A Cost Function Based Prioritization Method for Smart Grid Communication Network

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Abstract. In Smart Grids (SG) scenarios, the different nodes composing the system have to communicate to the Control Stations several type of information with different requirements. There are many communication technologies (CTs), with different Quality of Service characteristics, able to support the SG communication requirements. By focusing on wireless communications, it is possible to notice that spectrum is becoming a rare source due to its exponential increasing demand. Thus, resource allocation to support different types of SG nodes should be performed in order to maximize the resource efficiency and respect the SG requirements. Defining a cost function (CF) helps to accomplish this goal. To this aim, it is also needed to prioritize the different SG nodes based on their goals. By using the SG nodes prioritization and the CF, a priority table is defined in which the nodes and the CTs are put in order, based on their weights. The numerical results show that the proposed method allows selecting the best CT for each type of SG nodes.

Keywords: Smart grid network · Cost function · Resource allocation

1 Introduction

The conventional power grids are no more efficient and new paradigms are needed to accomplish current needs effectively: the Smart Grids (SG). There are different types of SG devices and nodes, whose number is always increasing. They report electrical power information details to the Control Station (CS) through the collectors. Demands/responses, such as dynamic consumption costs and controlling commands, are then sent back to the SG devices. Each SG cluster of nodes can have different communication characteristics, even all the type of nodes usually generate low data rate traffic. Such data are usually collected by the aggregators and transferred to the CS by using the communication technologies (CT).

Among several alternatives, the wireless CTs are considered useful for Smart Grid Communication Network, SGCN, due to several advantages [1, 2]. However, due to the SG nodes requirements, designing a SGCN based on wireless technologies becomes an important issue [1]. Among others, due to the increasing number of deployed SG nodes,

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the increased demand of resources and the requirements in terms of response latency are becoming two critical issues [1, 3]. Indeed recently, spectrum scarcity is gaining an increased interest in the research world, in particular when applied to machine type communications (MTC), where SGCN can be considered as a specific type of MTC [3]. Hence, it is even more important to find proper solutions for the allocation of the limited wireless resources and for respecting the SGCN requirements.

The scope of this work is to design a method for properly allocating the communication resources to the SG nodes having different requirements, by exploiting heterogeneous CTs. In particular, we will focus on latency and data rate requirements. On one hand, we aim at respecting a minimum required data rate and a maximum latency to be assured, but at the same time, we focus on a solution that allows reducing the resource wasting by limiting the allocation of unnecessary resources to the SG nodes. Indeed, it is more preferable that the nodes having lower latency requirements should be supported by CT having intrinsic delays, e.g., satellite communications, and leaving the CTs with lower delays for the nodes requesting a lower latency. However, usually, there is a tradeoff between latency and bandwidth. To this aim, a properly designed cost function is proposed aiming at selecting the priority of each available CT for the different SG nodes.

The proposed method is very effective with respect to other methods because it is simple and it has a low complexity. To the best of our knowledge, the other methods proposed in the literature are not simple resource allocation methods for respecting the SGCN requirements with the given constraints [1–4].

2 The Smart Grid Requirements

There are several types of SG nodes, each one with different uses and requirements. In this section, we will focus on the most important SG node types by describing their requirements.

Advanced Metering Infrastructure (AMI) are 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]. The *Wide Area Situational Awareness* (WASA) nodes monitor the power system across wide geographic areas. Thus, WASA has the important role in SG status and surveillances issues. *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. In addition, DERS work as the power supply resources for emergency usage during outages and disasters are notable. The *Plug in Electrical Vehicle* (PHEV) nodes are beneficial for emissions and fossil fuel energy dependency reductions since they can manage and provide the information about the electrical device charger for electrical vehicles. Finally, the *Distributed Grid Management* (DGM) section allows utilities to remotely monitor and control the parameters in the SG distribution network.

Table 1 summarizes the requirements of the above mentioned 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 study are reported. UTC has defined such communication requirements based on specific studies for each Smart Grid application, by taking into account also an average number of devices or nodes and the average number of collectors per branch of the network [3].

Table 1. Communication requirements of SG nodes [3]

	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

3 The Resource Allocation Cost Function

An evaluation method is needed for properly allocating the communication resources to the different types of nodes in the SG. To this aim, a proper cost function is introduced for managing the resource allocation policy for different nodes with different communication requirements over different communication networks. For achieving these aims, it is needed to define the weights of the most important users Key Performance Indicators, KPIs, and their normalized proportional value in a certain communication network.

Required data rate, or BW, and the delay sensitivity of the SG nodes are two most important KPIs considered in this study. For a certain scenario, the SG nodes having the lowest data rate have the lowest weight and vice versa.

For defining the normalized value, a reference BW and the reference data rate in each different CT are considered. Then, the amount of data rate required to respect the requirements of a certain type of nodes is divided by each CT data rate (for a certain BW in Hz). The same policy is applied to evaluate the weight of the latency based on the delay sensitivity of each type of SG node. Thus, the nodes with lower delay sensitivity have lower weight. The obtained cost function is:

$$CF_{ij} = \frac{\left(W_{bw_{ij}}.N_{bw_{ij}}\right) + \left(\mathrm{W}_{delay_{ij}}.N_{delay_{ij}}\right)}{\left(W_{bw_{ij}} + \mathrm{W}_{delay_{ij}}\right)} \tag{1}$$

where CF_{ij} is the CF value for the user type i when using the CT j, and $W_{bw_{ij}}$ and $N_{bw_{ij}}$, are the BW weight and normalized value for user type i and CT type j respectively. $W_{delay_{ij}}$ and $N_{delay_{ij}}$ are the delay weight and normalized value for user type i and CT type j, respectively.

It is possible to note that in such a way the communication network with the delay closer to the delay sensitivity of SG nodes has the lower value. Therefore, the node requirements are respected and the resources of the best CT in terms of delay can be allocated to the user with the highest delay sensitivity. The characteristics of the CTs selected for this study are in Table 2.

Table 2. RTT and spectrum efficiency for the three selected communication configuration which are corresponded to the certain CTs [2]

	RTT (ms)	Spectrum efficiency (b/s/Hz)
LTE	10–20 [6]	(1.4 MHz, 64 QAM Modulation)≃3.6 [7]
GSM	150–200 [6]	≃1.36 [8]
(Satellite) LEO	[9, 10] 100–150 <	(8PSK Modulation)≃1.8 [11]

In (1), the BW weight for each node can be defined as $W_{bw_{ij}} = R_{Ni}/M$, where R_{Ni} is the data rate required by the i-th node type, and M equal to $\max\{R_{N1}, R_{N2}, \ldots, R_{Nn}\}$ is maximum requested rate among all the possible node types. The CTs that support a certain type of SG nodes can be ordered by their CF value, where the lowest CF value is the best choice. Therefore, the nodes with the lowest data rate have the lowest weight. The normalized BW value for the node i in the network j is:

$$N_{bw_{ij}} = \frac{R_{Ni}}{PbpsNET_j} \tag{2}$$

where $PbpsNET_j$ is the proportional rate for a certain fixed amount of BW. For example, 1 MHz generates different data rate in different technologies and even in same technology with different modulation scheme (e.g., 5 Mbps in LTE and 1.3 Mbps in GSM). The latency weight for node i can be defined as:

$$W_{delay_{ij}} = 1 - \frac{NWLAT_i}{MAX_{NLAT}} \tag{3}$$

where $NWLAT_i$ is the maximum latency requirement for node i (the last column of the Table 1) and MAX_{NWLAT} is the maximum value among $NWLAT_i$. As mentioned before, the lowest CF value stands for a more efficient allocation. Thus, the node with the higher difference between the delay requirement and delay of the allocated CT, has the higher weight. The normalized latency for node i, when using the network j, can be defined as:

$$N_{delay_{ij}} = 1 - \frac{TotLat_{ij}}{NWLAT_i}. \tag{4}$$

The communication networks having the latency higher than the maximum delay sensitivity of a certain node are ignored since they cannot respect the latency requirements of the node and, based on (4), the normalized value is negative.

Since RTT is the value for the round trip time for each type of communication network and TP is the processing time, considered as 5 ms [12], we will refer in the following to $TotLat_{ij}$ equal to $(RTT + TP)$, as the overall latency value.

As an example, Fig. 1 shows the normalized delay as a function of RTT of CT and the SG node delay sensitivity. As it can be seen, the normalized delay is higher if RTT and SG node delay sensitivity difference is higher and vice versa. This factor helps to define a KPI in which it is preferable to allocate CT with higher RTT to a lower delay sensitivity SG node.

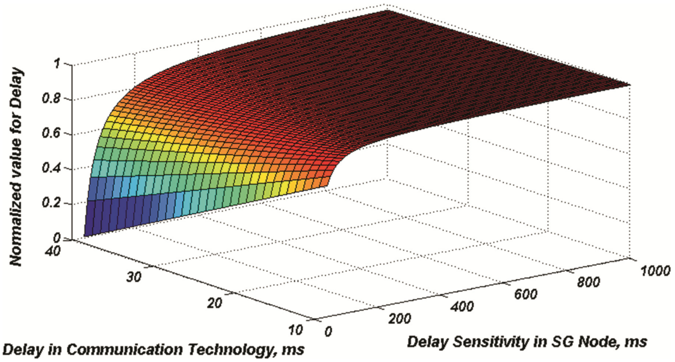

Fig. 1. Normalized value

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 be served earlier. Therefore, it is needed to define the SG goals in terms of 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. For a certain type of nodes, giving more importance to a certain KPI depends on how much that node can fulfill that KPI. The intuitive concept we propose is proportional to a quantitative value, as follows: Very high: 5, High: 4, Medium: 3, Low: 2 and Very low: 1.

CF effectiveness in achieving SG goals depends strongly on how SG goals and KPIs are related. The weights given to the KPIs of each node type are used for comparing the behavior of the different types of nodes with respect to certain SG goals. 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. The main goals of SG have been declared in many references, while in the term of KPIs are described in [3].

In the following, a description of different types of services relying on the SGs is done, and a qualitative prioritization is performed. The main goals of SG are: Green Energy, Reliability in power grid, Security in power grid, Outage Avoidance, Users Cooperation, Automated maintenance, Consumption cost minimizing and Disaster Avoidance [3].

Green energy concept in SG is generally defined as energy usage efficiency, decrease using of fossil fuels and try to use the sustainable energy. *Reliability in power grid*, controlling and distribution grid management have the main roles. Increased reliance on renewable improve reliability in associated extreme events. Moreover, its demand side effects in reliability are high [3]. As the technology develops, dependency on the *secure* electricity supplies, transmission and distribution is increased. Grid monitoring and surveillances due to its characteristics has a significant role on SG security. [3].

Outage and blackout avoidance as the result of high consumption or any unpresented faults in the power grid should be considered as an important goal of SG [3, 13]. *User cooperation* is considered as the users' assistance to increase power grid functionality; it is respected on the demand side of the SG. Although, power system status makes information as a feedback to the CS and then CS demand response changes based on it [3]. *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 [3, 4, 13]. 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, controlling power status and distributing part have effects on it by detecting the fault over the power grid [3]. *Disaster avoidance* is another important goal of SG achieved through higher rates of survivability following a natural disaster. Beside it, DGM by balancing the power distribution is helpful. Demand side role by communicating with CS on disaster avoidance is notable [3, 4].

Based on the nodes functions in the SG described in the Sect. 2 and the above explained policy to allocate a numerical value to the nodes based on an intuitive understanding of their functions on fulfilling a certain SG goal, the results can be shown in Table 3. As an explanation, the demand side nodes includes AMI, PHEV and even DERS. Large number of users in AMI part, which includes the real users using SMs rather than PHEV, may cause to highlight importance of AMI to fulfill some SG goals rather than PHEV. Although, DERS based on its characteristics has important role to respect to some of SG goals [3, 13].

Table 3. SG nodes weights for different SG goals

Smart Grid Goals	*Smart Grid Nodes and Applications*				
	AMI	*PHEV*	*WASA*	*DGM*	*DERS*
Green Energy	*4*	*3*	*3*	*4*	*5*
Reliability	*3*	*3*	*5*	*5*	*3*
Security	*4*	*4*	*5*	*4*	*3*
Outage Avoidance	*4*	*2*	*5*	*4*	*4*
Users Cooperation	*5*	*3*	*3*	*2*	*4*
Automated Maintenance	*1*	*1*	*5*	*3*	*1*
Minimize Consumption Cost	*5*	*4*	*3*	*2*	*3*
Disaster Avoidance	*3*	*1*	*5*	*4*	*2*
Sum of Weights	*29*	*21*	*34*	*28*	*25*
Normalized Weights	*0.852941176*	*0.617647059*	*1*	*0.824*	*0.735*

4 Numerical Results

Based on the cost function in (1), the SG nodes priority has been evaluated by a proper simulation framework in MATLAB. The weight of data rate and delay for different SG node are calculated by using (2) and (4).

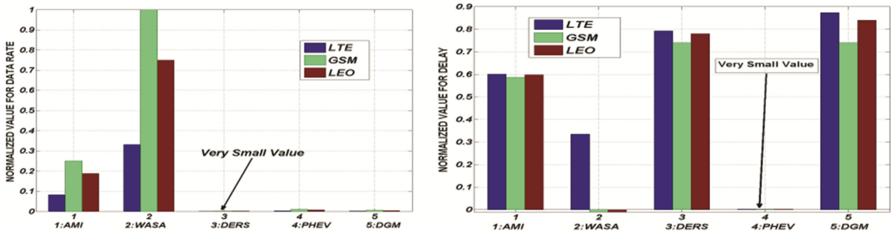

Fig. 2. (a) Data rate normalized value and (b) Delay normalized value

Figure 2a and b show the data rate and delay normalized value respectively for different type of the SG node over three different CTs. As it can be seen, WASA is negative for in case of LEO and GSM since their delay is higher than WASA delay sensitivity. Its negative value by using the CF in (1) can be seen in Fig. 3.

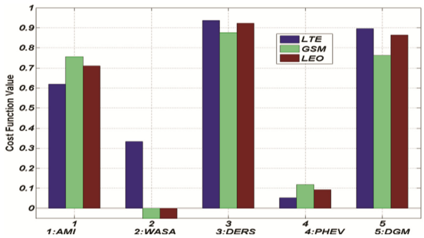

Fig. 3. CF value for different type of the SG node over 3 different communication network

Table 4. 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

As it is shown in Fig. 3, 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 Table 4 have been ordered from up to down based on their priority of respecting the SG goals described in the Sect. 3. The priority values in Table 3 and the CF are used jointly for deriving the Table 4. Although LTE is the first priority CT for WASA, AMI and PHEV but at the first step, this resource will be allocated to the SG node with higher priority. This is because a certain CT is not able to support all the nodes, hence, first of all, the highest priority nodes should be supported. Based on the CF values, CFV, and SG node prioritization, SGNP, a priority table is generated. For certain SG node types, the CFV for each different CTs is achieved. The CFV of a certain type of SG node, calculated for all different CTs, are compared and the lowest stands for the most proper technology; based on the CFV and SGNP, the priority table is generated, and used as a criteria to decide which is the best CT for each SG node.

5 Conclusion

Finding a way to allocate the spectrum as the scarce resources to fulfill all smart grid nodes communication requirements in an efficient way is a big challenge. A method was introduced and investigated to properly allocate spectrum of different types of communication technology to a bunch of user types with different characteristics in which all users type meet their communication requirements and avoiding as much as possible the unnecessary allocation of the specific low delay CT resource to a user that is not delay sensitive. Thus a method is introduced based on a proper cost function. Furthermore, the smart grid different nodes types were prioritized based on the smart grid goals and then a defined scenario is investigated based on it.

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