

Non-uniform Hierarchical Modulation for Wireless Communication in Smart Grid

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Abstract—The deregulation and liberalization of power market allows greater integration of renewable power resources at all stages of electrical networks but it makes the balance between supply and demand more difficult to reach. Thus, efficient and reliable communications between electrical network nodes must be guaranteed in order to dynamically use the power system as optimally as possible. The electrical protection decisions and real time pricing are among the categories of power system information. However, these categories have different priorities depending on their importance in the whole power system. Communication system must then take into consideration such requirements. This paper proposes the use of wireless links to transmit these information differentially protected by using non-uniform hierarchical quadrature amplitude modulation (16-QAM) where high (low) reliable symbols are assigned to critical (basic) information.

Index Terms—Non-uniform hierarchical QAM Modulation, Wireless Communications, Smart Grid, Real time pricing, Electrical protection.

I. INTRODUCTION

The liberalization of power market requires the ability to communicate power consumption and energy prices, to monitor operational informations, to control power balance and to ensure the safety of the grid. Thus, the electric power systems are facing unprecedented changes. They move from dumb to smarter systems [1]. Since the main goal of smart grid is to provide flexibility, effectiveness and reliability in the use of the electricity network, the quality of communication must be efficient due to the importance and the amount of information exchanged between all the parts of the grid. For these reasons, it is essential to use a robust communication infrastructure with the optimal cost. In fact, wireless technologies present several advantages such as rapid deployment, low cost installation, high throughput and mobile communication.

The transition from the conventional electric networks to smart grids requires the deployment of smart monitoring and control devices throughout the whole networks. Thus, this evolution will bind the improving of the wireless infrastructure performance to avoid a gap between the smart devices and the current wireless communication technology. Among the needed evolution, is the efficient use of bandwidth to transmit simultaneous multi-class data over wireless link without neglecting the robustness and the quality of the data transmission.

In wireless networks, the bandwidth is a crucial parameter that should be efficiently used. Thus, the multi-class data transmission is becoming increasingly attractive in wireless communication. These latter can be disturbed by changes in path attenuation, noise and/or variation in interference. For

these reasons, it is important to use a robust modulation technique whose performances can meet the mentioned constraints.

Many efforts have been investigated to propose solutions based on conventional modulation for smart grid. In [2], the proposed idea for emergency communications over LTE is based on QPSK, 16-QAM and 64-QAM modulation. In [3], the proposed method is about an interactive communication structure with QPSK over coupled circuits models. The goal behind this method is to overlap the modulated data to the three-phase transmission line at the inverter and the grid side. These studies present solutions for transmitting different data classes without taking into account the importance of each data class and the channel conditions.

In this paper a non-uniform hierarchical 16-QAM modulation is proposed in order to transmit two classes of data, *electrical protection decisions* (EPD) and *real time pricing* (RTP), simultaneously with unequal priorities, high and low, respectively. Indeed, it transmits high priority data with smaller bit error rate (BER) than that of the low priority data.

The reminder of this paper is structured as follows. Section II presents the smart grid system and its main components. Besides, it defines the considered exchanged information in this paper. Section III describes the proposed modulation technique used in smart grid system communication. Section IV presents the details about the algorithm of the modulation technique and analyses its performance. The final section concludes this paper.

II. THE PROPOSED SMART GRID INFRASTRUCTURE

In this section, we describe the proposed smart grid infrastructure model as well as the considered exchanged information including the energy RTP and EPD data.

A. System description

The proposed smart grid architecture, shown in Fig. 1, is a liberalized grid relying on several generation sources merging conventional and renewable energy. We propose the following structured system to facilitate its management: smart grid, minigrid (*MiniG*) and microgrid (μ G).

The smart grid is composed by several *MiniGs*, the electrical transmission network (ETN) and energy sources. The whole *MiniGs* are connected to the ETN which is the interface between the energy sources and the remaining grid. Moreover, each *MiniG* is composed by many μ Gs where each one is controlled by a smart local manager (SLM). Finally, the SAM relies on the information exchanged both with the SGM and the SLM to manage its own *MiniG*.

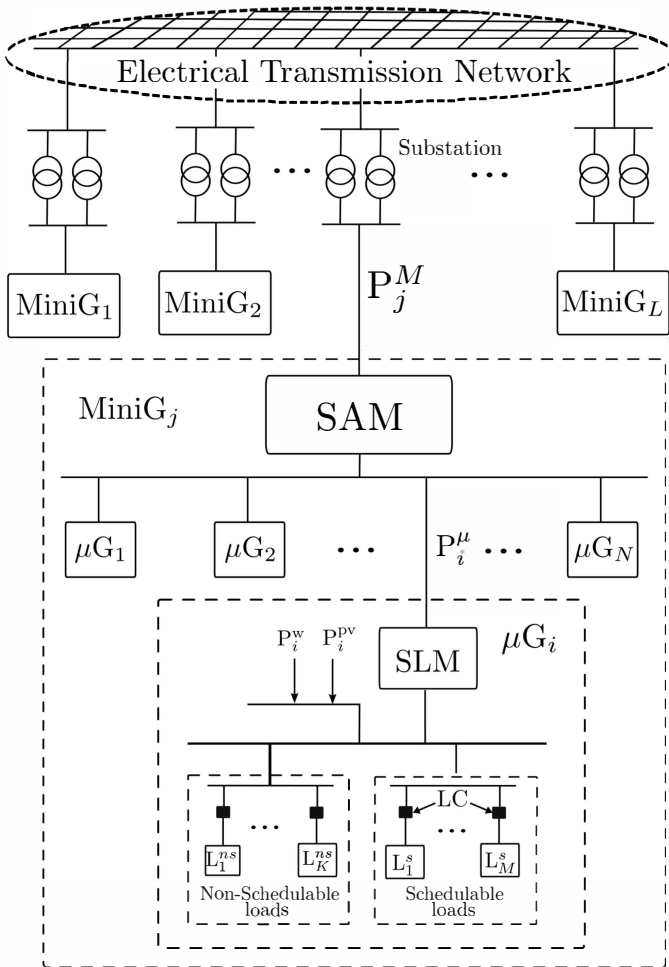


Fig. 1: Electrical power distribution in smart grid

The *MiniG* is an area system composed by many μG s, as shown in Fig 1, where each one has its own green power generation including photovoltaic and wind sources. Each μG supplies two kind of loads including schedulable and non-schedulable loads.

- *Non-Schedulable loads* are loads which turning on or off can not be determined, because they present a paramount need and depend extremely in random behavior of users. Such as lighting, television, computer, fridge, etc.
- *Schedulable loads* are the electrical equipments which don't have time constraints in turning on and for which a user can prioritize, such as washing machine, electrical vehicle, air conditioning, etc. In fact, their switching on is executed by the load controller (LC) depending on the electricity prices communicated by the SLM. The reason behind this is to give to the customer the ability to control his/her energy consumption automatically with respect to market price [4]. to control the customer supply these equipments with the lowest price, then

As shown in Fig. 2, this ETN has a smart grid manager (SGM) which controls the whole power grid relatively to the information exchanged with *MiniG*s managers called smart

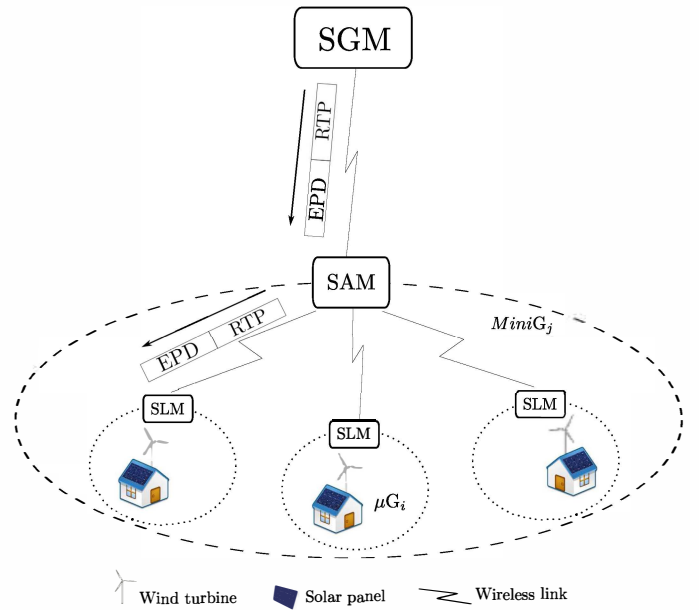


Fig. 2: Smart grid architecture

area manager (SAM).

B. The exchanged information

In the existing electrical grid, ETN presents the transfer infrastructure of electrical energy, from generating power plants to electrical substations located near demand centers. Then, the energy flow is unidirectional from generation to customers. However, the use of renewable energy sources (RES), as a power source at the different voltage levels, leads to a bidirectional energy flow aspect. In order to overcome this new behavior, it is essential to improve the existing infrastructure by introducing smart devices which can support several functionalities such as pricing, protection control, power monitoring, etc. In his paper, we focus on the RTP and the EPD data, as shown in Fig 2.

Real time pricing is the quantity of electricity utilization priced in each scheduled time interval (STI) [5]. The strategy of RTP is set by the SGM through the information collected from all SAMs about load forecasting and marketing management which combines information of supply and generation. Then, the SGM communicates two kind of RTP to each SAM which broadcasts them to all SLMs in the same area. The first kind of RTP is for the consumption energy unit and the second kind of RTP is for the produced green energy unit by the μG s. Afterwards, in one hand decisions are taken from each SLM to switch on the schedulable loads. This smart behavior allows to benefit from best tariffs announced from the SGM. In the other hand, the quantity of the renewable energy produced by the μG is adjusted relatively to the price communicated by the SGM. This variation in price contributes into power balancing.

In the classical grid, the selectivity protection is based mainly on the short-circuit power at each bus which becomes more important in terms of voltage levels. This specification is due to the unidirectional power flow from high to low voltage.

However, In smart grids, The power flow is bidirectional due to the introduction of RES in all voltage stages [6]. Consequently, the existing protection philosophy must be changed in order to avoid a gap between the protection devices used in a classical grid and this new operational specification of power system. Indeed, the use of smart protection devices becomes an obligation to ensure the safety of the grid. These smart devices are equipped with wireless interfaces which make them able to exchange short-circuit power, power flow direction and their identification information directly with the SAM/ SGM or via the SLM. Furthermore, the SGM/SAM combines these information to take and to send the EPD to the appropriate protection device in order to avoid problems in the grid operating system.

Since, the introduction of RES to the existing grid leads to a bidirectional energy flow which must be well controlled to avoid breakdown or damages in the whole system. It is primordial to keep the safety of this grid at all levels. For this reason, it is essential to ensure a good communication between all the entities of the proposed grid model, specifically, for the EPD data. In the following section, we propose a modulation technique which is modeled to transmit simultaneous data-classes where a high protection priority is given to the critical information.

III. HIERARCHICAL NON-UNIFORM 16-QAM

The modulation is a technique of conveying a message signal (digital or analog signal) inside another sinusoidal carrier signal that can be transmitted over a wired or wireless link. The aim behind using modulation technique is to achieve a long transmission distance and to overcome transmission constraints such as attenuation, fading channel, noise, interference, etc. The modulation process is divided into analog and digital modulation.

In analog modulation, an analog carrier signal is varied continuously in response to a low frequency analog message (input data). However, in the digital modulation, an analog carrier signal is modulated by a discrete signal where the changes that the carrier signal undergoes are determined by a finite number of symbols. This paper focused on 16-QAM which is a digital modulation, it is a process for sending digital information by changing the amplitude and the phase of the carrier periodically. In fact, it combines two amplitude-modulated signals into a single channel. The two signals are orthogonal in phase, one of them is in-phase called the I-signal and the other is in quadrature and called the Q-signal. Each combination of amplitude and phase represents a symbol of a digital bit stream. The characteristic of combining two orthogonal signals into one signal gives to M-QAM modulation an attractive performance of doubling the effectiveness of data transmission. Since, in smart grid it is needed to transmit different classes of data over the wireless infrastructure with a good quality. Thus, the modulation, as explained above, is a technique which allows to achieve a long transmission distance and also to overcome the transmission constraints especially over wireless link. From this perspective, it is proposed in this

paper to use a new modulation technique called non-uniform hierarchical modulation 16-QAM [7] which can reply to these requirements including providing a reliable and effective transmission of different data-classes. The goal behind proposing this new technique is to guarantee a reliable reception of the exchanged information between the elements of the considered smart grid model even if the channel conditions are not good. This technique supports transmitting simultaneously multi data-classes over wireless link where each data-class has a priority depending on its importance in smart grid operations. In this paper, the system is modeled bi-directionally in term of transmission. The communicated EPD data has a high priority (HP) whereas the RTP information has a low priority (LP). The stream with high priority has a big probability to be received even if the channel conditions are bad. However, the second information are well received when the channel condition allows.

The hierarchical 16-QAM is the conventional 16-QAM plus a hierarchical specification. In fact, the 16-QAM constellation is coded 4 bits per symbol. Thereby, in hierarchical 16-QAM the four bits of each symbol are divided in two categories, as shown in Fig 3a, where the first most significant bits (MSB) are used for the data stream with high priority while the three low significant bits (LSB) are used for the data stream with low priority [8]. The principle of this idea, is that the MSB (The bit on the right of each symbol) is represented in all symbols of the quadrants with same real sign axis and the LP stream indicates the position inside the same quadrant. Consequently, the HP stream is more reliably transmitted and protected than the LP stream. Indeed, as explained above, the LP stream requires a good channel condition and that means a high Signal-to-noise ratio (SNR). However, the HP stream require just a low SNR ratio and that guaranties the receiving of HP stream in bad conditions. This property of hierarchy introduces a new behavior to conventional QAM technique allowing a continuous transmission of data even if the conditions channel are bad. In fact, the HP stream can benefits from the channel bandwidth more than the LP stream in this case. Otherwise, both HP and LP benefit from the transmitting over the channel. Then, the hierarchical 16-QAM allows a simultaneous transmission of both data-classes in each transmission direction. As a result, this modulation guaranties an effective use of bandwidth as well as a good protection for the HP stream.

In order to give a robust structure to the proposed modulation, other modifications are added to this latter in the ratio constellation α which represents the ratio a/b [9]. The parameter (a) is the distance between symbols located in adjoining quadrants and the parameter b is the distance between adjacent symbols in the same quadrant as shown in Fig. 3a. In the conventional M-QAM α is equal to 1 ($\alpha = 1$) and that makes the M symbols positioned within a uniform distribution, which means that the distance b is the same as the distance a . That's why the conventional M-QAM is called uniform. Indeed, the parameter α of the proposed hierarchical 16-QAM is increased to give a non-uniform behavior [7] to this new modulation

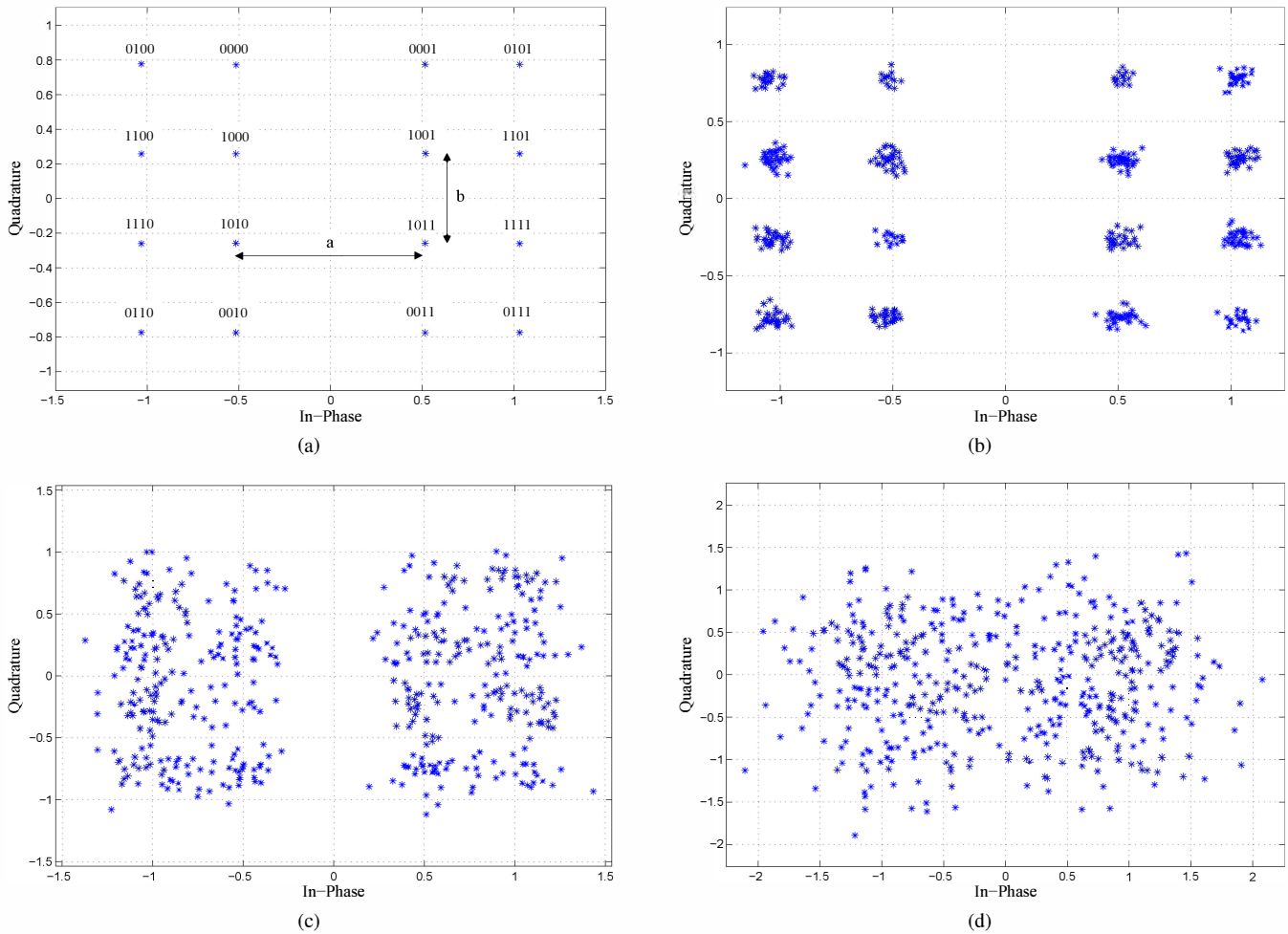


Fig. 3: Non-uniform Hierarchical 16-Quadrature Amplitude Modulation Constellations for (a) the case without noise, (b) SNR=25dB, (c) SNR=15dB and (d) SNR=5dB.

technique. There are many values that the parameter α can take such as $\alpha = 2, 4, 8, \dots$. Then an increase in its value leads to an increase in the average transmission power, but also to a decrease in the required SNR ratio for the HP stream [8]. Moreover, changing the value of alpha allows increasing the spatial separation between the symbols located in adjacent quadrants. Fig. 3 shows different symbol constellation for the same $\alpha = 2$ and for different SNR. for SNR= 25dB, both HP and LP data are well protected. For SNR= 15dB, it is clear that the HP data is well protected whereas the LP data is affected by noise. Finally, both data are confused for SNR= 5dB. This case could be avoided by increasing the the α value which allows a rise in transmission power. In fact, the symbols of adjacent quadrants could be less confused when they are affected by noise and consequently it becomes easy to extract the original information and especially for the HP stream.

IV. SIMULATION AND RESULTS

As explained in section II, through the SAM, the SLM receives the RTP of renewable energy calculated by the SGM. In

the *MiniG* area scale, the SAM collects the useful information from all SLMs to make the right decisions and send them to all appropriate SLMs. In this section, we have focused on the exchanged information in the down-link between the SAM and the SLM. As shown in Fig. 2, these information include both EPD (HP) and RTP of electrical energy (LP) information. In fact, to demonstrate the performance of the proposed non-uniform hierarchical 16-QAM, we use the calculated RTP, in [5], for 24 hours with a step of 6 minutes as shown in Fig. 6a, 6c. Besides, we consider that the EPD of the SAM are a vector of '0' or '1', where '0' means the decision of switching off the protection device and '1' means the decision of switching it on or keeping it switched. This vector, is composed by many bits where each one is assigned to one protection device within a fixed order.

Hierarchical 16-QAM modulation using non-uniform constellation can not be simulated with default functions in Matlab. In fact, we have proceed as follows: The first step includes preparing the full data which is a combination of EPD and RTP information. Fig. 4 shows the procedure followed to prepare the transmitted signal. We have extracted in each row

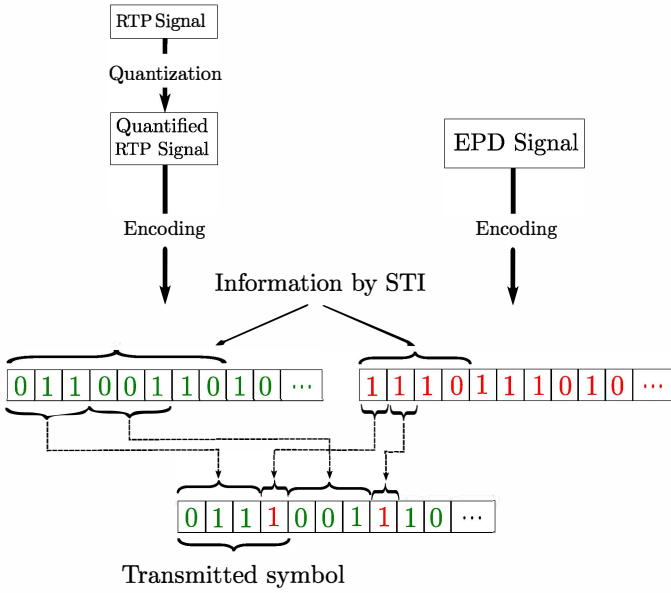


Fig. 4: Transmitted information

of data RTP matrix and EPD vector respectively three bits and one bit in order to create the stream matrix. This latter, contains in each row the formed symbols with four bits.

The second step is to add the hierarchical property to the existing 16-QAM modulator object (modem.genqammod) by adjusting the mapping functionality. Indeed, it is needed to change the default "constellation" from the binary distribution to a customized gray one. The role of this functionality is to define the order in which symbols will be mapped. The proposed constellation can be determined through a vector of symbols coordinates. The mapping used in this paper is described in the Fig. 3a, where the symbols are organized within a gray and a hierarchical distribution. The HP and LP information are represented in each symbol by one and three bits respectively. As the HP bits are designed to be protected more than the LP bits, the HP bit "0" (bit "1") is represented in all symbols of the two quadrants in the left (right). The rest bits of each symbol are inserted into the LP bits in order to provide the defined mapping.

The two steps described above allow modulating, according to the mentioned symbol mapping, the full data with the new released hierarchical 16-QAM. The next step is to change the separation distance in the modulation algorithm in order to give the non-uniformity character to this modulation technique. For this reason, a third step is needed. Some modifications are added to the ratio α . Since the goal behind this technique modulation is to protect the HP bits more than LP bits. We have separated symbols in the left from those in the right. Then, we have increased the ratio α from the value 1 to the values 2, 4, etc. Consequently, we have increased the distance "a", the distance between symbols in adjoining quadrants. This new character of non-uniformity allows avoiding any confusion between symbols of adjoining quadrants when the power of noise is important.

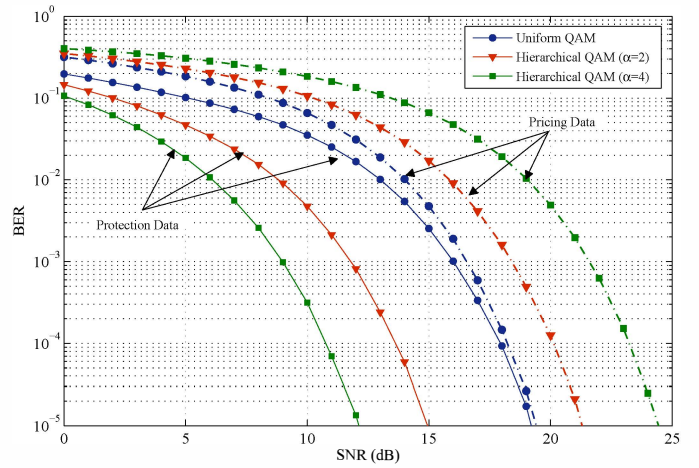


Fig. 5: BER of electrical protection decisions and electricity real time pricing information in terms of SNR for different values of α

SNR / α	$\alpha = 1$	$\alpha = 2$	$\alpha = 4$
5	HP : 10^{-1} LP : $2 \cdot 10^{-1}$	HP : $5 \cdot 10^{-2}$ LP : $2 \cdot 10^{-1}$	HP : $2 \cdot 10^{-2}$ LP : $3 \cdot 10^{-1}$
10	HP : $3 \cdot 10^{-2}$ LP : $6 \cdot 10^{-2}$	HP : $5 \cdot 10^{-3}$ LP : 10^{-1}	HP : $3 \cdot 10^{-4}$ LP : $2 \cdot 10^{-1}$
15	HP : $2, 5 \cdot 10^{-3}$ LP : $5 \cdot 10^{-3}$	HP : 10^{-5} LP : $2 \cdot 10^{-2}$	HP : 10^{-6} LP : $6 \cdot 10^{-2}$

TABLE I: BER of HP and LP for different values of α and SNR

The obtained signal, the concatenation of EPD and RTP, is modulated by the released modulation which allows to transmit simultaneously the two data with a protection priority for the first data (EPD) due to its importance in the safety of the whole grid.

Fig. 5 shows the simulations results of the released modulation. We have extracted some values represented in Table I. For SNR = 10 and $\alpha = 1$ (uniform constellation), we note that the BER for HP is 10^{-1} and for LP is $2 \cdot 10^{-1}$. However, when we increase the ratio constellation α , for the same SNR, in order to more protect the HP information, the results for the same SNR are as follows: For $\alpha = 2$, the BER of HP decreases approximately ten times to the value $5 \cdot 10^{-3}$ and the BER of LP increases slightly to the value 10^{-1} . Besides, for $\alpha = 4$, the BER of HP becomes lower to the value $3 \cdot 10^{-4}$ but the BER of LP increases to the value $2 \cdot 10^{-1}$. We observe that, increasing the α value, the HP information becomes more protected without much degrading the reception quality of LP information.

Finally, Fig. 6 shows the submitted and received signals of both EPD and RTP information in 24 hours. We note that, for SNR = 15 dB, the protection information is received with no errors whereas the RTP information is received with some errors. In the worst case of SNR = 5 dB, the protection data has one bit error however the RTP signal is much affected by noise.

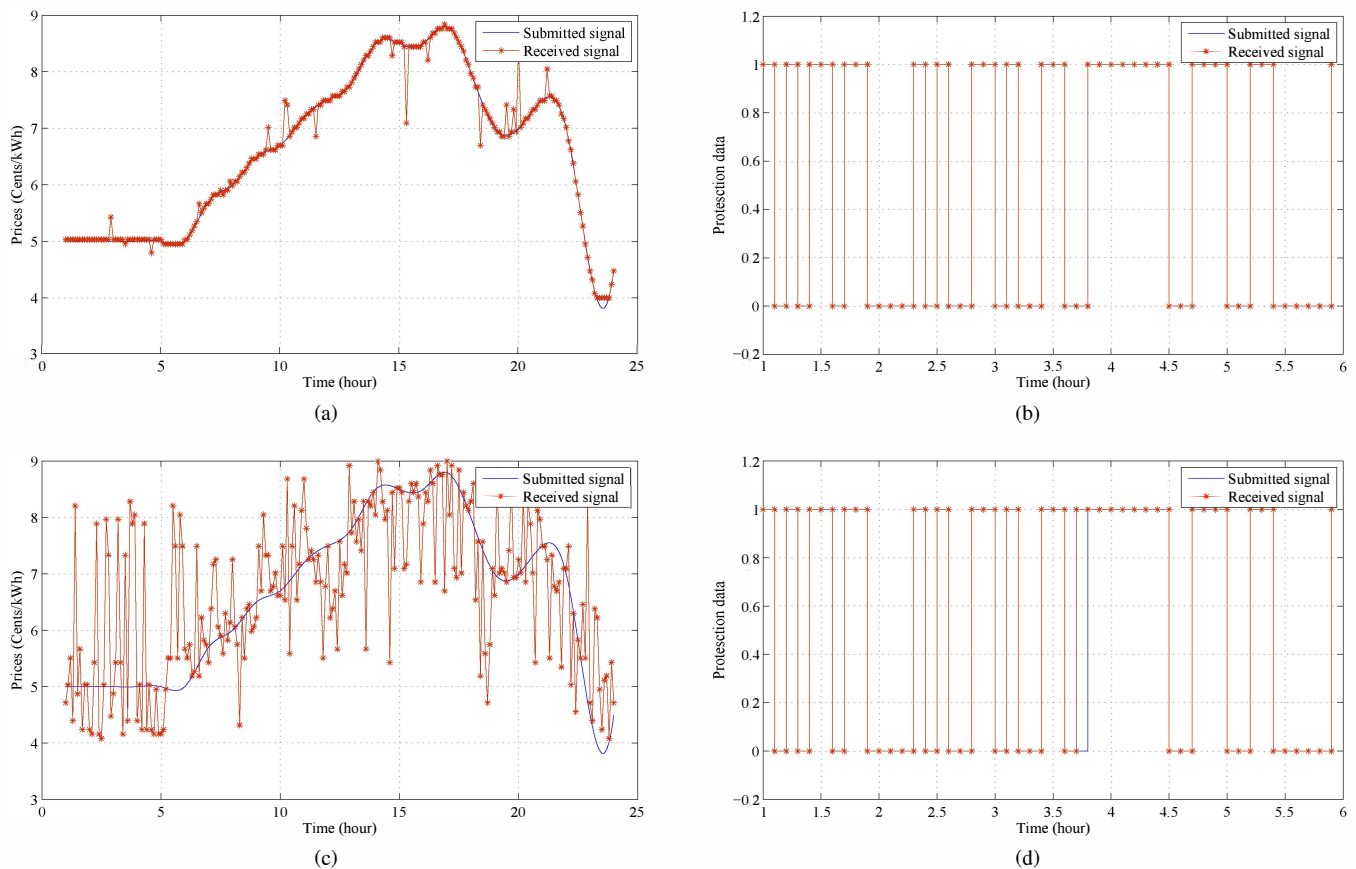


Fig. 6: Submitted and received signals of (a) prices with SNR=15dB, (b) protection data with SNR=15dB, (c) prices with SNR=5dB and (d) protection data with SNR=5dB.

V. CONCLUSION

This paper presents a non-uniform hierarchical 16-QAM for the exchanged data in the smart grid system. This modulation technique is applied both on the electrical protection decisions (HP) and real time pricing (LP) information with unequal priority. The reason behind this idea is not only to guarantee a simultaneous transmission of multi-class data but also to ensure a reliable reception under a low BER value specifically for the data with high priority. Simulation results confirm the effectiveness of the proposed modulation technique in promoting the reliable reception for the HP data without degrading the quality of LP data. When the channel is much affected by noise, the increase of the ratio constellation α leads electrical protection data to be more robust to the channel errors than the RTP data. This modulation technique could be applied for all exchanged data between the whole manager sub-systems of the proposed smart grid architecture.

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