On the Transmission Mode Selection for Substation Automation Traffic in Cellular Networks

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***Abstract*—In this paper, we propose device-to-device (D2D) communication over dedicated cellular resources, i.e., D2D-overlay mode, as a key enabling technology for reliable information exchange in power distribution grids. Motivated by the stringent requirements of substation automation traffic, we jointly address two fundamental issues: *i*) the seamless transition from cellular (i.e., communication via the base station) to D2D-overlay mode for smart grid entities upon detection of a surge of channel access attempts, and *ii*) the efficient orthogonal resource partition for cellular and D2D links. An analytical framework capturing the event-driven nature of substation automation traffic and both phases of uplink communication is introduced and the joint problem of mode selection and resource allocation (MSRA) is formulated as a sum-rate maximization problem. A dynamic heuristic MSRA mechanism is then proposed that adaptively allocates uplink resources for D2D links to prevent spectrum under-utilization and guarantees a minimum rate requirement for cellular users. The performance of our proposed scheme is evaluated through extensive simulations under different performance criteria and numerical results demonstrate the rate gains of a dynamic switch between D2D-overlay and conventional cellular mode for substation automation traffic.**

I. Introduction

Although not initially designed for smart grid services, cellular technology has been identified as a promising option to support reliable communication in the power distribution grid [1]. As an outcome of the continuous evolution of 3GPP-based standards, Device-to-Device (D2D) communication emerges as an enhancement of cellular technology to enable unprecedented decentralized functionalities and satisfy the demanding requirements of advanced distribution grid operations. Against the traditional centralized network architecture, neighboring devices can exchange information utilizing cellular licensed resources over a direct link, rather than transmitting/receiving signals through the base station [2].

In principle, uplink cellular communication for unsynchronized devices follows two sequential procedures: *i*) the initial network association phase, where the devices use the Random Access CHannel (RACH) procedure to request transmission resources or re-establish a connection to the base station, and *ii*) the actual data transmission phase, where communication may take place either in *cellular mode* through the base station or via the *D2D mode* in case of devices in close proximity of each other (D2D-capable). Bypassing the cellular infrastructure, D2D mode can yield a dramatic latency reduction which is of utmost importance especially for time-critical protection and control applications in the distribution grid, e.g., substation automation and outage management. The inband D2D links can either share data resources with cellular links (underlay operation) or utilize mutually orthogonal parts of the cellular spectrum (overlay operation). In D2D-underlay, the main challenge refers to the efficient management of intra-cell interference experienced by both cellular and D2D links, whereas in D2D-overlay the main objective resides in the efficient and fair partition of the cellular resources to achieve increased spectrum efficiency. The interference caused by D2D to cellular links and vice versa in underlay operation, requires high-complexity resource allocation methods, which result in increased computational overhead for the D2D-capable devices [3]. In this paper, we consider the D2D-overlay mode for the support of reliable smart grid communication with controlled interference environment and we leave the study of D2D-underlay mode to future work.

Mode selection, i.e., the process of determining whether a D2D-capable pair should exchange data in cellular or D2D mode, has recently become a topic of considerable interest. However, the majority of the available literature is focused on distance-based mode selection schemes and the channel-access loading state is not considered for switching between direct and conventional cellular communication [3]. While in D2D-underlay several works deal with the mode selection problem in an effort to achieve improved spectrum/power efficiency [4], [5], the focus in D2D-overlay has been mainly in the self-interference mitigation among D2D pairs [6]–[8]. Mode selection and spectrum partition techniques proposed in the literature so far, do not consider the sporadic nature of mission-critical smart grid information; hence, they are rendered insufficient for event-driven distribution grid operations where congestion may arise in a short period of time. Instead, here we propose a dynamic mode selection and resource allocation (MSRA) mechanism that adapts to the system traffic conditions, monitored during the initial network association phase. Motivated by the stringent requirements of mission-critical smart grid messages, we summarize the main contributions of the paper as follows:

1) Based on a realistic traffic model that accurately captures the event-driven nature of substation-automation traffic, we present a unified analytical framework that accounts for both uplink communication phases, i.e., random ac-

cess and data resource allocation, and we formulate the joint MSRA problem as a sum-rate maximization problem with a performance constraint for protecting the cellular users.

2) We introduce a load- and interference-aware MSRA mechanism for substation automation traffic in cellular-enabled distribution grids. Our proposed scheme captures use cases where event-driven D2D communication is required to achieve high transmission rates and relies on a dynamic orthogonal partition of the uplink spectrum; a part dedicated to D2D-overlay communication while the rest of the resources are allocated to regular cellular communication. Numerical results demonstrate that substation automation traffic can substantially benefit from a carefully designed MSRA mechanism.

The rest of the paper is organized as follows. In Section II the considered substation automation scenario is presented and a realistic model of the event-driven substation automation traffic is proposed. In Section III, the analytical framework of the MSRA problem is presented and a novel MSRA mechanism is introduced. Section IV provides numerical results through extensive simulations for evaluation of the proposed scheme under different performance criteria. Our concluding remarks are given in Section V.

II. Substation Automation Scenario and Traffic Model

In this paper, we focus on substation automation, a key module for the overall power system operation in the distribution grid. Substation automation systems often involve message-exchange among neighboring Intelligent Electronic Devices (IEDs) for real-time situational awareness and supervision of the power equipment, e.g., rapid diagnosis of system faults and initiation of control/isolation actions [9].

The network architecture of a cellular-enabled substation automation system is illustrated in Fig. 1. On top of a wide range of human-oriented services generated by synchronized mobile terminals (UEs) always connected in cellular mode, the cellular infrastructure accommodates the substation automation traffic exchanged among D2D-capable[1] IEDs. The IEDs, equipped with cellular communication interfaces, reside within the substation local area network and can be seen as controllers that get their input from voltage and current transformers/sensors and provide their output (commands, status data), e.g., to circuit breakers.

As shown in Fig. 1, an arc-fault detection scheme is implemented in a substation local area network. Each IED is equipped with three arc sensors and transits from idle to connected state when a state change is captured by one of its sensors. In particular, when IED A detects an arc in the busbar compartment via sensor 1, it transmits a substation-event message to notify its neighboring devices within the substation, e.g., to IED B, and issues a trip command to the corresponding circuit breaker. In turn, the reception of a

[1]We assume that the D2D-capable pairs are already peer-discovered.

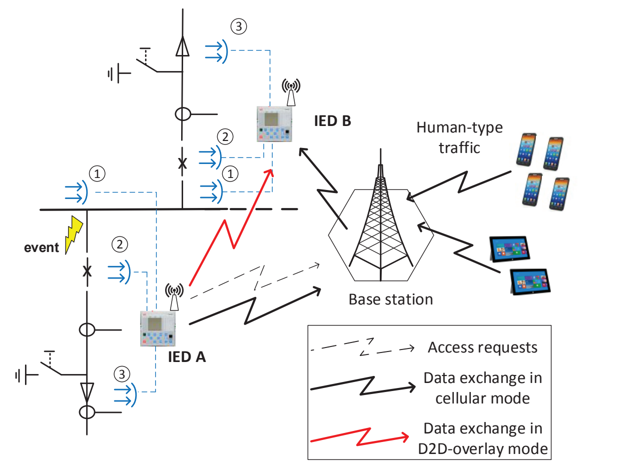

Fig. 1. Network model for a cellular-enabled substation automation system where an arc-fault detection scheme is implemented. The hybrid architecture in the radio access domain is characterized by the coexistence of cellular links that communicate via the base station and D2D-overlay links that communicate directly in a rather autonomous way.

substation-event message sequentially triggers the neighboring IEDs to transmit their own substation-event messages to allow for a fast distribution of the fault information within the substation. Due to the near-simultaneous channel access requests from neighboring IEDs, an abrupt increase in the network load of the contention-based RACH procedure can be detected [10]. While the network access requests are still sent to the base station, the transmission of the substation-event message may now switch from cellular to D2D-overlay mode, to ensure the timeliness of the message delivery and achieve reduced system response times.

To model the IED traffic behavior, in this work, we assume that the arrivals in each IED are governed by two application phases; a *regular* phase when no event occurs and an *event* phase where the inter-arrival time is shortened in case of an event (burst). Let $\mathcal{S}_i$ be the set of sensors that an IED i is equipped with and let $\mathcal{U}_i$ be the set of its neighboring IEDs. Let also $\alpha_{i,s}[t]$ be a binary parameter that indicates whether sensor s of an IED i captures a local event at time t. Then, the spatio-temporal correlation in the arrival stream of an IED i can be captured with the aid of the parameter $\beta_i[t]$,

$$\beta_i[t] = \begin{cases} 1, & \text{if } \sum_{s\in\mathcal{S}_i} \alpha_{i,s}[t] > 0\,, \\ 1, & \text{if } \sum_{j\in\mathcal{U}_i} \sum_{s\in\mathcal{S}_j} \alpha_{j,s}[t] > 0\,, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where an arrival in an IED i may be triggered due to a detection of a local event either by one of its own sensors or by one of the sensors of its neighboring IEDs.

In order to capture the interdependent inter-arrival times of an IED, we leverage the two-state Markovian Arrival Process (MAP) framework initially introduced in [11]. The MAP constitutes a stochastic counting process whose arrival rate is modulated by a continuous-time Markov chain. The states of the Markov chain correspond to the IED application phases and a transition between states generates an arrival with a given probability. The MAP is defined by an infinitesimal generator matrix $\mathbf{D}_0$ in case of no arrivals, and a rate matrix $\mathbf{D}_1$ in the case of an arrival leading to possible state change of the Markov chain. To account for the spatial and temporal correlation in the arrival stream of an IED i, the convex combination of the matrices in the regular and event phase is considered with the aid of $\beta_i[t]$, as in [12]. Therefore, MAP is characterized by the rate matrices $\{\mathbf{D}'_0, \mathbf{D}'_1\}$ where

$$\mathbf{D}'_0 = (1-\beta_{\mathrm{i}}[t])\,\mathbf{D}_{0,\,\mathrm{regular}} + \beta_{\mathrm{i}}[t]\,\mathbf{D}_{0,\,\mathrm{event}}, \tag{2a}$$

$$\mathbf{D}'_1 = (1-\beta_{\mathrm{i}}[t])\,\mathbf{D}_{1,\,\mathrm{regular}} + \beta_{\mathrm{i}}[t]\,\mathbf{D}_{1,\,\mathrm{event}}. \tag{2b}$$

For the calculation of the traffic generation probability, p_{on}, let

$$P_{i,j}(k,t) = \Pr(A_t = k, J_t = j | A_0 = 0, J_0 = i), \tag{3}$$

be the entry of a matrix $\mathbf{P}(k,t)$, where A_t denotes the number of arrivals during the time interval $[0,t)$ and J_t the phase of the Markov process at time t, respectively. The matrices $\mathbf{P}(k,t)$ satisfy the forward Chapman-Kolmogorov equations [11]

$$\frac{d}{dt}\mathbf{P}(0,t) = \mathbf{P}(0,t)\,\mathbf{D}'_0, \tag{4a}$$

$$\frac{d}{dt}\mathbf{P}(k,t) = \mathbf{P}(k,t)\,\mathbf{D}'_0 + \mathbf{P}(k-1,t)\,\mathbf{D}'_1,\; k=1,\ldots, \tag{4b}$$

and using the initial condition $\mathbf{P}(0,0)$=$\mathbf{I}$, the matrices $\mathbf{P}(k,t)$ can be determined. Then, p_{on} is calculated as

$$p_{\mathrm{on}} = 1 - \sum_i \sum_j P_{i,j}(0,t), \tag{5}$$

where t corresponds to the observed time duration.

Due to the event-driven nature of substation-automation messages, the seamless transmission mode selection for IEDs constitutes a significant challenge. In addition, an efficient spectrum partition for cellular and D2D-overlay links is required, while satisfying the performance requirements of the coexisting cellular UEs. In the following, we propose an efficient mechanism for the MSRA problem of D2D-capable IEDs transmitting substation automation traffic in cellular-enabled power distribution grids.

III. The Mode Selection and Resource Allocation Problem

A. System Model and Analytical Framework

We consider the uplink of a single-cell cellular network with total system bandwidth V that accommodates the traffic generated in a cellular-enabled substation automation system, as the one described in Section II. According to 3GPP, the available bandwidth can be seen as a time-frequency grid of physical resource blocks (RBs) for the initial network association and data transmission phases. The network considered consists of cellular UEs and D2D-capable IEDs which can transmit and receive data across a set of links, i.e., pairs of distinct nodes. Let $\mathcal{C}$ be the set of communication links between cellular UEs and $\mathcal{D}$ the set of communication links between D2D-capable IEDs with cardinalities C and D, respectively. We assume that the cellular UEs are always synchronized and connected in cellular mode; thus, they are not contending in the RACH for network association. On the other hand, the IEDs are considered unsynchronized and generate traffic with probability p_{on}; thus, they contend in the RACH by randomly selecting one of the available preambles for transmission over the random-access resources [10].

Given that an IED of a link $i \in \mathcal{D}$ attempts random channel access, the preamble collision probability, p_c, from the perspective of the IED, is defined as the probability that an IED of at least one of the remaining j links, $j \in \mathcal{D}\setminus\{i\}$, attempts random channel access and selects the same preamble. Let K be the number of available orthogonal preambles for contention-based random access, then p_c is given by

$$p_c = \sum_{j=1}^{D-1} \binom{D-1}{j} \tau^j (1-\tau)^{D-1-j} \left(1 - \left(1 - \frac{1}{K}\right)^j\right), \tag{6}$$

where τ denotes the probability that an IED attemps a channel access. Based on the generalized Markov chain model of the LTE random-access procedure developed in [13], τ can be expressed as a function of the probabilities p_c, p_{on}, and the various random-access parameters, as

$$\tau = \frac{1}{\frac{p_c - 1}{p_c^L - 1}\left(\frac{W_{\mathrm{off}}}{p_{\mathrm{on}}} + p_c^L T_f\right) + p_c T_1 + (1-p_c)(T_2 + T_s) + \frac{W-1}{2}}. \tag{7}$$

In Eq. (7), the parameter L denotes the maximum allowed preamble transmissions, W is the random-access backoff window size and W_{off} denotes the average holding time of the IED in idle state. The T_s, T_f represent the expected time durations of the success and fail states that model the successful and failed random-access attempt, respectively. The expected time durations T_1 and T_2 correspond to the elapsed times from the first access attempt until the end of the contention-resolution timer in case of access failure, and until the reception of the contention-resolution message in case of successful access, respectively [13].

Let $\mathcal{N}$ be the set of RBs available for data transmission and N the corresponding cardinality. Henceforth, we focus on the performance analysis of a typical transmitter-receiver link i belonging to any of the UE or IED sets. We denote by $x_{i,m}^n$ the decision variable that indicates whether RB $n \in \mathcal{N}$ is assigned to link i in mode m, where index $m = \{c,d\}$ denotes the cellular and D2D-overlay mode, respectively. Due to the orthogonal resource partition, the available RBs for links in cellular mode and D2D-overlay mode are $N_c = (1-\theta)N$ and $N_d = \theta N$ respectively, where θ represents the fraction of RBs allocated to D2D-overlay mode. Let $\mathcal{N}_c$ and $\mathcal{N}_d$ be the corresponding resource sets for the two modes, respectively. Then, the fraction θ can be expressed as

$$\theta = \frac{\sum_{i\in\mathcal{D}} \sum_{n\in\mathcal{N}_d} x_{i,d}^n}{N}. \tag{8}$$

Let also $\boldsymbol{x}_i = \{x_{i,m}^n : n \in \mathcal{N}_m, m = \{c,d\}\}$ denote the corresponding allocation vector. Then, according to the

Shannon-Hartley theorem, the maximum achievable rate for link i in mode m is

$$R_{i,m}(\boldsymbol{x}_i) = \sum_{n\in\mathcal{N}_m} x_{i,m}^n \frac{V}{N}\log_2\left(1+\mathrm{SINR}_{i,m}^n\right), \tag{9}$$

where $\mathrm{SINR}_{i,m}^n$ represents the signal to interference and noise ratio perceived at the receiver of link i in mode m when transmitting in RB n and is given by

$$\mathrm{SINR}_{i,m}^n = \frac{g_{ii,m}^n P_{i,m}}{\sigma^2 + I_{i,m}^n}, \tag{10}$$

where $P_{i,m}$ is the transmission power for link i in mode m, $g_{ii,m}^n = \left|h_{ii,m}^n\right|^2$ the power gain (the channel gain h captures the effects of path loss and Rayleigh small-scale fading) from the transmitter of link i in mode m and RB n, and σ^2 the noise power at the receiver of link i. The interference, $I_{i,m}^n$, experienced at the receiver of link i, is

$$I_{i,m}^n = \sum_{j\neq i} g_{ji,m}^n P_{j,m}, \tag{11}$$

where $g_{ji,m}^n = \left|h_{ji,m}^n\right|^2$ denotes the power gain between the transmitter of link j and the receiver of link i in mode m for RB n. For links transmitting in cellular mode, the N_c RBs are allocated orthogonally based on the legacy uplink single-carrier frequency-division multiple access (SC-FDMA) scheme of 3GPP-based standards; thus, $I_{i,c}^n = 0$, $\forall i$, $n \in \mathcal{N}_c$.

As discussed in Section II, in the case of a substation event, neighboring IEDs attempt near-simultaneous channel access resulting in a traffic surge of access requests. The limited number of random access opportunities (up to 64 preambles in LTE) compared to the increased resource demand results in an increased probability of collision in the transmission of the preambles. Based on a continuous monitoring of the preamble collision probability, p_c, by the base station, the D2D-capable IEDs may be signaled to switch from cellular to D2D-overlay mode to transmit substation-event information. However, mode selection should also consider the interference level among the D2D-overlay links due to the resource sharing of their N_d RBs. Therefore, to account for both, the mode selection probabilities for each link $i \in \mathcal{D}$, are given by

$$\Pr(m=d) = \Pr\left(p_c > p_{c,\mathrm{th}}\right) \Pr\left(\sum_{\substack{j\in\mathcal{D}\\ j\neq i}} x_{j,d}^n I_{i,d}^n \le I_{\mathrm{th}}^n\right), \tag{12}$$

and $\Pr(m=c) = 1 - \Pr(m=d)$, where $p_{c,\mathrm{th}}$ denotes the threshold value for the preamble collision probability and I_{th}^n is the interference tolerance level for RB n. Note that both $p_{c,\mathrm{th}}$ and I_{th}^n can be optimized to maximize the overall system achievable rate. In this work, we consider $p_{c,\mathrm{th}}$ and I_{th}^n as predefined parameters that depend on the reliability of the supported substation-automation service and we leave their joint optimization within the MSRA problem for future work.

By definition, cellular UEs always transmit in cellular mode, whereas D2D-capable IEDs dynamically switch between the cellular and the D2D-overlay mode according to the mode selection policy. Therefore, for the average achievable rate of a link i, it holds

$$R_i(\boldsymbol{x}_i) = \begin{cases} R_{i,c}(\boldsymbol{x}_i), & \text{if } i \in \mathcal{C}, \\ \Pr(m=c) R_{i,c}(\boldsymbol{x}_i) & \\ + \Pr(m=d) R_{i,d}(\boldsymbol{x}_i), & \text{if } i \in \mathcal{D}. \end{cases} \tag{13}$$

B. Problem Formulation

Our goal is to jointly consider the mode selection of D2D-capable IEDs and the orthogonal resource assignment of cellular and IED links, while maximizing the achievable sum-rate for all the links present in the system. Specifically, if $n_{i,c}^a$ and $n_{i,c}^b$ denote the first and last RB allocated to link i in cellular mode, the MSRA problem is formulated as

$$\max_{\boldsymbol{x}_i} \quad \sum_{i\in\mathcal{C}\cup\mathcal{D}} \sum_{n\in\mathcal{N}} R_i(\boldsymbol{x}_i) \tag{14a}$$

$$\text{s.t.} \quad \sum_i x_{i,m}^n \le 1, \ \forall n \in \mathcal{N}_c, \ m = c, \tag{14b}$$

$$\sum_m x_{i,m}^n \le 1, \ \forall i \in \mathcal{D}, \ \forall n \in \mathcal{N}, \tag{14c}$$

$$\sum_i x_{i,m}^n = 0, \ \forall i \in \mathcal{C}, \ \forall n \in \mathcal{N}_c, \ m = d, \tag{14d}$$

$$\sum_{n=n_{i,m}^a}^{n_{i,m}^b} x_{i,m}^n = n_{i,m}^b - n_{i,m}^a + 1, \ m = c, \tag{14e}$$

$$\sum_{i\in\mathcal{D}} \sum_{n\in\mathcal{N}_d} x_{i,m}^n \le N, \ m = d, \tag{14f}$$

$$R_i(\boldsymbol{x}_i) \ge R_{i,\min}, \quad \forall i \in \mathcal{C}, \tag{14g}$$

$$x_{i,m}^n \in \{0,1\}. \tag{14h}$$

Constraint (14b) ensures that each RB $n \in \mathcal{N}_c$ is allocated to at most one link in cellular mode. Constraint (14c) implies that each link among IEDs can be either in cellular or D2D-overlay mode, whereas cellular UEs operate always in cellular mode according to constraint (14d). Constraint (14e) captures the uplink resource contiguity constraint due to the SC-FDMA scheme for the links in cellular mode [14]. Constraint (14f) implies that the fraction θ of resources allocated to D2D-overlay must be at most equal to one, according to (8). Performance-protection constraint (14g) captures the requirement that the minimum rate requirement, $R_{i,\min}$, has to be met for each link $i \in \mathcal{C}$ associated with a guaranteed bit rate (GBR) of human-type services.

Due to the coupled variables p_c and τ in Eqs. (6) and (7) respectively, the expression of $R_i(\boldsymbol{x}_i)$ in Eq. (13) is not in closed-form, thus solving problem (14) is mathematically intractable. In addition, the decision variables $x_{i,m}^n$ are binary constrained and their presence in the performance constraint (14g) results in a nonlinear problem [15]. Finally, the contiguous allocation constraint (14e) for links in cellular mode renders the problem NP-hard [14].

While transmission scheduling for the links in cellular mode can be adequately addressed using our priority-aware resource

Algorithm 1 MSRA mechanism for D2D-capable IEDs

Assume $L, W, p_{\text{on}}, W_{\text{off}}$ known
$\mathcal{S}_c$: set of UE or IED links in cellular mode
$\mathcal{S}_d$: set of IED links in D2D-overlay mode
i: index for IED links
k: index for UE links
$\triangleright$ Initialization
$\mathcal{S}_c = \{\mathcal{C}, \mathcal{D}\}$; $\mathcal{S}_d = \varnothing$; n=1
for $\forall i \in \mathcal{D}$ **do**
  Initialize $p_c \leftarrow 0.9999$ $\triangleright$ Calculation of p_c
  Set allowed tolerance $\epsilon \leftarrow 1e-3$
  while $p_c > 0$ **do**
    Calculate τ from Eq. (7)
    Calculate p'_c from Eq. (6)
    if $|p'_c - p_c| < \epsilon$ **then** $\triangleright$ Convergence test
      break
    else
      $p_c \leftarrow p_c - 0.0001$ $\triangleright$ Update
    end if
  end while
  if $p_c > p_{c,\text{th}}$ **then** $\triangleright$ Traffic-aware
    $\mathcal{S}_c \leftarrow \mathcal{S}_c \setminus \{i\}$
    $\mathcal{S}_d \leftarrow \mathcal{S}_d \cup \{i\}$
    $x^1_{i,d} \leftarrow 1$
    while $\sum_{\substack{j \in \mathcal{D} \\ j \neq i}} x^n_{j,d} I^n_{i,d} > I^n_{\text{th}}, \forall n$ **do** $\triangleright$ Interference-aware
      $n \leftarrow n + 1$
      $x^n_{i,d} \leftarrow 1$
      $x^n_{k,c} \leftarrow 0, \forall k \in \mathcal{C}$
      Calculate $I^n_{i,d}$ from Eq. (11)
      Update R_i, $i \in \mathcal{D}$ and R_k, $k \in \mathcal{C}$ from Eq. (13)
      if $R_k < R_{k,\text{min}}$, $k \in \mathcal{C}$ **then** $\triangleright$ UEs protection
        $\mathcal{S}_c \leftarrow \mathcal{S}_c \cup \{i\}$
        $\mathcal{S}_d \leftarrow \mathcal{S}_d \setminus \{i\}$
        break
      end if
    end while
  end if
end for
Calculate θ from Eq. (8)

allocation algorithm proposed in [14], the joint consideration of D2D-capable IEDs requires an efficient mechanism for a dynamic selection of the transmission mode and allocation of data resources with performance guarantees. We provide the details in the following.

C. Solution Approach

Due to mathematical intractability of solving efficiently problem (14), we propose a dynamic heuristic MSRA scheme for the D2D-capable IEDs that employs a traffic load- and interference-aware discipline. We assume that the base station has full knowledge of the channel gains between all transmitters and receivers within the cell; a realistic assumption based on the static or slowly-moving nodes in the network deployment of Fig.1. Besides the known channel state information, the proposed scheme relies on a continuous monitoring of the network loading state by the base station during the contention-based RACH procedure of the unsynchronized IEDs. The steps of the MSRA mechanism are presented in Algorithm 1.

Initially, we assume that all D2D-capable IEDs are in cellular mode and are scheduled for transmission with the cellular UEs following the contiguous resource allocation algorithm proposed in [14]. For each link $i \in \mathcal{D}$, the preamble collision probability is first calculated using an iterative numerical method, since the expressions of p_c in Eq. (6) and τ in Eq. (7) form a system of non-linear equations. Then, upon detection of higher levels of p_c than the predefined threshold, $p_{c,\text{th}}$, the link i is signaled to switch from cellular to D2D-overlay mode. Resource allocation for link i is then performed by adaptively assigning adjacent RBs until the interference at the receiver of link i for each RB gets lower than the allowed tolerance level, I^n_{th}. While the base station keeps increasing the number of allocated RBs for each IED link, if the minimum rate requirement for the cellular UEs is violated, the IED link switches back from D2D-overlay to cellular mode and is scheduled for transmission with the cellular UEs, following the contiguous allocation algorithm proposed in [14].

Iteratively, mode selection and resource allocation proceeds by processing all the D2D-capable IEDs and once allocation is performed, the system updates all the relevant parameters. It is noted that, in every iteration, the proposed scheme dynamically assigns adjacent uplink data resources aiming to allocate the minimum possible for each D2D-overlay IED link and thus minimize the impact on the background traffic generated by cellular UEs. In the following section, we evaluate the performance of our proposed MSRA scheme under various performance metrics and we quantify the throughput gains for IEDs due to the seamless transition between cellular and D2D-overlay mode.

IV. Numerical Results and Discussion

Our aim in this section is twofold: *i*) to assess and evaluate the performance of our proposed MSRA scheme through extensive simulations and *ii*) to derive useful insights for the transmission mode of IEDs conveying substation automation traffic in cellular networks.

A. Simulation Setup

The numerical results are obtained by simulating the uplink of a single-cell network where synchronized cellular UEs are randomly (uniformly) dropped within the cell coverage area and generate background traffic. The random dropping model is also used for the location of the IED transmitters whereas the location of each IED receiver is distributed according to a uniform distribution in a circular area around its associated IED transmitter. We perform independent Monte Carlo experiments, each with a random network topology, to build statistics over the performance measures of interest when employing our MSRA mechanism. The MAP framework is used to capture the spatio-temporal correlation of the event-driven IED traffic and the well-studied expectation-maximization statistical framework [11] has been used for parameter $\left\{\mathbf{D}'_0, \mathbf{D}'_1\right\}$ fitting, based on the arrival traces of substation automation traffic captured by a real-time digital simulator that implements the IEC 61850 GOOSE protocol [9].

TABLE I
SIMULATION PARAMETERS

Parameter	Value/Description
System bandwidth	10 MHz
RB bandwidth	180 kHz
Cell radius	1km
IEDs in a substation LAN, cellular UEs	{20, 20}
Transmit power in {cellular, D2D-overlay} mode	{24, 16}dBm
Thermal noise power	-114dBm
Channel model	Suburban
Path-loss coefficient	3.5
User distribution	Uniform
Distance between D2D-capable IEDs	50-100m
Preambles for contention-based access K	54
RACH configuration index	6
Backoff window size W	20ms
Preamble duration	1ms
Max. allowed preamble transmission attempts L	10
RAR window size	5ms
Contention resolution timer	24ms
Master information block periodicity	40ms
Payload for IED, UE	{250, 500} bytes
Min. rate requirement for UEs	$R_{i,\min}$=12Kbps

Table I summarizes the basic parameters used in our simulations. The unsynchronized IEDs are assumed to contend for RACH access after a substation event and are dynamically signaled to transmit either in cellular or D2D-overlay mode according to the MSRA mechanism described in Section III-C. Starting from a medium-load scenario, new channel access requests from IEDs appear progressively in the system until it is driven to overload. The performance of the MSRA mechanism is then evaluated in terms of the average achievable rate when the system operates close to its capacity limits. In addition, we conduct a comparative evaluation of the MSRA scheme with the default case when IED transmission occurs solely in the conventional cellular mode and the priority-aware scheduler of [14] is used as a benchmark for the allocation of resources between the UE and IED links.

B. Performance Evaluation

The average achievable rates for cellular UEs and D2D-capable IEDs for different $p_{c,\text{th}}$ with increasing IED traffic load are illustrated in Fig. 2. Compared to the default case when IED transmission occurs solely in cellular mode, our proposed MSRA mechanism achieves significant rate gains for both IEDs and UEs. By dynamically switching to D2D-overlay mode, the IEDs can exploit the shorter communication path and transmit data in higher rates. Interestingly, the average rate gains can be leveraged even in heavy traffic load conditions. In particular, we observe that with the MSRA scheme, the average rate of cellular UEs slightly increases with increasing IED rate, since IEDs switch to D2D-overlay mode more often, thus reducing the waiting time for the cellular UEs in the scheduling queue for cellular mode. In addition, the average rate of IEDs initially increases since the threshold $p_{c,\text{th}}$ gets violated and an increasing number of D2D-capable IEDs choose the D2D-overlay mode; however, the rate then starts decreasing due to the increased interference among the D2D links. This can intuitively be justified by the fact that

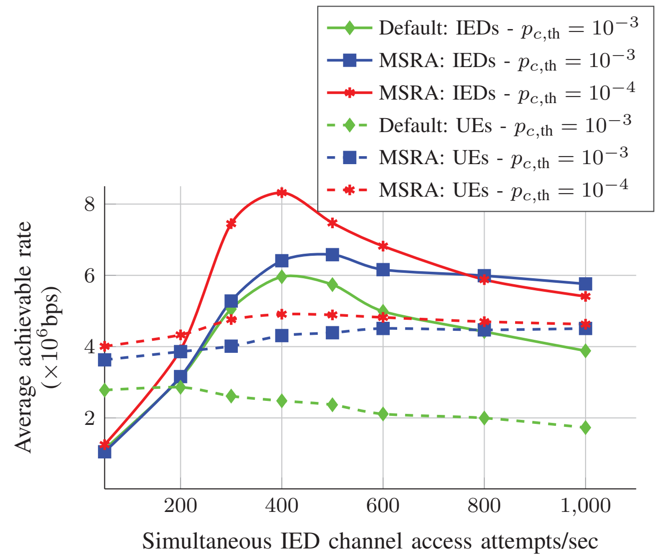

Fig. 2. Average achievable rates for cellular UEs and D2D-capable IEDs in the default transmission case and with the proposed MSRA scheme for different preamble collision probability thresholds with given I_{th}^{n} = 0dB and increasing IED traffic load.

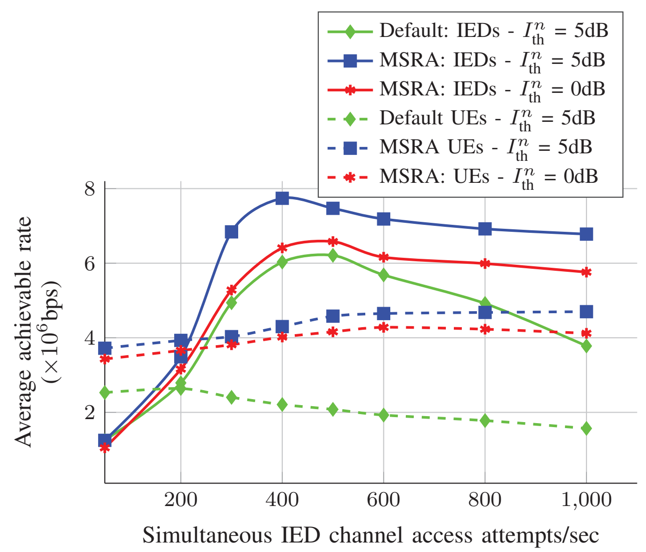

Fig. 3. Average achievable rates for cellular UEs and D2D-capable IEDs in the default transmission case and with the proposed MSRA scheme for different interference tolerance levels with given $p_{c,\text{th}}$ = 10^{-3} and increasing IED traffic load.

the average rate of D2D-capable IEDs is determined by the rates for both cellular and D2D-overlay modes, as in (13). We further observe that a tighter $p_{c,\text{th}}$ initially results in higher average rates for both network entities, since more and more IED links switch to D2D-overlay; however, the higher D2D interference causes a quicker performance degradation for IEDs.

The effect of I_{th}^{n} in the average achievable rates of cellular UEs and D2D-capable IEDs with increasing IED traffic load is illustrated in Fig. 3. Once again, our proposed MSRA mechanism outperforms the default scheme in terms of the rate performance of both IEDs and UEs, especially in high traffic load. In particular, we observe that for the MSRA scheme the

TABLE II
FRACTION OF IED LINKS IN D2D-OVERLAY MODE WITH INCREASING IED TRAFFIC LOAD

Mode selection performance criteria	Sim. IED access attempts/sec				
	200	400	600	800	1000
$p_{c,\text{th}} = 10^{-4}$, I^n_{th} = 0dB	0.41	1	0.92	0.73	0.51
$p_{c,\text{th}} = 10^{-3}$, I^n_{th} = 0dB	0.3	0.85	0.83	0.78	0.6
$p_{c,\text{th}} = 10^{-3}$, I^n_{th} = 5dB	0.28	0.91	0.86	0.82	0.69

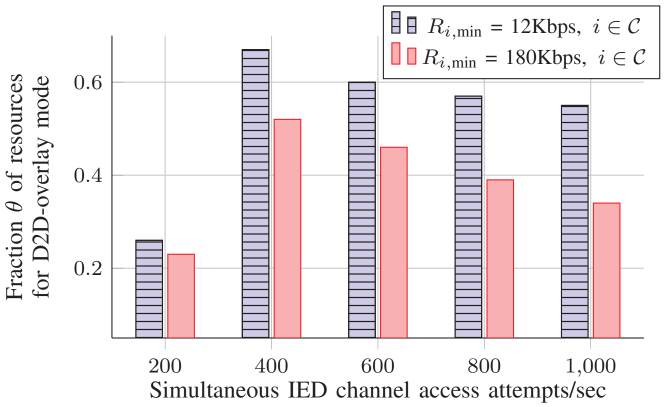

Fig. 4. Fraction of RBs allocated to IEDs in D2D-overlay mode for different minimum rate requirements of cellular UEs, for given $\{p_{c,\text{th}}, I^n_{\text{th}}\}$ = $\{10^{-3}, 0dB\}$ and increasing IED traffic load for the MSRA scheme.

average rates are slightly affected by the different I^n_{th} in case of medium load, since the level of interference remains low. However, as IED load increases, the accumulated interference causes performance degradation for the D2D-capable IEDs which becomes even more severe when I^n_{th} is set to a more restrictive value. The impact of the performance parameters, $p_{c,\text{th}}$ and I^n_{th}, in the mode selection procedure is summarized in Table II, where the fraction of IED links switching to D2D-overlay mode is quantified as a function of the IED load. It can be observed that the insights acquired from the observation of the rate figures are reflected in the amount of IED links transmitting in D2D-overlay mode.

Regarding the orthogonal partition of uplink cellular resources for cellular and D2D-overlay modes, Fig. 4 illustrates the fraction, θ in (8), of RBs allocated to D2D-overlay mode as a function of the increasing IED load for different minimum rate requirements of the cellular UEs. In particular, θ initially increases since more and more IEDs switch to D2D-overlay mode. However, its value tends to decrease when the performance-protection requirement of cellular UEs is violated. In addition, the decrease is more rapid in the case of demanding cellular services with higher minimum rate requirements, e.g., video services with GBR of 180Kbps instead of voice services with GBR equal to 12Kbps.

V. CONCLUSION

A joint mode selection and resource allocation (MSRA) mechanism has been introduced for the support of event-driven substation automation traffic in cellular-enabled power distribution grids. In our proposed load- and interference-aware MSRA scheme, unsynchronized IEDs may seamlessly switch to D2D-overlay mode for data transmission, thus achieving higher transmission rates with respect to the conventional cellular mode, even in high traffic load conditions. In addition, the orthogonal resource allocation to cellular and D2D-overlay links is performed in a way that prevents the under-utilization of the scarce cellular spectrum. Numerical evaluation of the proposed scheme under different performance criteria offers useful insights for the design of such cellular systems. Future work will consider the case of D2D-underlay mode as an additional option for IEDs and the study of latency-reliability trade-off with respect to the D2D-overlay mode.

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