LTE-D2D Communications to Smart Grid Applications with Reliability and Latency Constraints

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***Abstract*— Device-to-device (D2D) communication is a potential technology to improve capacity and energy efficiency of the current wireless communication systems. This work is focused on the application of D2D communication underlaying LTE network for distributed automation (DA) in the smart grid (SG) context. The communication aspects of SG and DA are introduced, and considering the strict reliability and latency constraints imposed by IEC 61850 standard, it is presented a resource allocation optimization problem for such scenario. The optimization problem is a mixed-integer non-linear program, with a non-convex feasible set, i.e., it is a NP-hard problem, which is relaxed by replacing non-convex by convex constraints. Finally, the multi-hop and full-duplex communication concepts are briefly introduced in the resource allocation problem, as promising technologies.**

***Keywords*— Smart grid, D2D, LTE, resource allocation, reliability, latency, IEC 61850.**

I. INTRODUCTION

In a nutshell, smart grid (SG) refers to an intelligent power grid which is operated over a communication network. The SG concept uses two-ways flows of electricity and information, aiming to increase efficiency, flexibility and reliability. Using a digital and reliable communication with some intelligence in the management system, it is possible to achieve self-monitoring, remote check/test, self-healing, among others [1].

Among the features of SG, it is discussed here the distributed automation (DA). The demanded services for DA consist in wide-area monitoring systems and distributed control/protection, which involve the collection of real-time information over many substations and equipments, in order to provide the required information to the control center for agile actuation and to keep the system available [2]. Due this demand, these applications have rigid latency and reliability constraints.

Nevertheless, almost the entire Brazilian power grid system is deployed with protocols that are not compatible with rigorous latency and reliability requirements, such as DNP3.0 and IEC 60870-104. For dealing with these strict conditions, the global standard "IEC 61850 – Communication Networks and Systems in Substations" must be exploited, since it can deal with protection, control and communication in such scenario. Nowadays, there is a gradual migration of world power grid communication, and also the Brazilian one, to this standard.

For SG, it is expected IEC 61850 standard to be implemented over one of the following well established potential wireless alternatives: IEEE standards 802.15.4, 802.11 and 802.16, satellite and LTE cellular standards. Also, there exist emerging RF technologies for Internet of Things (IoT), such as LoRa, SigFox, Weightless, and UNB, which have to be considered as potential alternatives.

Furthermore, there are promising technologies for next wireless communication, such as the multi-tier heterogeneous networks; the densification of existing cellular networks with small cells and device-to-device (D2D) communication; full-duplex (FD) communications; massive multiple-input multiple-output (massive-MIMO); millimeter-wave communications technologies; improved energy efficiency by energy-aware communication and energy harvesting; cloud-based radio access network (C-RAN); and virtualization of wireless resources [3]. In this paper, it is studied the resource allocation in LTE networks for granting densification with spatial reuse via D2D communications.

II. COMMUNICATION SOLUTIONS FOR SG

Copper and fiber-wired technologies constitute reliable and secure data transfer options, offering increased capacity and low latency. Optical fiber systems are immune to electromagnetic interference and they have been used for long-distance applications, while Ethernet has been used for real-time monitoring, control and protection functions inside substations. Another alternative is the power line communication (PLC), which enables data transmission through the existing electrical power lines. However, the nature of transmission medium degrades the signal quality due to attenuation, dispersion, noise and sometimes interference effects, particularly for high frequencies [4].

The use of wired communication solutions can be economically and/or physically prohibitive for most SG applications, and wireless technologies arise as alternatives for enabling communication almost anywhere at relatively low cost, and at the same time being scalable and dynamic. In the sequence, the potential wireless communication standards in SG context are briefly discussed.

The IEEE 802.15.4 standard is the foundation of the ZigBee Alliance. In particular, the amendment "g" corresponds to medium access control modifications, so as to cover outdoor

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low data rate and wireless smart metering utility network, with a data gateway and multi-hop techniques, where devices operate in a very large scale and low-power applications [5]. Despite the low-cost and low-energy advantages, the low data rate (up to 250kbps), short range, security vulnerability and susceptibility to interference are compelling drawbacks when applying this standard for SG.

The IEEE 802.11 standard, used by the WiFi Alliance, constitutes a mature and widely adopted wireless technology that is suitable for home applications in the SG, with data rates reaching the Gbps [6], [7]. Some advances have been done in amendment "s" so as to allow multi-hop networks; in amendment "ah" aiming to support large-scale wireless networks, and in amendment "e" to provide the QoS support to WiFi networks, in terms to layer 2 traffic class differentiations and priorities. However, the main limitations for its use in SG refer to the relatively short coverage range (up to 250 meters outdoors) and the use of unlicensed frequency bands (interference and security).

The IEEE 802.16 standard, used for WiMAX technology, has been also proposed to support the bi-directional communications for SG. It is designed to provide larger and sufficient coverage for the SG distribution system, with low latency (less than 100ms for round trip time), high data rates (up to tens of Mbps), coverage range in the order of tens of kilometers, advanced security protocols and QoS support [8]. The main drawback of using WiMAX for SG remains in the required investments for installation and maintenance.

Alternatively, satellite communication has advantages such as the significant broadband and reliability capabilities. As disadvantages, the few number of public satellites; the increased energy consumption associated to the large communication distance could be a limitation for autonomously operating smart devices; communication latency and the installation and maintenance costs are relatively larger compared with other wireless technologies [9].

Regarding cellular technology, the preferred technology is the Long Term Evolution (LTE) due to be more recent than other ones and also to its potential/flexibility. It has the following advantages: operation in licensed bands, mature and ubiquitous coverage, high data rate, low latency, high system reliability and availability. As deficiency, it is oriented for human broadband applications (voice and data) and it does not support time-critical applications [10]. Also, if power operators prefer deploying their own backhaul for full control and security perspectives in data traffic, the cost becomes comparable to WiMAX technology.

About recent RF technologies designed for IoT, such as LoRa and SigFox, they usually have low data-rate ($< 50kHz$) and also high latency, which drive them to metering and non-critical control applications. Otherwise, LTE-based systems, and particularly LTE-M, are more expensive than other IoT technologies, but with higher data-rate and low latency, being suitable for applications with high-reliability requisites.

III. OVERVIEW FOR IEC 61850

The *IEC 61850 – Communication Networks and Systems in Substations* is a global standard for substation protection, communication and control. The standard works with the concept of a virtual model comprising both physical and logical device models. A physical device is the device that connects to the network, defined by its network address.

In order to support different automation applications, the standard specifies seven types of messages mapped over the OSI-7 layer stack. The time-critical messages are type 1 and 4, the generic object oriented substation event (GOOSE) and sampled values (SV), respectively, which are directly addressed to second-layer Ethernet data link, since they require immediate action at receiving Intelligent Electronic Devices (IEDs). Other types are more easy-going, mapped over the TCP/IP or UDP/IP stack [11]. Applications with different latency and reliability requirements are shown in Table I, with QoS field from 0 (low) to 7 (high). This way, the different message types can have distinct priorities/QoS according to the allowed delay and reliability.

TABLE I: Performance requirements for different SG applications in a distribution substation [7].

Smart Substation Distribution Applications	**IEC 61850 Message**	**Allowed Delay [ms]**	**QoS**
Control and Monitoring			
Automatic Capacitor Bank Control	GOOSE	500 − 1000	4
Load Tap Changer Control and Monitoring	GOOSE	250 − 500	6
Fast Transfer Trip Scheme for Bus	GOOSE	400 − 500	5
Automation and Metering Application			
Watt/VAR Measurement	IP Messages/ Sample Values	1000 − 5000	3
Centralized IED Configuration	IP Messages	1000 − 10000	2
Protection			
Feeder Overcurrent Protection	Sample Value and GOOSE	20	7

Hence, one can see in Table I that each performance class can be mapped to a different message type, so as to satisfy its requirements [12]. So, the challenge is to provide communication which respects the requirements and the well-defined IEC 61850 performance classes. So as to provide such demand, it is discussed in the sequence the resource allocation problem for adoption of D2D communication over LTE [13], where DA devices share the spectrum with conventional cellular users.

IV. LTE-D2D FOR DA APPLICATIONS

The LTE standard development contemplate mainly voice and data traffic for smart-phones. Scaling back the LTE network for other applications, such as DA and IoT, is quite difficult, however 3GPP community is moving quickly to implement LTE-M and NB-IoT.

Regarding the QoS, which covers latency and reliability, the approach adopted for LTE is simple, based on the concept of data flows and bearers. The performance characteristics are resource type, guaranteed bit rate (GBR) or not (non-GBR); priority; packet delay budget; and packet error loss rate [14]. Particularly for the *latency constraints*, in Release 13, there is a study on latency reduction techniques for LTE. The LTE communication delay involves: grant acquisition, random access, transmission time interval (TTI), processing, HARQ Round Trip Time (RTT), Core / Internet and handover.

A key component for achieving an efficient utilization of the available radio resources is the scheduler. The scheduling activity needs, simultaneously, to optimize the system capacity and to ensure QoS for different types of users. In its operation, the physical layer at the eNodeB (eNB) collects the channel state information (CSI) and uses it to determine the modulation (QPSK, 16QAM or 64QAM) and coding scheme through adaptive modulation and coding (AMC) schemes.

The LTE standard supports scalable carrier bandwidth, allowing resource allocation on a subcarrier-by-subcarrier basis for a specified number of OFDM symbols. One can see in Fig. 1 the physical resource for LTE communication, with frequency division duplex (FDD) [15]. Each frame has a duration of 10 ms and is divided into 10 subframes, and each subframe is further divided into two slots of 0.5 ms length. Assuming a normal short cyclic prefix (CP), each slot consists of 7 OFDM symbols. In the time domain, radio resources are distributed over every transmission time interval, which is considered the minimum scheduling unit in LTE and corresponds to a subframe with a duration of 1 ms. In the frequency domain, the available bandwidth (1.4, 3, 5, 10, 15 or 20 MHz) is divided into a number of sub-channels each including 12 subcarriers with spacing of 15 KHz. Each sub-channel has a bandwidth of 180 KHz and along with the 7 symbols in the time domain constitutes a resource block (RB).

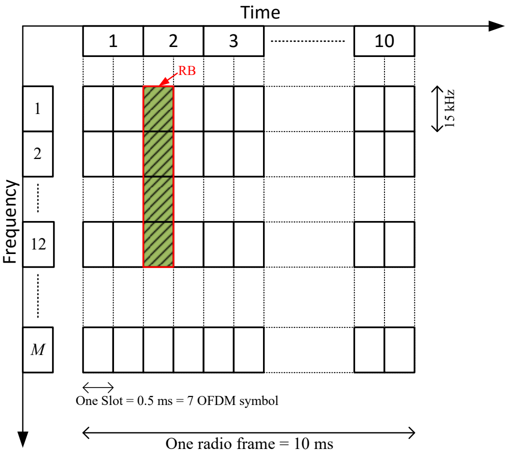

Fig. 1: The LTE physical resource [15].

The number of RBs varies from 6 to 110, according to the available bandwidth. Two consecutive RBs form a scheduling block, which is the smallest resource unit that a scheduler can allocate to a user. Each scheduling block has 7 symbols and 12 subcarriers, and each combination of one symbol and one subcarrier is called a resource element (RE).

A. Resource Allocation

Consider initially an LTE system, in a single cell environment (one eNB), where cellular user equipments (CUEs) share the spectrum with machine user equipments (MUEs). Let $\mathcal{C} = \{1, 2, \ldots, C\}$ and $\mathcal{M} = \{1, 2, \ldots, M\}$ denote the set of CUEs and the set of MUEs, respectively. Moreover, the system bandwidth is divided into F orthogonal sub-bands with set $\mathcal{F} = \{1, 2, \ldots, F\}$. One Resource Block (RB) is defined as a sub-band over one scheduling time unit. It is assumed that MUEs are able to establish only D2D communications links, while CUEs are able to establish only communication via eNB. The single-cell network scenario is presented in Figure 2, regarding only the uplink communication.

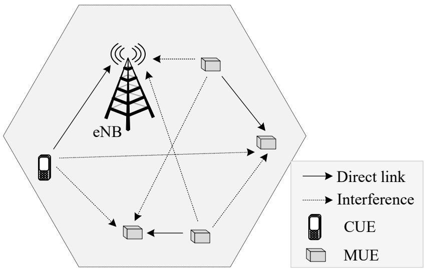

Fig. 2: Network scenario for uplink communication with D2D underlaying LTE [16].

To execute the resource allocation management, the eNB needs the CSI for all links, including the channel gains and interference, which implies that each MUE receiver has to report them back to the eNB. Assuming the MUEs static, a time scale of hundreds of milliseconds is established, with only the large scale fading (path loss and shadowing) being considered for refresh [17]. After executing the resource allocation, all information is sent to the users as an update. An overview of the resource allocation process is shown in Fig. 3.

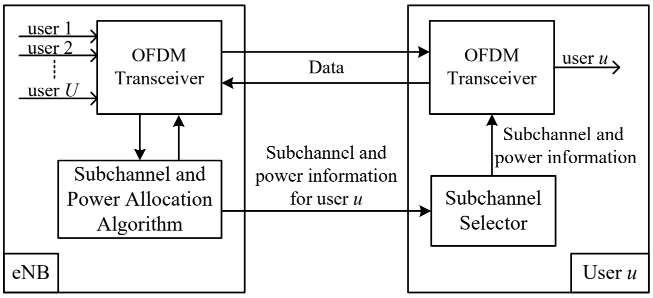

Fig. 3: Overview of resource allocation problem in OFDMA systems [18].

The capacity of a communication link between a CUE u_c and eNB, over a sub-band $B^{(f)}$ is [19]

$$r_{u_c}^{(f)} = B^{(f)} \log_2 \left(1 + P_{u_c}^{(f)} \gamma_{u_c, eNB}^{(f)} \right), \quad \text{[bits/s]} \qquad (1)$$

where $\gamma_{u_c, eNB}^{(f)}$ is the unit power instantaneous signal to interference noise ratio (SINR) and $P_{u_c}^{(f)} \geq 0$ is the transmit power for such communication link. The value of the SINR for each user depends on the system configuration, and it must take into account the transmit power, the complex channel gains (direct and interference links) and the noise power. Consider the following notation for the communication link between node u_c and eNB, over the fth RB, with $u_c \in \mathcal{C}$: the desired and interference channel response are expressed as $h_{u_c,eNB}^{(f)}$ and $g_{u_c,eNB}^{(f)}$, respectively; $S_{u_m}^{(f)} \geq 0$ is the transmission power of $u_m \in \mathcal{M}$ and σ^2 is the noise power. The unit power SINR can be expressed as [16]

$$\gamma_{u_c,eNB}^{(f)} = \frac{h_{u_c,eNB}^{(f)}}{\sum\limits_{\forall u_m \in \mathcal{M}} x_{u_m}^{(f)} S_{u_m}^{(f)} g_{u_m,eNB}^{(f)} + \sigma^2}, \tag{2}$$

with $x_{u_m}^{(f)} \in \{0,1\}$ being 1 if RB f is assigned to user u_m and 0 otherwise. Since the sub-carrier allocation is assumed to be orthogonal among CUEs, the interference comes only from the MUEs, which perform D2D communication links among them. It is assumed non-orthogonal transmission between CUEs and MUEs, which results in intra-cell interference. Also, as long as the link quality can be assured, it is possible to exploit spatial reuse, with multiple and concurrent D2D transmissions of MUEs on the same RB [17].

The optimization for the resource allocation problem must fulfill the requirements of CUEs and MUEs at the same time. To summarize, the objective is to maximize the CUEs' sum rate, while satisfying latency and reliability constraints of MUEs. Let the achievable data rate for a CUE be denoted as

$$r_{u_c} = \sum_{f=1}^{F} q_{u_c}^{(f)} r_{u_c}^{(f)}, \forall u_c \in \mathcal{C}, \tag{3}$$

with $r_{u_c}^{(f)}$ being defined as Equation (1), and $q_{u_c}^{(f)} \in \{0,1\}$, being 1 when RB f is assigned to user u_c, and 0 otherwise. Hence, the objective function of the optimization problem becomes

$$\max_{q_{u_c}^{(f)}, x_{u_m}^{(f)}, P_{u_c}^{(f)}, S_{u_m}^{(f)}} \sum_{\forall u_c \in \mathcal{C}} r_{u_c}. \tag{4}$$

The proposed communication model requires a stringent latency and reliability for MUE links, while are more easy-going for the CUEs. Moreover, there exist the power and RB allocation constraints for both MUEs and CUEs. Hence, aiming to ensure data rate and to avoid harmful interference, these requirements are incorporated as constraints in the objective function.

The reliability constraint described in the sequence is applicable to MUEs, which perform D2D communication. The RBs assigned to each MUE have to be in a limited time span, and the frequency bandwidth is also limited, which results in a limited number of RBs available for each MUE transmission. Based on [17], [20], when assuming a finite number of RBs $F_{u_m}^{\mathrm{all}}$ for the u_m MUE transmission, regarding the large scale fading, the outage probability evaluated at a required number of bits N_{u_m} is defined as

$$p_{u_m}^{\mathrm{out}} = \Pr\left\{ \sum_{f=1}^{F_{u_m}^{\mathrm{all}}} x_{u_m}^{(f)} \rho \log_2\left(1 + P_{u_m}^{(f)} \gamma_{u_m}^{(f)}\right) < N_{u_m} \right\}, \forall u_m \in \mathcal{M} \tag{5}$$

where ρ is the number of complex symbols per RB. Hence, the outage probability represents the reliability constraint $p_{u_m}^{\mathrm{out}} \leq p_o, \forall u_m \in \mathcal{M}$, with p_o being the maximum outage probability tolerable. Introducing $\overline{\gamma}_{u_m}^{(f)}$ for only the large scale fading, and $\overline{\gamma}_{u_m}^{(f)*}$ being derived from $F_{u_m}^{\mathrm{all}}$ and other system variables, after some mathematical manipulation, the reliability constraint become [17]

$$\overline{\gamma}_{u_m}^{(f)} \geq \overline{\gamma}_{u_m}^{(f)*}, \quad \forall f = 1, 2, \ldots, F_{u_m}^{\mathrm{all}}, \forall u_m \in \mathcal{M}. \tag{6}$$

Furthermore, to meet the latency constraint, the limited number of RBs defined for communication, $F_{u_m}^{\mathrm{all}}$, has to be allocated within the RB region $F \times \mathcal{T}_{\mathrm{tol}}$, where $\mathcal{T}_{\mathrm{tol}}$ is the maximum tolerable latency of D2D communications in terms of the number of scheduling time units. It is noticeable there are multiple MUEs which may appear at different times. So it is hard to find a common two dimensional (time-frequency) region to implement RB allocation for all the MUEs. Therefore, in the sequence, the two dimensional RB allocation problem is reduced into a sequence of one-dimensional problems, i.e., only over frequency [17]. Correspondingly, the requirement on latency for the u_m MUE becomes

$$F_{u_m} = \left\lceil F_{u_m}^{\mathrm{all}} / \mathcal{T}_{\mathrm{tol}} \right\rceil, \forall u_m \in \mathcal{M}, \tag{7}$$

where F_{u_m} is the number of RBs allocated to the u_m MUE during each scheduling time unit, and $\lceil \cdot \rceil$ is the ceiling operator. Thus, the calculation of F_{u_m} in Equation (7) ensures that at least $F_{u_m}^{\mathrm{all}}$ RBs is allocated to the u_m MUE within $\mathcal{T}_{\mathrm{tol}}$ time units.

Based on these definitions the resource allocation problem for maximizing the CUEs data rates can be written as follows.

$$\max_{q_{u_c}^{(f)}, x_{u_m}^{(f)}, P_{u_c}^{(f)}, S_{u_m}^{(f)}} \sum_{\forall u_c \in \mathcal{C}} r_{u_c} \tag{8a}$$

$$\mathrm{subject to}$$

$$P_{u_c}^{(f)} \geq 0, \ \sum_{f=1}^{F} q_{u_c}^{(f)} P_{u_c}^{(f)} \leq P^{\max}, \forall u_c \in \mathcal{C} \tag{8b}$$

$$S_{u_m}^{(f)} \geq 0, \ \sum_{f=1}^{F} x_{u_m}^{(f)} S_{u_m}^{(f)} \leq S^{\max}, \forall u_m \in \mathcal{M} \tag{8c}$$

$$x_{u_m}^{(f)} \in \{0,1\}, q_{u_c}^{(f)} \in \{0,1\}, \sum_{\forall u_c \in \mathcal{C}} q_{u_c}^{(f)} \leq 1, \forall f \in \mathcal{F} \tag{8d}$$

$$\sum_{f=1}^{F} q_{u_c}^{(f)} B^{(f)} \log_2\left(1 + P_{u_c}^{(f)} \gamma_{u_c,eNB}^{(f)}\right) \geq r_{u_c}^{\min}, \forall u_c \in \mathcal{C} \tag{8e}$$

$$\overline{\gamma}_{u_m}^{(f)} \geq \overline{\gamma}_{u_m}^{(f)*}, \forall u_m \in \mathcal{M}, \forall f \in \mathcal{F} \tag{8f}$$

with $P^{\max}$ and $S^{\max}$ being the maximum transmit power for CUEs and MUEs, respectively, and $r_{u_c}^{\min}$ the minimum data rate allowed for $u_c \in \mathcal{C}$.

Therefore, the problem of resource allocation becomes the objective function presented in Equation (8a) and the set of constraints described in Equations (8b)-(8f). Clearly, this is a mixed-integer non-linear program with a non-convex feasible set. This way, the resource allocation problem is NP-hard, i.e., there is no polynomial time algorithm to solve problem optimally. Thus, it is appropriate to apply relaxation methods on RB allocation constraints [16]. Instead of a binary value, the variables $q_{u_c}^{(f)}$ and $x_{u_m}^{(f)}$ can be evaluated on the half-open interval of $(0, 1]$, being defined as the sharing factor of a sub-channel by a user. Then, convex optimization techniques can be applied in order to prove the proposed relaxed problem is convex, with a unique optimal solution [16], [21], [22]. The solutions for such optimization problem can be centralized or distributed, and in order to achieve a suitable trade-off between complexity and performance, heuristic approaches are usually adopted.

B. Multi-hop and Full-duplex

Unlike traditional D2D communication presented in previous section, when there is no proximity such that the mobile devices can establish a direct local link bypassing the base station, it can be adopted the relay-aided D2D communication [16]. Relay-aided transmission could enhance the performance of D2D communication, ensuring the reliability and latency required for MUEs communication, particularly when the direct channel conditions are degraded. However, when using a relay-aided communication, the capacity of the channel is reduced by [16]

$$r_{u_c}^{(f)} = \frac{1}{2}\min\left\{r_{u_c,1}^{(f)}, r_{u_c,2}^{(f)}\right\}, \tag{9}$$

where $r_{u_c,1}^{(f)}$ and $r_{u_c,2}^{(f)}$ are the data rate for the first and second hop, respectively. The objective becomes to increase reliability of the communication, since there the capacity and latency are degraded.

Another alternative is to adopt full-duplex communication, which is particularly interesting for densification of network and in small cells [3]. The drawback of the FD communication is the residual self-interference, i.e. a loopback signal from the transmit to the receive antenna remaining after cancellation, which degrades the SINR. In this case, the unit power SINR becomes

$$\gamma_{u_c,eNB}^{(f)} = \frac{h_{u_c,eNB}^{(f)}}{I_{u_c}^{(f)} + \sigma^2}, \tag{10}$$

with $I_{u_c}^{(f)}$ being the interference, which involves MUEs, CUEs and also the remaining self-interference. If the self-interference is diminished after processing, the capacity gain becomes substantial, specially for relay-aided communication.

V. CONCLUSION

A comprehensive discussion on the application of LTE cellular communications in the smart grid context for distributed automation was carried out, considering requirements of IEC 61850 standard. Due to the strict reliability and latency constraints for DA applications, this work led to using LTE communication with D2D aggregated, which can achieve higher throughput and lower latency, provides network offloading and energy efficiency and increases the reliability of the SG network. Moreover, so as to enable such application for DA, the resource allocation problem with reliability and latency constraints was discussed. The optimization problem is a mixed-integer non-linear program, with a non-convex feasible set (NP-hard problem), which is relaxed by replacing a non-convex constraint by a convex one, where the application of convex optimization techniques is indicated. A brief introduction to multi-hop and full-duplex communication, as potential alternatives to increase reliability and capacity of the network, is presented and contextualized to resource allocation.

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