlink/uplink.

The characteristics of the considered RATs are given in **Table 7** in which different parameters of each RAT for different scenarios are given.

4. Cost function-based allocation

In order to support the smart grid communication requirements of the different node types by using different RATs, it is needed to define a method able to assign the nodes of each SG node type to the RATs in an efficient way. We propose to use a suitably defined cost function of all SG node communication requirements and RAT communication characteristics. The cost function is modeled in a way that the SG node requirements and the RAT characteristics are matched for maximizing their suitability. The cost function minimization allows to find the optimal percentage of nodes for ach SG node type to be allocated to each RAT.

4.1 Cost function definition

The CF is composed of two jointly coupled cost functions: the communication cost function and the energy cost function. The CCF is characterized by some parameters defined as KPIs; among others we focused our attention on data rate, delay, reliability, and security [20]. The ECF is based on the energy consumption per bit and based on the consideration that there is a trade-off between the spectral efficiency and energy per bit at the transmitter side [26, 27]. By using a joint CCF and ECF, an efficient method is introduced to design a heterogeneous network for different SG nodes.

The aim of the CCF is to map the matching degree of the SG nodes' requirements and the RAT characteristics by setting a RAT desirability value for each SG node type. The CCF is defined between the ith node type and the jth RAT which can be defined as

$$CCF_{ij} = \frac{\sum_{q=1}^{N_{KPI}} \left(W_{q_i} \cdot N_{q_{ij}} \right)}{\sum_{q=1}^{N_{KPI}} W_{q_i}} \tag{1}$$

where N_{KPI} is the number of KPIs we are considering and W_{q_i} and $N_{q_{ij}}$ are the weight of the qth KPI for the node type i and the normalized value of the qth KPI when considering the jth RAT type and the ith node type, respectively [20]. Eq. (1) can be rewritten by considering the four KPIs previously introduced as [20]

$$CCF_{ij} = \frac{W_{R_i} \cdot N_{R_{ij}} + W_{D_i} \cdot N_{D_{ij}} + W_{REi} \cdot N_{REij} + W_{SEi} \cdot N_{SEij}}{W_{Ri} + W_{Di} + W_{REi} + W_{SEi}} \tag{2}$$

where $i = 1, \ldots,$ N and $j = 1, \ldots,$ F represent the node types and the RATs; W_{R_i} and $N_{R_{ij}}$ are the data rate weight and normalized value for user type i and RAT type j, respectively; $W_{D_i}$and $N_{D_{ij}}$ are the delay weight and normalized value for user type i and RAT type j, respectively; W_{REij} and N_{REij} are the weight and the normalized value for reliability; and W_{SEij} and N_{SEij} are the normalized values for reliability and security, respectively.

Through the definition of proper weight and normalized values for every KPI, it is possible to integrate in a simpler way. This approach is also convenient for those KPIs, such as the reliability and the security that cannot be defined directly in a quantitative way, while a class categorization is used.

4.1.1 KPIs

The data rate weight for the ith node type is defined as

$$W_{R_i} = \frac{R_i}{R^{max}} \tag{3}$$

where R_i is the data rate required by the ith node type and $R^{max} = \max\{R_1, R_2, \ldots, R_N\}$ is the maximum rate among all the SG node types. The data rate normalized value can be written as

$$N_{R_{ij}} = \frac{R_i}{R_j^{RAT}}$$

in which R_j^{RAT} is the jth RAT proportional data rate.

The latency corresponds to the end-to-end delay to send the generated data at the SG node to the CS including the processing time, the propagation delay, the payload time, and the buffering time. The delay weight for node i is defined as

$$W_{D_i} = 1 - \frac{D_i}{D^{max}} \tag{4}$$

where D_i is the delay requirement for node type i and $D^{max} = \max\{D_1, \ldots, D_n\}$ is the maximum value among D_i. The latency normalized value for node i when using the RAT j is defined as

$$N_{D_{ij}} = 1 - \frac{D_{ij}}{D_i}$$

where

$$D_{ij} = D_{ij}^{B} + \hat{\alpha}_{ij}\left(D_{ij}^{proc} + D_{ij}^{prop}\right) + D_{ij}^{t}$$

and [10]

$$\hat{\alpha}_{ij} = \min\{\alpha_{i1}, \dots, \alpha_{ij}\}$$

D_{ij} is the overall delay including the buffering delay D_{ij}^{B}, the processing delay D_{ij}^{proc}, the propagation delay D_{ij}^{prop}, and the transmission delay D_{ij}^{t}, and

$$\alpha_{ij} = \frac{D_i}{D_{ij}^{B} + D_{ij}^{proc} + D_{ij}^{prop}}$$

is a coefficient that can be assigned by the designer to highlight the propagation and processing delay. This is an arbitrary option for the designer to highlight the latency effect. The propagation and processing time are multiplied by α_{ij} to reflect the RAT with high delay like satellite communication (i.e., GEO) that should have a lower CF value for the nodes with lower delay sensitivity necessities.

The reliability value in a RAT is not easy to be defined. There are lots of issues and parameters which should be evaluated in the different fields [19]. The reliability in a network is often defined in terms of network availability in an end-to-end connectivity. Reliability weight for each node type is defined as

$$W_{REi} = \frac{RE_i}{RE^{max}} \tag{5}$$

where RE_i is the target reliability value for node type i and $RE^{max} = \max\{RE_1, RE_2, \dots, RE_N\}$. The required reliability of the different SG node types is categorized from high to fairly medium, and a numerical value is allocated to each one. These values are allocated as the weights to the SG reliability requirement values (**Table 2**).

The reliability normalized value for node i when using the RAT j can be defined by resorting to the mismatch probability (MMPR) concept which is introduced in [18]. In this method the ith node type packet generation period, λ_i, is considered as a variable of the system, and μ_j is the service rate of the jth RAT BS. The delay requirement of the node is considered as a sufficient value for the target MMPR and RAT latency and is D_{ij}. MMPR depends also on the packet loss probability, $P_{l ij}$, that is usually considered equal to 0.01 in the literature [10, 28]. Hence, the MMPR between the SG node type i and the RAT j can be defined as.

$$MMPR_{ij} = 1 - \left(1 - P_{l ij}\right)^2 \cdot \left(\frac{v_{ij}}{\lambda_i + v_{ij}}\right) \tag{6}$$

Reliability	High, 1–0.99999	Fairly high, 0.99999–0.9999	Medium, 0.9999–0.999	Fairly medium, 0.999–0.99
RE_i	0.8	0.6	0.4	0.2

Table 2.
Reliability values of KPI for the weight evaluation.

where [29]

$$\mathrm{v_{ij}} = \frac{1}{D_{ij}} \tag{7}$$

$$MMPR_{ij} = 1 - \left(1 - \frac{\left(\left(1 - \frac{\lambda_i}{\mu_j}\right) \times \left(\frac{\lambda_i}{\mu_j}\right)^{K_j}\right)}{\left(1 - \left(\frac{\lambda_i}{\mu_j}\right)^{K_j+1}\right)}\right)^2 \left(\frac{\frac{1}{D_{ij}^B + \alpha_{ij}\cdot\left(D_{ij}^{proc} + D_{ij}^{prop}\right) + D_{ij}^t}}{\lambda_i + \frac{1}{D_{ij}^B + \alpha_{ij}\cdot\left(D_{ij}^{proc} + D_{ij}^{prop}\right) + D_{ij}^t}}\right) \tag{8}$$

and K_j is he jth RAT BS buffer size. Hence.

$$\mathrm{N}_{RE\mathrm{ij}} = \frac{MMPR_{\mathrm{ij}}}{N^{max}} \tag{9}$$

where

$$N^{max} = \max\left\{\mathrm{MMPR_{i1}}, \mathrm{MMPR_{i2}}, \ldots, \mathrm{MMPR_{ij}}\right\} \tag{10}$$

for a certain node type i and different RATs.

Security in a network and assessing it is not a straightforward issue, and to the best of our knowledge, there is no work to evaluate it for a certain type of the RATs [19]. The SG node 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 [10].

$$\mathrm{W_{SEi}} = \begin{cases} 1 \text{ if Node i security requirement is High} \\ 0.8 \text{ if Node i security requirement is Slightly High} \\ 0.6 \text{ if Node i security requirement is Medium} \\ 0.4 \text{ if Node i security requirement is Low} \\ 0.2 \text{ if Node i security requirement is Very Low} \end{cases}$$

To define the normalized value for each different type of nodes in the SG supported by different communication technologies, some RAT characteristics should be considered [10]. The main parts are the response time (RST), encryption policy (ENP), and RATs communication standards complexity (COMC). In **Table 3** the values of each security standard for a certain RATs are shown.

	RST	ENP	COMC
LTE	Very low	High	Very high
GSM	Low	Fairly high	Fairly high
SAT (LEO)	Fairly high	Fairly high	Very high
SAT (LEO)	High	Fairly high	High
SAT (LEO)	Very high	Fairly high	Fairly high

Table 3.
Fulfillment of each security criterion for the considered RATs [10].

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. Based on the ENP mode in a certain RAT and the complexity of the RAT, using symmetric and asymmetric cryptography model [10] [29], the value can be given to each parameter. The weights of ENP based on these algorithms are defined as w_{enj}, while $\mathrm{rep_j}$ indicates the number of consecutive encryption algorithms. The $\mathrm{ENP_j}$ is defined as.

$$\mathrm{ENP_j} = 5\frac{w_{enj}{}^{\left(1/rep_j\right)}}{w_{en}^{max}} \tag{11}$$

where the ENP value has been normalized to 5 (based on the defined value for security parameters); as it can be seen by increasing the number of consecutive encryption algorithms, $\mathrm{ENP_j}$ decreases significantly, indicating an increased security level in the system, where its default value is 1 (**Table 4**).

The security non-normalized value for RAT j can be defined as [10]

$$NSE_j = \frac{\alpha_{ENP} \cdot ENP_j + \alpha_{COM} \cdot COMC_j + \alpha_{RST} \cdot RST_j}{\sum_{SEC=1}^{3} \alpha_{SEC}} \tag{12}$$

where the parameter α_{SEC} represents the weight of the security KPIs, while α_{ENP}, α_{COM}, and α_{RST} are the encryption, complexity, and response time weights; by making a set, the normalized value for security is achieved from Eq. (12) and is shown in **Table 5** with $0 < \alpha_{SEC} < 1$.

To include energy part in our proposed method, energy per bit of information to noise power spectral density ratio, E_b/N_0, for RAT j is considered. The rationale is that using a specific communication configuration for RAT j causes having different $\mathrm{E_b/N_0}$ values. Let us recall the Shannon formula expressing the capacity of a given link:

$$R_b = B \cdot \log_2\left(1 + \frac{S}{N}\right) \tag{13}$$

where S and N are the signal and noise power, respectively. Thus, the link efficiency expressed in bits per Hz is

$$\eta_j = \frac{R_b}{B} = \log_2\left(1 + \frac{S}{N}\right), \tag{14}$$

and $S = E_b \cdot R_b$ and $N = N_0 \cdot B$ where N_0 is the noise spectral density. By using Eqs. (13) and (14), we have [5].

	RSA	DES	3DES	AES
Decryption velocity	Slowest	Slow	Very slow	Fast
Security weight: w_{enj}	4–5 least secure	3–4 not secure enough	2–3 adequate security	1–2 excellent security

Table 4.
Encryption algorithm weight mapping.

Node type	Data rate [bps]	Delay sensitivity [s]	Average packet generation period [s]	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	15,000	15	15	High	99.999–99.9999%
WASA9	75,000	15	15	High	99.999–99.9999%
DGM1	10,000	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	250,000	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%

Table 5.
Node communication requirements.

$$\begin{aligned}\eta_j &= \log_2\left(1+\frac{E_b\cdot R_b}{N_0\cdot B}\right)\\ &= \log_2\left(1+\frac{E_b\cdot \eta\cdot B}{N_0\cdot B}\right)\\ &= \log_2\left(1+\frac{E_b\cdot \eta_j}{N_0}\right)\\ &= \log_2\left(1+\frac{E_b}{N_0}\eta_j\right)\end{aligned} \tag{15}$$

thus, we can state that

$$2^{\eta_j} = 1+\frac{E_b}{N_0}\cdot\eta_j \tag{16}$$

If we rewrite $\frac{E_b}{N_0} = \eta en_j$, thus

$$\eta en_j = \frac{2^{\eta_j}-1}{\eta_j} \tag{17}$$

For the same bandwidth, B, N_0 remains fixed since it depends on B and temperature K and Boltzmann coefficient, which are fixed. Hence, if the spectral efficiency changes, E_b or energy per information bit is changed. 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 in the following way:

$$Nb_j = \frac{\eta en_j}{\eta en^{max}} \tag{18}$$

where ηen_j is the set of $\frac{E_b}{N_0}$ for different RATs. Thus, $\eta en^{max} = \max\left\{\eta en_1, \ldots, \eta en_j\right\}$ and $0 < Nb_j < 1$; hence the ECF when the node type i uses the RAT j can be defined as

$$\mathrm{ECF_{ij}} = \frac{\frac{2^{\eta_j}-1}{\eta_j}}{\eta \mathrm{en}^{\max}}$$

4.2 Optimal allocation

At first it should be mentioned that allocation is based on the number of the nodes as a result of the node densities. The number of the nodes is achieved by multiplying the density of the node in the size of the area. For different scenarios and nodes, these values are given in **Table 6**. The certain type of the node traffic is achieved as a function of its density in a certain area. Using the previously defined CCF and ECF, it is possible to define an allocation rule β_{ij}^C is RAT j (communication) desirability value for node type i that shows the percentage of the node type i (using CCF) traffic which should be supported by RAT j and for a certain node type i, $\sum_{j=1}^{F} \beta_{ij}^C = 1$:

$$\beta_{ij}^C = \frac{\left(1 - CCF_{ij}\right)}{\sum_{j=1}^{F}\left(1 - CCF_{ij}\right)} \tag{19}$$

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

Table 6.
The different scenarios, for different node types, coverage area radius (R), and node densities (D).

Similarly β_{ij}^{E} is RAT j (energy aspect) desirability value that shows the percentage of the node type i (using ECF) traffic which should be supported by RAT j and for a certain node type i, $\sum_{j=1}^{F} \beta_{ij}^{E} = 1$:

$$\beta_{ij}^{E} = \frac{\left(1 - ECF_{ij}\right)}{\sum_{j=1}^{F}\left(1 - ECF_{ij}\right)} \tag{20}$$

If we define with w_C and w_E the weights used for the node allocation based on CCF and ECF, respectively, showing the importance of communication and energy aspects of node (they can depend on designer goals; in this paper $w_\eta = w_\beta = 1$), P_{ij} is the percentages of the node type i that is assigned to RAT j based on both CCF and ECF values and can be rewritten as

$$\mathrm{P_{ij}} = \frac{\mathrm{w_C}\beta_{\mathrm{ij}}^{\mathrm{C}} + \mathrm{w_E}\beta_{\mathrm{ij}}^{\mathrm{E}}}{\mathrm{w_C} + \mathrm{w_E}}$$

$$= \frac{\mathrm{w_C}\dfrac{\left(1 - \mathrm{CCF_{ij}}\right)}{\sum_{\mathrm{j}=1}^{\mathrm{F}}\left(1 - \mathrm{CCF_{ij}}\right)} + \mathrm{w_E}\dfrac{\left(1 - \mathrm{ECF_{ij}}\right)}{\sum_{\mathrm{j}=1}^{\mathrm{F}}\left(1 - \mathrm{ECF_{ij}}\right)}}{\mathrm{w_C} + \mathrm{w_E}}$$

$$= \frac{w_C \cdot \dfrac{\left(1 - \dfrac{\sum_{q=1}^{N_{KPI_u}}\left(W_{qi} \cdot N_{q_{ij}}\right)}{\left(\sum_{q=1}^{N_{KPI_u}} W_{q_i}\right)}\right)}{\sum\limits_{j=1}^{F}\left(1 - \dfrac{\sum_{q=1}^{N_{KPI_u}}\left(W_{qi} \cdot N_{q_{ij}}\right)}{\left(\sum_{q=1}^{N_{KPI_u}} W_{q_i}\right)}\right)} + w_E \cdot \dfrac{\left(1 - \dfrac{\dfrac{2^{\eta e_j} - 1}{\eta e_j}}{\eta en^{max}},\right)}{\sum\limits_{j=1}^{F}\left(1 - \dfrac{\dfrac{2^{\eta e_j} - 1}{\eta e_j}}{\eta en^{max}},\right)}}{w_C + w_E} \tag{21}$$

It should be mentioned that by increasing the density of the nodes, the generated traffic is increased which affect the weights and normalized value of the CF in KPIs.

5. Numerical results

Considering an average number of nodes and collectors per branch defined by UTC, the numerical results based on the first proposed method show that regarding the number of KPIs which are used in the CF, 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, are changed.

Tables 6 and 7 showed the RAT, node density, and area size, respectively, for five different scenarios. In **Table 7** the RAT characteristics in terms of goodput, spectral efficiency (SE), coding rate and forward error correction (FEC), packet

		LTE	GSM	LEO	MEO	GEO
Scenario 1	Goodput	0.9	0.9	0.9	0.9	0.9
	SE	5.4	1.35	1.87	1.25	1.87
	Modulation	64 QAM	GMSK	4 PSK	4 PSK	8 PSK
	FEC rate	0.9	7/8	5/6	3/4	2/3
	PLP	0.001	0.007	0.009	0.01	0.015
	RTT	0.001	0.009	0.025	0.150	0.350
	Process	0.001	0.002	0.003	0.004	0.005
	Encryption	AES	DES	3 DES	AES	AES
Scenario 2	Goodput	0.9	0.9	0.9	0.9	0.9
	SE	4.8	1.35	2.9	3.2	3.9
	Modulation	32 QAM	GMSK	8 PSK	16 PSK	32 PSK
	FEC rate	1	0.95	8/9	7/8	5/6
	PLP	0.01	0.01	0.03	0.01	0.1
	RTT	0.005	0.009	0.025	0.150	0.350
	Process	0.001	0.002	0.003	0.003	0.003
	Encryption	AES	RSA	DES	3 DES	AES
Scenario 3	Goodput	0.9	0.9	0.9	0.9	0.9
	SE	2.9	2.4	2.07	3.1	1.87
	Modulation	8 QAM	8 PSK	8 PSK	16 PSK	4 PSK
	FEC rate	1	8/9	2/3	4/5	7/8
	PLP	0.001	0.02	0.02	0.04	0.05
	RTT	0.008	0.009	0.025	0.150	0.350
	Process	0.001	0.004	0.003	0.002	0.003
	Encryption	DES	DES	RSA	3 DES	AES
Scenario 4	Goodput	0.9	0.9	0.9	0.9	0.9
	SE	4	1.5	1.60	2	3
	Modulation	16 QAM	4 PSK	PSK	4 PSK	8 PSK
	FEC rate	1	8/9	7/8	3/4	2/3
	PLL	0.001	0.001	0.02	0.03	0.04
	RTT	0.005	0.008	0.025	0.150	0.350
	Process	0.005	0.005	0.005	0.005	0.005
	Encryption	AES	3 DES	AES	AES	AES
Scenario 5	Goodput	0.9	0.9	0.9	0.9	0.9
	SE	4	4	4	4	4
	Modulation	16 PSK	16 PSK	16 PSK	16 PSK	16 PSK
	FEC rate	1	8/9	3/4	3/4	3/4
	PLL	0.01	0.01	0.01	0.01	0.01
	RTT	0.005	0.005	0.025	0.150	0.350
	Process	0.001	0.001	0.001	0.001	0.001
	Encryption	AES	3 DES	DES	AES	3 DES

Table 7.
The different RAT features for the defined scenario.

loss probability (PLP), and round trip time (RTT) are given; complexity of the Radio Access Technologies, encryption at data link layer, RAT access point buffer size, access method, and other communication parameters are given, whose values are used to define CFs.

In Scenario 1, presented in **Table 7**, LTE and GSM have the maximum and the minimum SE, respectively. As depicted in **Figure 1**, due to the 64 QAM modulation scheme that allows to achieve the lowest CF and the reduced densities of the nodes, the LTE has the lowest CF, making it the preferable for Scenario 1. It is worth to be noticed that node types 5–8 and 11 and 12 cannot support the MEO and GEO satellite communications due to the strict latency requirements, while LEO is not supported only by 5 and 6. In general it can be noticed that LTE is the best choice for the CCF, while GSM and LEO are the second choice. In **Figure 2** the ECF is shown where it is possible to see that the highest cost is for the LTE, while the other three RATs have a similar behavior in terms of ECF; it affects the ECF based node allocation that foresees a lower amount of nodes allocated to the LTE. **Figure 3** shows instead the node assignment percentage to different RATs based on the CCF that reflect the CCF values depicted in **Figure 1**, by assigning more nodes to the RATs with a lower CCF value. Finally, in **Figure 4**, the joint CCF and ECF are

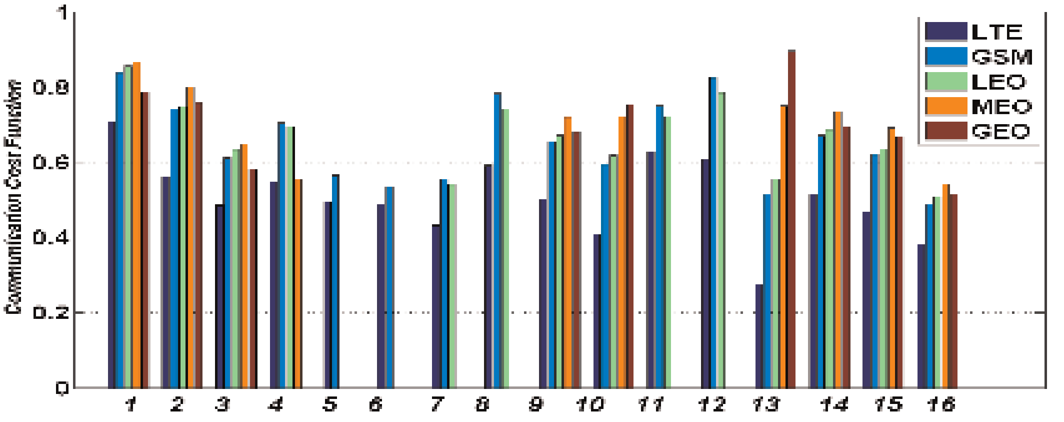

Figure 1.
CCF in S1.

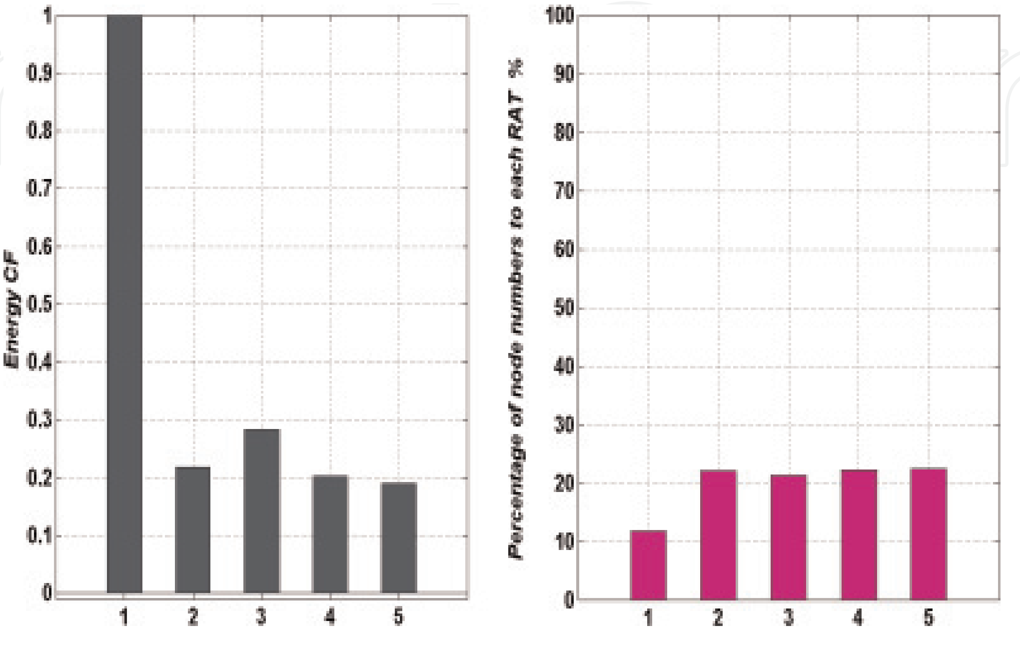

Figure 2.
ECF value and allocation percentage in S1.

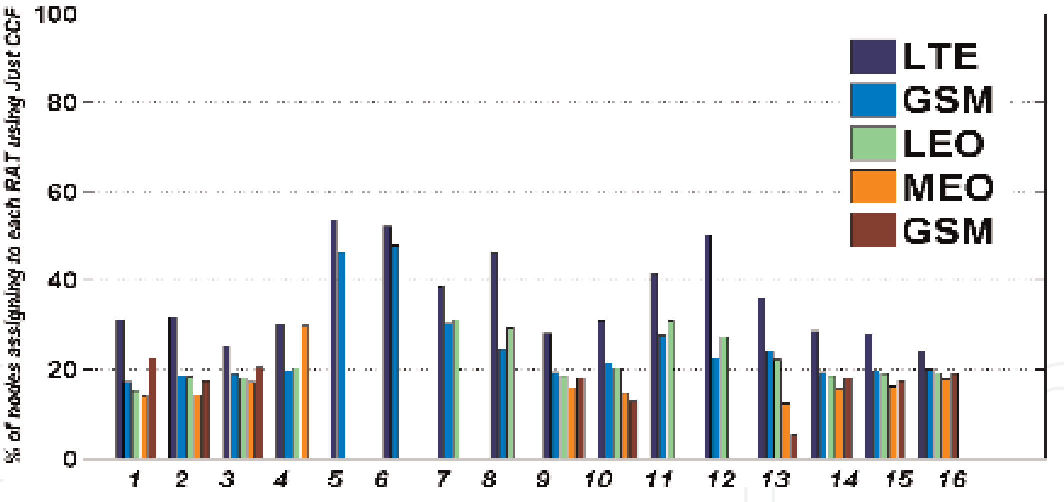

Figure 3.
Node allocation based on CCF in S1.

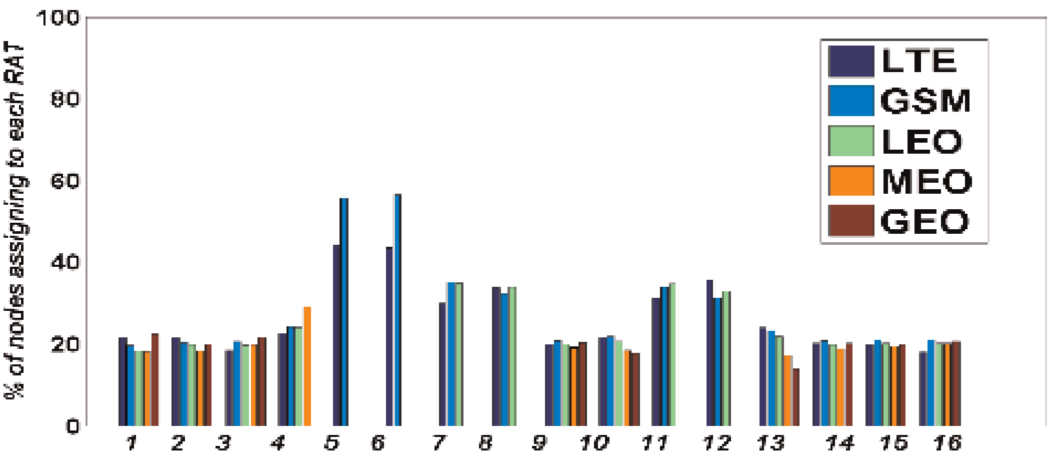

Figure 4.
Node allocation based on the joint CF in S1.

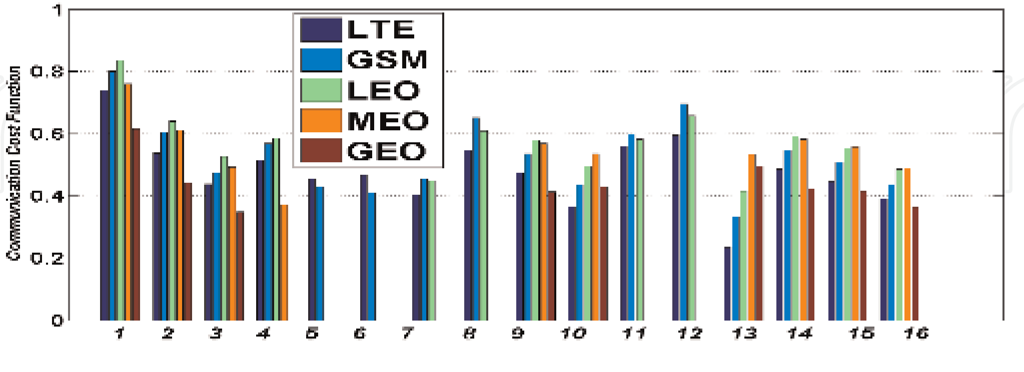

Figure 5.
CCF in S2.

considered for the node assignment; it is possible to notice both communication and energy effects on the nodes' assignment.

Scenario 2 represents a low-density node area. Also in this case, it is possible to notice that node types from 5 to 8 and 11 and 12 cannot use the satellite MEO and GEO, while LEO can be used for node types 7 and 8. By comparing SMs in Scenario 2 with SMs in Scenario 1, it is possible to notice that in Scenario 2 MEO has a better behavior than LEO and GSM, due to a higher SE. A similar behavior is noticed also

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for node types 2, 3, and 9. For the node type 4 in Scenario 2, we can instead notice a different behavior. The MEO is the best RAT in terms of CCF, but GSM has a lower CCF than the same node in Scenario 1. However, MEO with higher SE joined with its higher delay causes it to be a better choice than LTE. For nodes 5 and 6 in Scenario 2, though still LTE SE is higher than GSM SE, GSM with higher RTT and handling time makes GSM better in terms of CCF, while in nodes 7 and 8, CCF is slightly different if compared with the same node in Scenario 1, but, even with lower LTE SE, due to the density of the nodes, it has a better behavior in Scenario 2 than Scenario 1. For node 10, GEO CCF is lower than GSM, LEO, and MEO, but in node 13, GEO CCF is just lower than MEO. By looking at the node densities in these two scenarios, node 13 is lower. Higher density in node 10 rises the CFs for RATs with lesser SE. The RAT priorities for nodes 14, 15, and 16 are similar but are different compared with Scenario 1 because of different node densities using different communications in S2 (**Figure 5**). With the same ECF method, node assigning based on the CCF and based on both CCF and ECF is depicted in **Figure 6**.

In Scenario 3, it is worth to mention that in node type 7 (due to a high number of nodes whose data rate requirement is high) the SE and ECF weights are reduced (**Figures 7** and **8**). The other nodes have a similar behavior than the previous scenarios. The impact of the lower modulation order considered in Scenario 3 is clearly seen in the CCF differences and in node 16 CCFs (**Figures 9–12**).

In Scenarios 4 and 5, a similar behavior can be noticed. Though the RATs in these scenarios have different communication characteristics and, also, the node

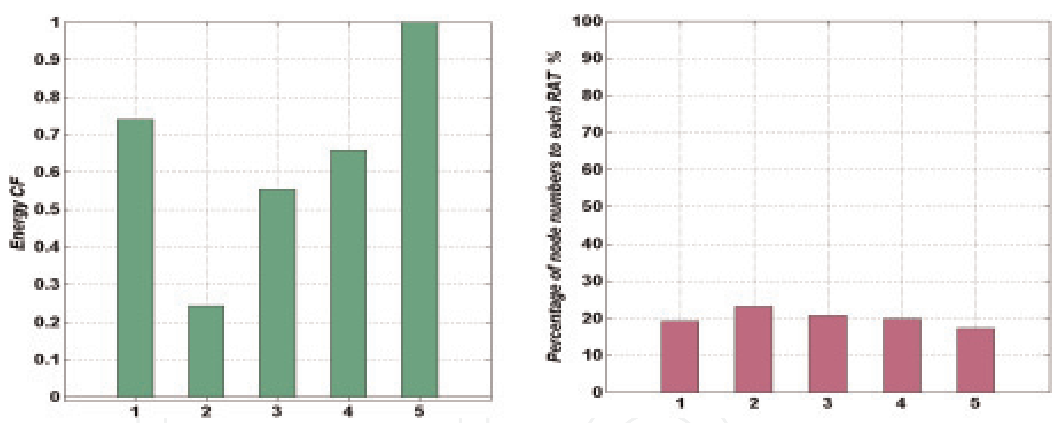

Figure 6.
ECF value and allocation percentage in S2.

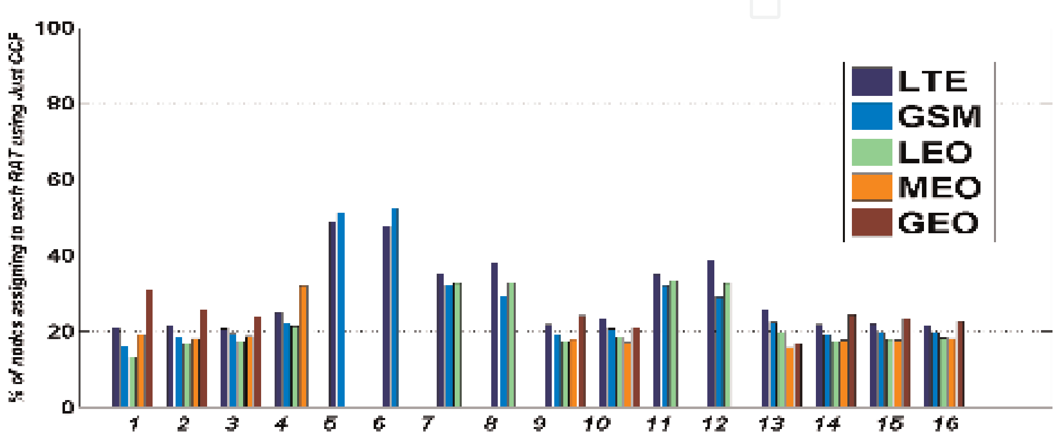

Figure 7.
Node allocation based on CCF in S2.

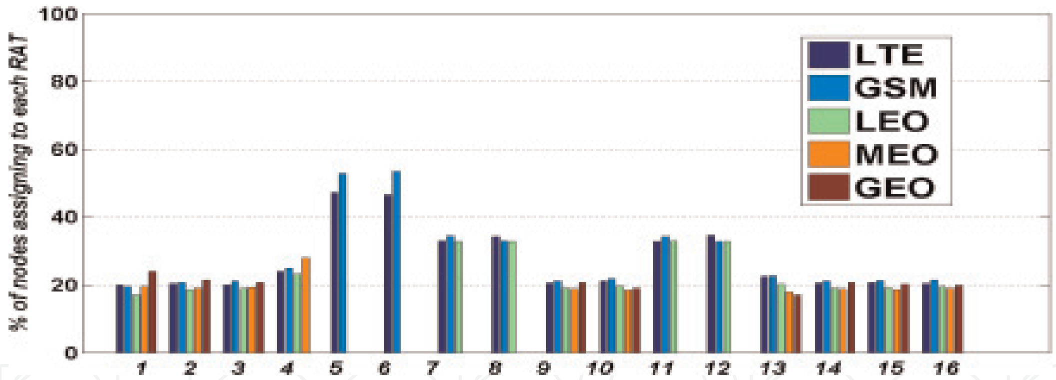

Figure 8.
Node allocation based on the joint CF in S2.

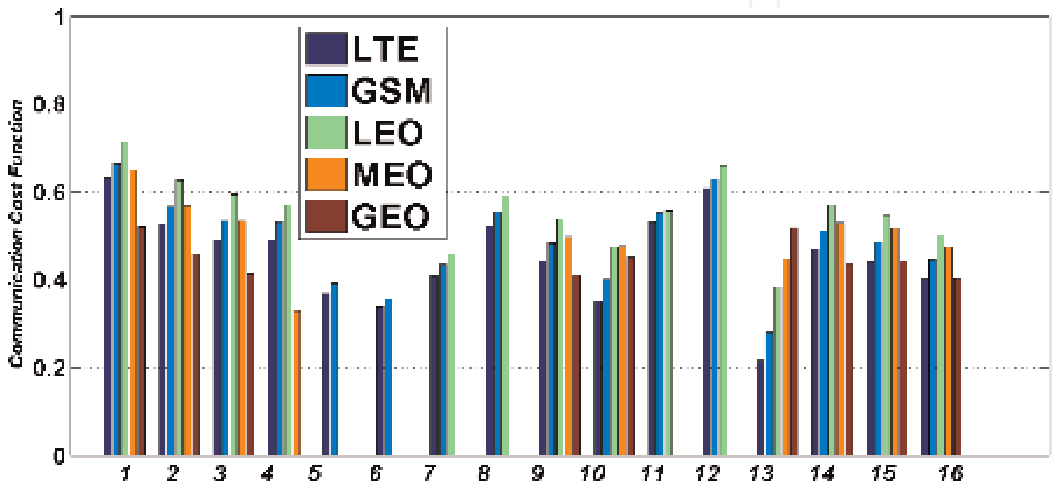

Figure 9.
CCF in S3.

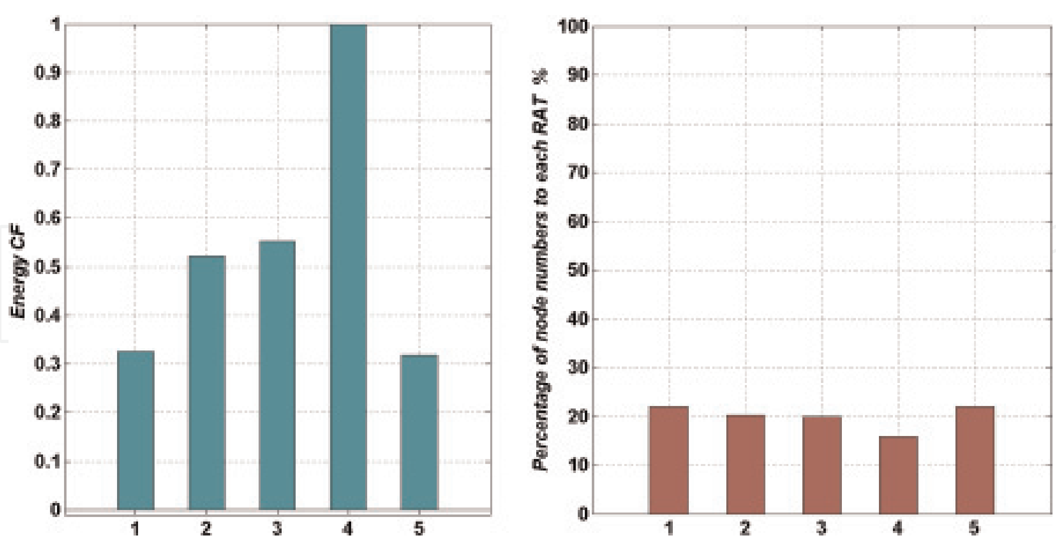

Figure 10.
ECF value and allocation percentage in S3.

densities and numbers are different, a similar behavior of RAT importance for different node types is present, although some important changes can be noticed. In Scenarios 4 and 5, node types 1, 2, 3, 4, 5, 6, 9, 11, 12, 13, 14, and 16 show the same behavior in terms of RATs when considering the CCF. For nodes 1–3, LTE is the

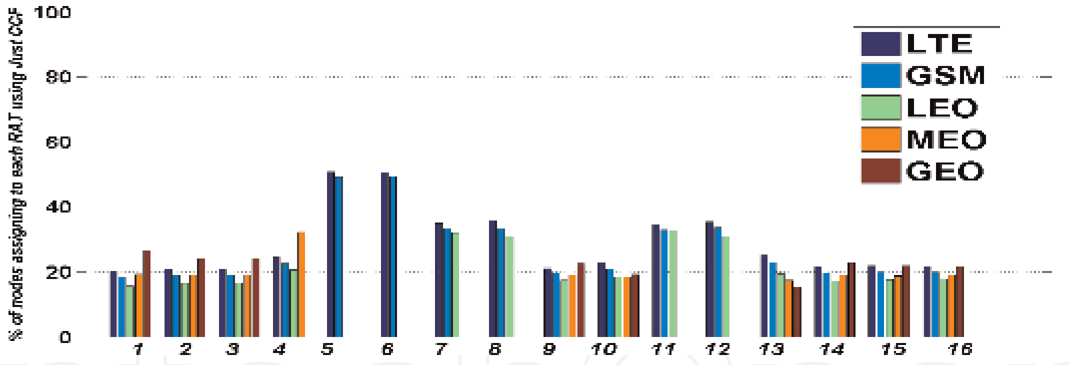

Figure 11.
Node allocation based on CCF in S3.

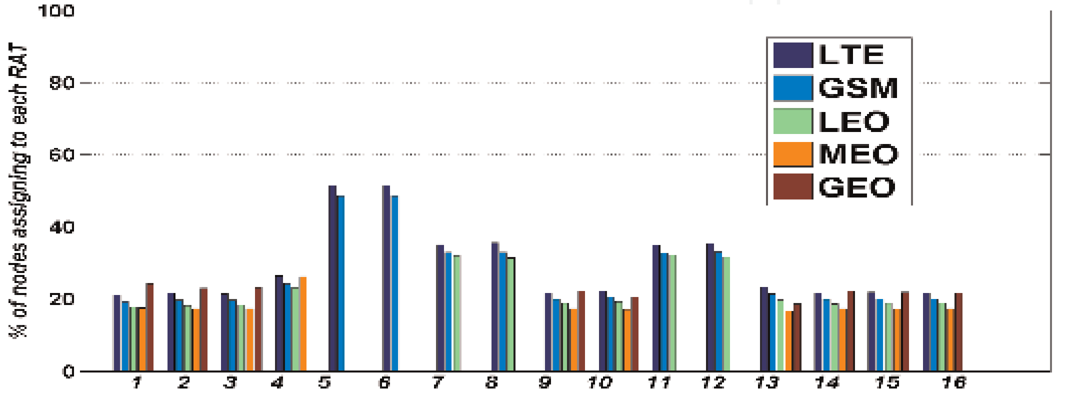

Figure 12.
Node allocation based on the joint CF in S3.

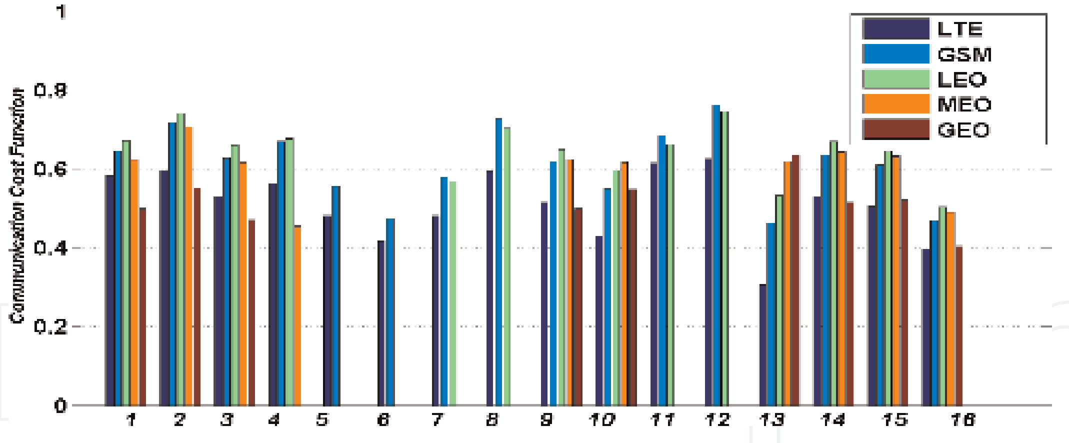

Figure 13.
CCF in S4.

best choice when considering the CCF, while in the case of node 4, MEO is the best selection. Node 4, due to its high data rate requirement and high delay sensitivity, cannot be supported by GEO.

In Scenario 4, the high PLP in GEO RAT type causes to have a lower reliability. Moreover, low PLP in MEO causes to have lower required data rate (i.e., node 13) resulting in having a lower CCF. Because of the high amount of data rate required by nodes 5 and 6 and due to the similar latency in GSM and LTE, LTE is better than GSM. In S4 node types 4, 5, 6, 9, 13, and 14, **Figures 13–16** show the same behavior in the sense of RATs used by the proposed CCF. The level of encryption, which is

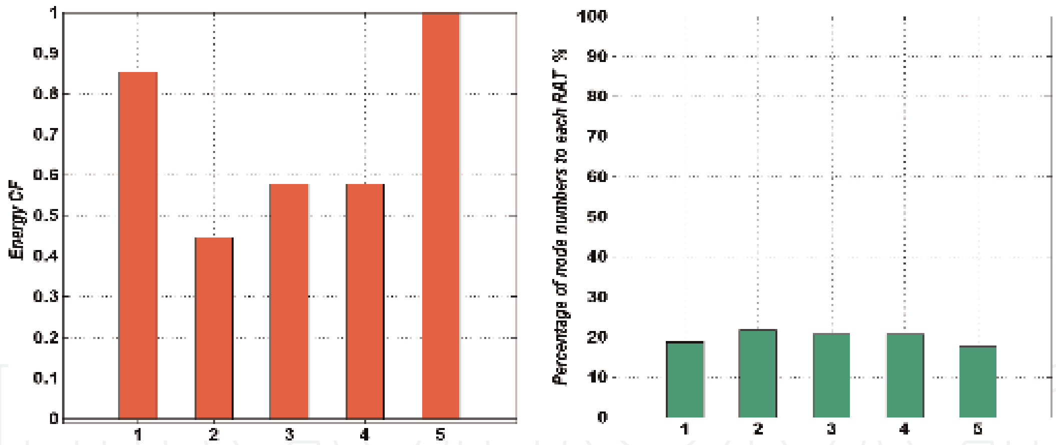

Figure 14.
ECF value and allocation percentage in S4.

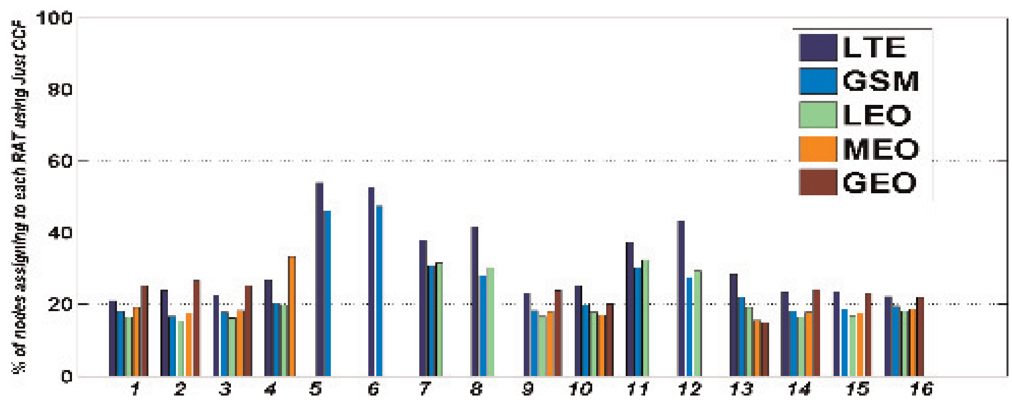

Figure 15.
Node allocation based on CCF in S4.

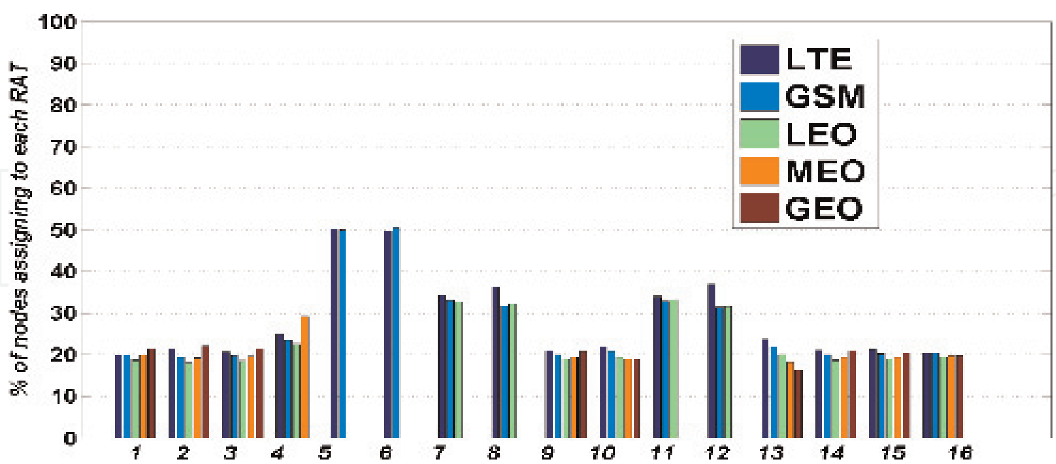

Figure 16.
Node allocation based on the joint CF in S4.

used as a part of security KPIs, is another criterion changing the node allocation strategy. In S5, for the node type 8, GSM has a lower CCF than LEO. Because of its encryption algorithm and coding rate which is better than LEO RAT and also delay fitting degree of LEO is improved, it has a lower CCF (**Figures 17–20**).

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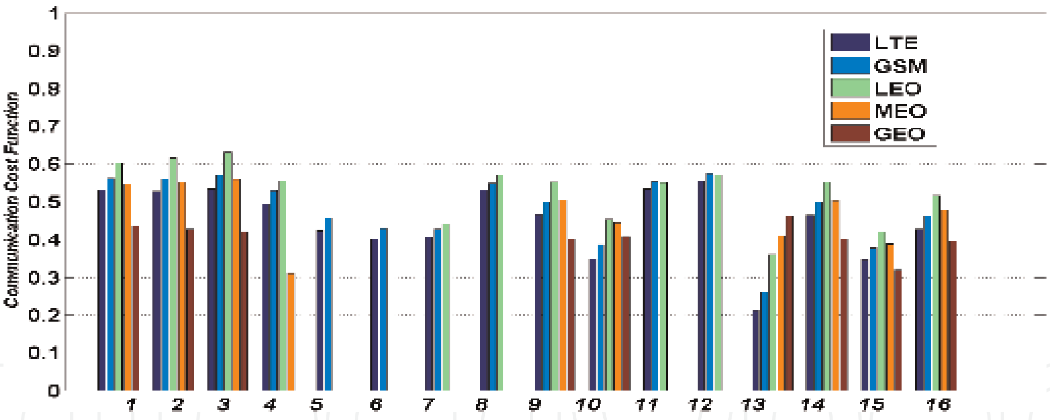

Figure 17.
CCF in S5.

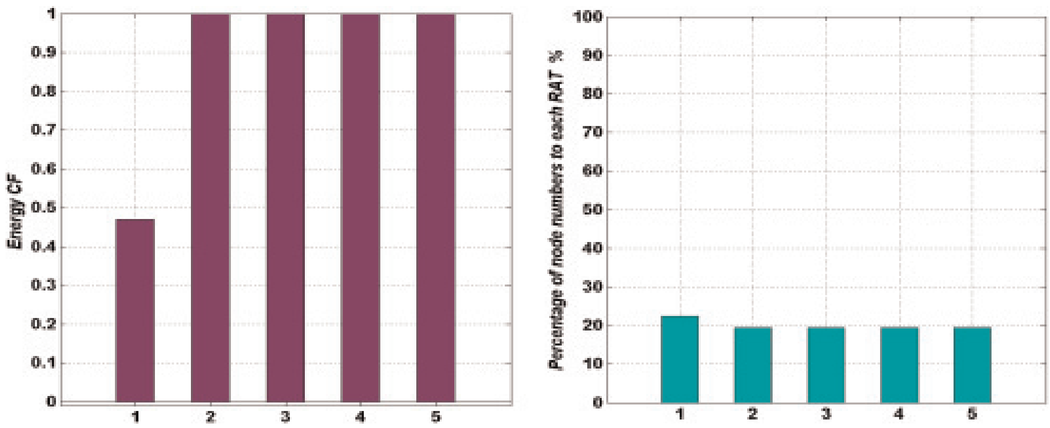

Figure 18.
ECF value and allocation percentage in S5.

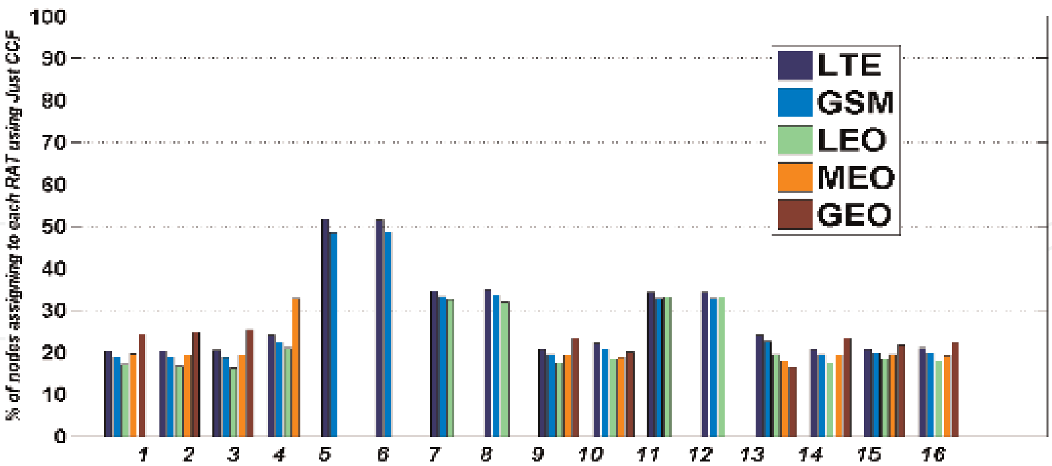

Figure 19.
Node allocation based on CCF in S5.

As it is shown, changing the RATs factor and its configuration consequences in changing the allocating percentage of the nodes to different RATs. For instance, in the different defined scenarios, the high-level modulation does not make the RAT as the priority. It means lots of well-defined criteria as the input of CCF define the popularity value of RATs for a certain node in a certain scenario.

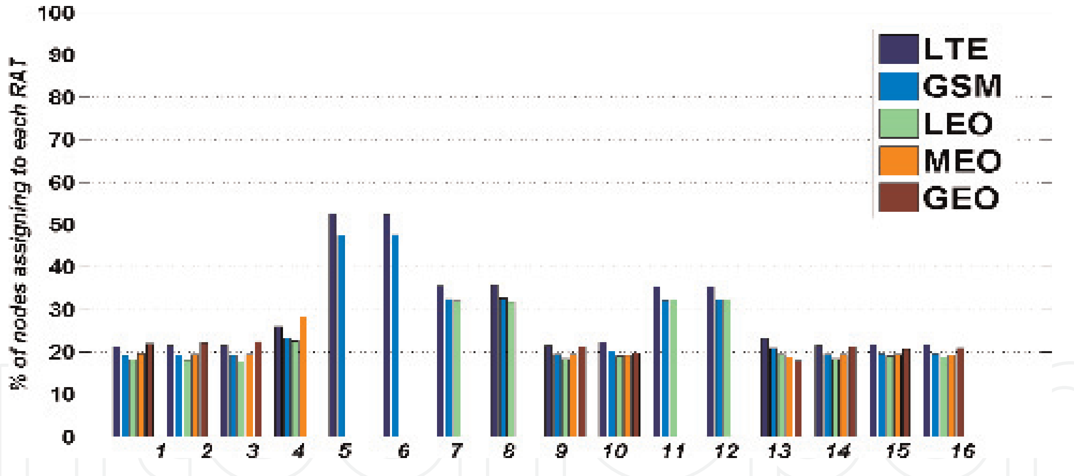

Figure 20.
Node allocation based on the joint CF in S5.

6. Conclusions

Different SG node types need to interact with a centralized management center by exchanging data with different requirements. Such communication can be implemented through different RATs, having different characteristics supporting the SG node communication requirements. A high-level fitness function is here defined aiming at matching the RAT communication characteristics and SG node type communication requirements. To this aim a joint communication and energy cost function is introduced for evaluating the effectiveness of the RATs when supporting different SG node types. Through the CF, the fraction of SG node types to be assigned to different RATs is obtained. The solution allows to achieve advantages in terms of load balancing and resource allocation. Thanks to the interesting results, this method can be extended to the inclusion of novel communication paradigms, such as those based on the presence of unmanned aerial vehicles (UAVs) as well as to the IoT-based communication paradigms.

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