Efficient Cell Planning for Reliable Support of Event-Driven Machine-Type Traffic in LTE

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Abstract—**The reliable support of event-driven massive machine-type communication (MTC) requires radical enhancements in the standard LTE random access channel (RACH) procedure to avoid performance degradation due to a high probability of collision in the preamble transmission. In this paper, we investigate the relation between the cell size and the number of preambles generated from a single or multiple root sequences and we study their impact on the achieved reliability. Based on an analytical expression of the RACH reliability per cell, we introduce an interference- and load-aware cell-planning mechanism that efficiently allocates the root sequences among multiple cells and regulates the traffic load to guarantee reliable support of MTC. In addition, we propose a realistic traffic model that accurately captures the event-driven nature of MTC traffic. Finally, a performance evaluation of a power distribution automation scenario with MTC-overload reveals the superior performance of our proposed mechanism in terms of RACH reliability against benchmarking network-deployment schemes.**

I. Introduction

The efficient and reliable support of massive machine-type communication (MTC) constitutes a significant challenge for the current cellular systems. In LTE networks, the devices use the Random Access CHannel (RACH) to request transmission resources or re-establish a connection to the eNodeB [1]. In particular, the devices contend for network access by randomly selecting one of the available preambles, generated by one or several Zadoff-Chu (ZC) root sequences and their cyclic shifts, to transmit over the random-access slots. As the MTC traffic load and the number of channel-access attempts increase, the RACH becomes highly susceptible to congestion, due to the scarce random-access resources compared to the increased demand. In addition, unlike traditional human-type communication, MTC involves the transmission of sporadic and event-driven messages that are often highly correlated in space and time, e.g., cascading power-grid failures, synchronization after system-wide power outage [2].

Ongoing 3GPP standardization efforts and research activities focus on the redesign of the channel-access mechanisms of cellular systems to handle applications that involve a high density of MTC devices per cell. In this context, several overload-control methods have been proposed in the literature to manage congestion and improve the random-access procedure of LTE networks. Most of the available solutions are based on initial proposals compiled by the 3GPP [3], including separation of random-access resources [4], [5], access class barring (ACB) schemes [4], [6]–[8], and parameter optimization in the medium access control layer. In [5], a load-adaptive preamble-allocation scheme is proposed and the random-access resources are dynamically assigned to different priority classes based on a tuning parameter. A similar load-aware approach is presented in [9], where the standard access mechanism is enhanced by estimating the anticipated network load. Other MTC congestion-avoidance approaches focus on the deployment of denser access networks, i.e., using numerous small cells or access points, to create ultra-dense deployments and reduce contention in each network cell. In [10], the authors investigate the random-access performance of two-tier LTE-based small-cell networks and employ a partial preamble-sharing scheme to avoid cross-tier interference. A cluster-based aggregation scheme for MTC connectivity is presented in [11] along with an analysis of the aggregation process. However, in all previous works, the fact that the number of orthogonal preambles available for contention decreases as the cell radius increases has not been considered; this relation imposes an additional challenge for the reliable support of machine-type traffic due to the non-orthogonality of preambles originated from different ZC roots.

To the best of our knowledge, [12] and [13] are the only works where the relation between the cell radius and the availability of orthogonal preambles is considered. However, the effect of the preamble non-orthogonality in the achieved reliability is not analytically studied. In [12], a contention-resolution access mechanism based on a tree-splitting algorithm and a distributed queue is proposed; however, a single macro-cell deployment is considered and the 3GPP-based model for synchronous traffic generation is adopted. A configuration of the ZC root sequences among small cells to enhance the random-access performance with massive MTC is proposed in [13]. However, a static cell-size configuration is considered and the traffic-load conditions are not taken into account. In addition, traffic modeling relies on a simple Poisson arrival process; hence, the spatiotemporal correlation of event-driven MTC is not accurately captured.

Contribution: The contribution of this paper is threefold. First, we investigate the relation between the cell size and the availability of orthogonal preambles in an LTE cell and we derive the analytical expression of the achieved reliability with the aid of our analytical model of the RACH procedure developed in [14]. In addition, we introduce an efficient cell-planning and ZC root-sequence allocation mechanism that *i)* properly allocates the root sequences among multiple cells to minimize the inter-cell interference, and *ii)* regulates the traffic load via a barring parameter to ensure reliable channel access for massive MTC. Finally, we propose a realistic traffic model that accurately captures the event-driven nature of MTC traffic. A performance evaluation of a power distribution automation scenario under MTC-overload reveals the superior performance of our proposed mechanism in terms of RACH reliability with respect to benchmarking network-deployment schemes.

Organization: The rest of the paper is organized as follows. Section II provides an overview of the system model along with a discussion on the LTE cell size and the availability of orthogonal preambles. In Section III, our proposed cell-planning and ZC root-sequence allocation mechanism is presented based on an analytical expression of the achieved reliability for an MTC device in a cell. In addition, a realistic traffic model is introduced to accurately capture the spatiotemporal correlation of event-driven MTC traffic. In Section IV, a performance evaluation of our proposed mechanism is presented along with a comparative study against benchmarking network-deployment schemes. Section V concludes the paper.

II. Cell Size and Availability of Orthogonal Preambles

We consider a cellular LTE network that accommodates machine-type traffic generated by a high number of MTC devices. A regular deployment of C circular cells with radius r_n, $n = 1, \dots, C$, is assumed to provide coverage to the MTC devices. We further consider that the base stations are located in the center of the cells. A fixed number of K available preambles is prescribed for each LTE cell and MTC devices randomly choose a preamble to contend in the RACH. The preambles are generated from a single or multiple ZC root sequences and their cyclic shifts. The ZC root sequences satisfy a constant-amplitude zero-autocorrelation property, that guarantees the orthogonality of the preambles generated from the same root [15]. On the other hand, preambles generated from different ZC roots are non-orthogonal inducing interference in the preamble reception.

Each RACH preamble consists of a cyclic prefix and a preamble sequence. Let T_{seq} denote the duration of the preamble sequence and N_{ZC} be the length of the ZC root sequence in samples. The minimum length of the cyclic shift duration N_{CS} in terms of number of samples is given by [15]

$$N_{\text{CS}} = \left\lceil \frac{T_{\text{RTT}} + T_{\text{ds}}}{T_{\text{seq}}} N_{\text{ZC}} \right\rceil, \quad (1)$$

where $T_{\text{RTT}} = 2r_n/c$ and T_{ds} denote the maximum round-trip time and delay spread in a cell of radius r_n, respectively. The maximum number of orthogonal preambles constructed by a single ZC root sequence is then determined by

$$N_p = \left\lfloor \frac{N_{ZC}}{N_{CS}} \right\rfloor, \quad (2)$$

TABLE I
Random-Access Parameters in LTE Networks

Parameter	Value
Preambles K	64
Preamble sequence length, T_{seq}, in μs	800
Zadoff-Chu root sequences N	838
Zadoff-Chu sequence length, N_{ZC}, in samples	839
Maximum delay spread, T_{ds}, in μs	5.2 - 16.67

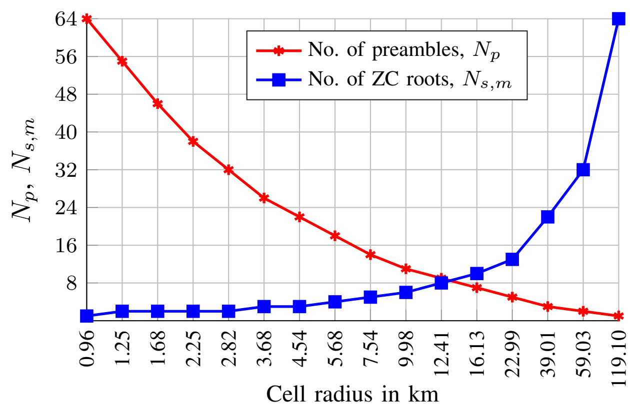

Fig. 1. Relation among the cell size, the availability of orthogonal preambles per ZC root sequence and the number of ZC root sequences required to generate 64 preambles in a single LTE cell.

whereas the number of ZC root sequences required to produce the K available preambles in a single cell m is

$$N_{s,m} = \left\lceil \frac{K}{N_p} \right\rceil. \quad (3)$$

Table I summarizes the default values of the random-access parameters in LTE-based networks [15]. Based on this configuration, Fig. 1 shows that the number of orthogonal preambles N_{p} that can be constructed from a single ZC root sequence decreases as the cell radius becomes larger. A greater number of $N_{s,m}$ is then required to generate the 64 available preambles per cell. In particular, it can be observed that when the cell radius exceeds the 59km, each preamble sequence is generated from a different root sequence. On the contrary, in a cell with radius shorter than 958m, all 64 preamble sequences can be constructed by cyclic shifts of a single root sequence.

The use of different root sequences for the generation of the preambles results in higher interference in the preamble reception due to the orthogonality loss. Therefore, RACH becomes more prone to congestion in cases where a single macrocell is used to cover a geographical area with a widespread deployment of MTC devices. Instead, as illustrated in Fig. 1, the deployment of multiple smaller cells would require fewer root sequences and thus would mitigate the intra-cell interference in the preamble reception at the eNodeB due to the higher number of orthogonal preambles.

Henceforth, we focus on the RACH performance analysis in a reference cell m, where $N_{s,m}$ out of the N in total ZC root sequences are allocated for preamble generation of the K preambles. Let $d_{\max}$ denote the maximum preamble-decoding distance which, given T_{seq}, can be estimated by the minimum

$$p_{\text{seq,m}} = \sum_{n=1}^{C-1} \binom{C-1}{n} \nu_m^n (1-\nu_m)^{C-1-n} \left(1 - \left(1 - \frac{N_{s,m}}{N}\right)^n\right). \quad (4)$$

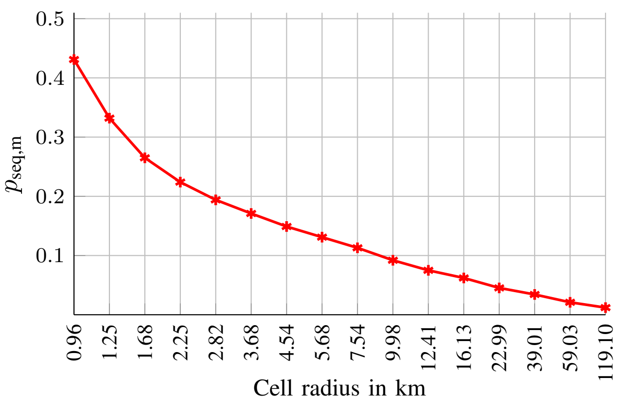

Fig. 2. Relation between the probability $p_{\text{seq,m}}$ and the cell size for a homogeneous cell deployment. As the cell size decreases, $p_{\text{seq,m}}$ increases reflecting a higher inter-cell interference.

required preamble-signal power received at the eNodeB to meet a target missed detection and false alarm probability of less than 1% [15]. We define by ν_m the probability that a neighboring cell n resides within the d_{max} of a preamble used in cell m. That is,

$$\nu_m = \Pr\left(\gamma_{\text{mn}} \leq d_{\text{max}} + r_n\right), \quad n = 1, \dots C, n \neq m, \quad (5)$$

where γ_{mn} denotes the distance between the base stations of the reference cell m and of the neighboring cell n. In the default case where the N available ZC root sequences are randomly allocated among the cells for their preamble generation, the probability $p_{\text{seq,m}}$ that at least one of the neighboring cells selects one of the $N_{s,m}$ root sequences of cell m for preamble generation can be expressed as in Eq. (4).

The probability $p_{\text{seq,m}}$ can be seen as an indicator of the level of inter-cell interference experienced in cell m related with the allocation of the N root sequences. Fig. 2 illustrates how $p_{\text{seq,m}}$ evolves with the cell radius in the case of a homogeneous deployment of multiple cells with equal radius r. As the cell radius decreases, or equivalently the number of required cells to cover a geographical area A increases[1], the N available sequences need to be distributed among a higher density of cells. This naturally leads to an increase in $p_{\text{seq,m}}$ since it becomes more possible for a neighboring cell to be allocated the same ZC root sequence as in the reference cell m.

The discussion presented above reveals an important design trade-off regarding the relation between the cell radius and the reliability level achieved in each cell. If a single macro-cell is used to cover an area A, then a higher number of ZC root sequences is required to generate the K preambles in the cell. The non-orthogonality between the preambles

[1]In the case of a homogeneous deployment of cells with equal radius r, the required number of cells to provide coverage is $C = \left\lceil \frac{A}{\pi r^2} \right\rceil$.

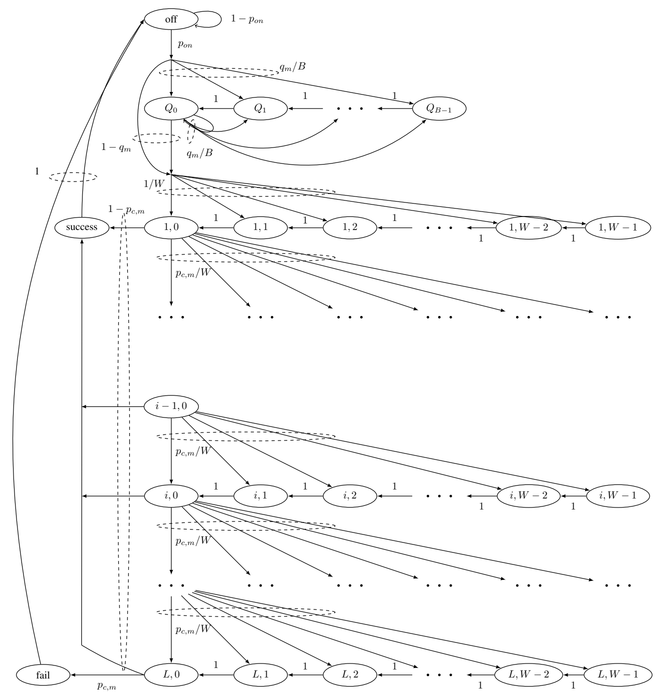

Fig. 3. Markov chain model for the contention-based LTE random-access mechanism enhanced with an ACB scheme [14].

generated from different roots results in higher probability of collision due to preamble decoding failure. On the other hand, if multiple smaller cells are deployed in A, then less ZC root sequences are required for the generation of the K preambles. However, this comes at the expense of additional installation of base stations and increased inter-cell interference regarding the allocation of roots among the cells. Therefore, an efficient cell-planning mechanism is required to properly allocate the ZC root sequences among the different cells and ensure the reliability level achieved in each particular cell.

III. Cell Planning for Reliable Support of MTC

A. Reliability Expression

In the random-access procedure, the reliability is defined as the probability that an MTC device successfully completes a channel-access attempt before exceeding the maximum allowed preamble transmissions. In [14], we derive an analytical expression for the achieved reliability per cell based on a generalized Markov chain model of the LTE random-access. An ACB scheme is further considered as an overload-control mechanism where each MTC device performs a Bernoulli trial to determine whether it is barred or not, based on a barring rate, b_{th}.

As shown in Fig. 3, the finite state space of the Markov chain includes:

$$p_{c,m} = \sum_{i=1}^{D-1} \binom{D-1}{i} \tau^i (1-\tau)^{D-1-i} \left[\frac{K_{z,m}}{K} \left(1 - \left(1 - \frac{1}{K_{z,m}} \right)^i \right) + \left(1 - \frac{K_{z,m}}{K} \right) \right]. \quad (8)$$

$$\tau = \frac{1}{\frac{p_{c,m}-1}{p_{c,m}^L - 1} \left(\frac{W_{\text{off}}}{p_{\text{on}}} + \frac{q_m}{1-q_m} \frac{B+1}{2} + p_{c,m}^L T_f \right) + p_{c,m} T_1 + (1-p_{c,m})(T_2 + T_s) + \frac{W-1}{2}}. \quad (9)$$

- The *idle* (off) state, where an MTC device expects a new packet arrival. The traffic generation probability is denoted as p_{on}.
- The *barring* states $(Q_0, \ldots, Q_{B-1})$, where channel access for an MTC device is barred to relieve RACH congestion. The probability of barred access and the barring backoff window size are denoted by q_m and B, respectively.
- The *random-access* states $(i, 0)$, $i \in [1, L]$, where an MTC device attempts a preamble transmission. The parameter L denotes the maximum allowed number of preamble transmissions.
- The *backoff* states $(i, 1)$ to $(i, W-1)$, $i \in [2, L]$, due to an unsuccessful access attempt. The random-access backoff window size is denoted by W and a random backoff is also considered upon the initialization of the RACH procedure, i.e., the states $(1, j)$, $j \in [1, W-1]$.
- The *success* and *fail* states that model the successful and failed random-access attempt, respectively.

Let D be the number of MTC devices in the cell m. Based on the analysis in [14], the reliability, R_m, can be expressed as

$$R_m = 1 - p_{c,m}^L, \quad (6)$$

where $p_{c,m}$ denotes the preamble collision probability experienced by an MTC device in cell m. For the calculation of R_m, we first need to determine the expression for $p_{c,m}$.

Let $K_{z,m}$ denote the number of orthogonal preambles generated by the ZC root sequence z, $z = 1, \ldots, N_{s,m}$, of the reference cell m. As explained in Section II, if the required number of K preambles in the cell cannot be generated by cyclic shifts of a single root sequence, then additional ZC root sequences should be used. Therefore,

$$K_{z,m} = \begin{cases} N_p, & \text{for } z = 1, \ldots, N_{s,m} - 1, \\ K - (N_{s,m} - 1) N_p, & \text{for } z = N_{s,m}, \end{cases} \quad (7)$$

since less than N_p preambles generated by the last root sequence may be required for the generation of the K available preambles. Given that an MTC device selects one of the $K_{z,m}$ preambles generated from root sequence z for network access, the $p_{c,m}$ is defined as the probability that at least one of the i devices (from the remaining D-1 devices) attempting channel access, selects the same preamble of the orthogonal $K_{z,m}$ preambles or selects a non-orthogonal preamble generated by a ZC root sequence other than z. We assume no capture effect in the collided preambles and that the interference from non-orthogonal preambles constructed by different ZC root sequences results in a preamble-decoding failure at the RACH receiver (eNodeB). Then, $p_{c,m}$ is given by Eq. (8), where τ denotes the probability that an MTC device is attempting a channel access.

Algorithm 1 Iterative method to solve non-linear equations

Assume $L, B, W, q_m, b_{\text{th}}, p_{\text{on}}, W_{\text{off}}$ known
Initialize $p_{c,m} \leftarrow 0.9999$
Set allowed tolerance $\epsilon \leftarrow 1e-3$
while $p_{c,m} > 0$ **do**
  Calculate τ from Eq. (9)
  Calculate $p'_{c,m}$ from Eq. (8)
  if $|p'_{c,m} - p_{c,m}| < \epsilon$ **then** ▷ Convergence test
    break
  else
    $p_{c,m} \leftarrow p_{c,m} - 0.0001$ ▷ Update
  end if
end while

By applying the normalization condition of the Markov chain and owing to the chain regularities, the state stationary probabilities can be expressed as a function of the probabilities $p_{c,m}$, p_{on}, q_m and the random-access/barring parameters [14]. Then, assuming that a preamble transmission holds for 1ms, τ is given by Eq. (9). In Eq. (9), W_{off} denotes the average holding time of the idle state and T_f, T_s represent the expected time durations of the fail and success states, 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.

Note that for given random-access/barring parameters $(L, B, W, q_m, b_{\text{th}})$ and known MTC traffic characteristics $(p_{\text{on}}, W_{\text{off}})$, the expressions of the preamble collision probability $p_{c,m}$ in Eq. (8) and the probability τ of attempting a random access in Eq. (9) form a system of non-linear equations that can be solved via an iterative numerical method, as shown in Algorithm 1. Therefore, by plugging the obtained value of $p_{c,m}$ in Eq. (6), the value of R_m can be calculated.

Since the expression of R_m is not in closed-form, finding the optimal cell radius r_m that maximizes the achieved reliability is mathematically intractable. Therefore, we propose a heuristic interference- and traffic load-aware mechanism that determines the cell sizes in a generic heterogeneous cell deployment for the reliable support of event-driven MTC. We provide the details in the following.

B. Proposed Cell Planning and ZC Root-Sequence Allocation

We assume that the mobile network operator is aware of the number of cells C required to provide full coverage in a geographical area A and defines a range of supported radii $[r_{\min}, r_{\max}]$ for a heterogeneous cell deployment. Initially, a random radius is uniformly selected for each cell. Our proposed cell-planning mechanism employs a spatial ZC root-sequence allocation scheme where the ZC root sequences selected by each cell are spatially-separated and can only be reused by cells located at a distance larger than the preamble-decoding distance $d_{\max}$. In this way, the allocation of the same root sequences in neighboring cells is avoided and the resulting inter-cell interference decreases since the power falloff with distance is exploited. In addition, the mechanism dynamically modifies the ACB barring rate, b_{th}, to relieve congestion and prevent access failures. The steps of the mechanism are presented in Algorithm 2.

Starting from the cell m with the higher number of neighboring cells, the maximum available radius $r_{\max}$ is selected. Using Eqs. (1)–(3), $N_{s,m}$ is calculated and the minimum reuse distance of the selected ZC root sequences is determined by $d_{\max}$. Based on the iterative method described in Algorithm 1, the preamble collision probability $p_{c,m}$ is obtained and the value of R_m can thus be calculated using Eq. (6). The mechanism keeps decreasing the cell radius and appropriately updates the ZC root-sequence selection until the achieved reliability surpasses a predefined threshold R_{th} that depends on the particular MTC application. In case the updated reliability value is lower than in the previous iteration due to increased inter-cell interference or the minimum available radius is reached, a traffic-aware scheme is employed where the ACB barring rate, b_{th}, is set to a more restrictive value to disperse the access attempts in time. In this way, the congestion is reduced and preamble collision probability decreases resulting in an improved reliability value. The dynamic configuration of the b_{th} ends when R_{th} is satisfied. The value of b_{th} is assumed to be periodically broadcast by the eNodeB to the MTC devices of each cell, as part of the system information block message in the physical downlink broadcast channel. Once the cell radius and the root allocation for cell m is completed, all the relevant parameters are updated and the mechanism iteratively proceeds to the neighboring cell with the higher number of neighbors until all cells are processed.

In the following section, we derive the analytical expression for the traffic generation probability, p_{on}, based on a realistic traffic model selected to capture the spatiotemporal correlation of MTC. The value of p_{on} is required for the calculation of the reliability, as shown in Algorithms 1 and 2.

C. Traffic Model of Event-Driven MTC

MTC often involves the transmission of highly space- and time-correlated messages. In the use case of MTC in power systems [2], a cascading power fault affects neighboring segments in the grid and triggers the transmission of notification alarm messages among geographically-adjacent protection devices. To model this varying traffic behavior, in this work, we assume that the arrivals in each MTC device are governed by two application phases; a *regular* phase when no event occurs and an *event* phase where the inter-arrival time is shortened to ensure a timely message-delivery in case of an event (burst).

Algorithm 2 Cell planning and ZC root-sequence allocation

1: Assume $L, B, W, q_m, b_{\text{th}}, p_{\text{on}}, W_{\text{off}}, R_{\text{th}}$ known
2: Initialize $l \leftarrow 0$ iteration index
3: Pick cell m with max. number of neighbors and set $r_m^{(0)} \leftarrow r_{\max}$
4: Determine $N_{s,m}^{(0)}$ from Eqs. (1)–(3)
5: Reuse $N_{s,m}^{(0)}$ only beyond $d_{\max}$ ▷ Interference-aware
6: Calculate $p_{c,m}^{(0)}$ and $\tau^{(0)}$ using Algorithm 1
7: Calculate $R_m^{(0)}$ from Eq. (6)
8: **while** $R_m^{(l)} < R_{\text{th}}$ **do** ▷ Main iteration
9: $l \leftarrow l+1$
10: Decrease $r_m^{(l)}$
11: Repeat steps 4-7 and update $N_{s,m}^{(l)}, p_{c,m}^{(l)}, \tau^{(l)}, R_m^{(l)}$
12: **if** $R_m^{(l)} < R_m^{(l-1)}$ || $r_m^{(l)} < r_{\min}$ **then**
13: Set $r_m^{(l)} \leftarrow r_m^{(l-1)}$
14: Update $N_{s,m}^{(l)}$
15: **do**
16: Set $b_{\text{th}} \leftarrow b_{\text{th}} - 0.01$ ▷ Traffic load-aware
17: Update $p_{c,m}^{(l)}$ and $\tau^{(l)}$ using Algorithm 1
18: Calculate $R_m^{(l)}$ from Eq. (6)
19: **while** $R_m^{(l)} < R_{\text{th}}$
20: **end if**
21: **end while**
22: Repeat for neighboring cell with max. number of neighbors

Let $\mathcal{S}_i$ be the set of sensors that an MTC device i is equipped with and let $\mathcal{U}_i$ be the set of its neighboring devices. Let also $\alpha_{i,s}[t]$ be a binary parameter that indicates whether sensor s of an MTC device i captures a local event at time t. Then, the spatiotemporal correlation in the arrival stream of an MTC device i can be captured with the aid of the parameter $\beta_i[t]$,

$$\beta_i[t] = \begin{cases} 1, & \text{if } \sum_{s\in\mathcal{S}_i} \alpha_{i,s}[t] > 0\,, \\ 1, & \text{if } \sum_{j\in\mathcal{U}_i} \sum_{s\in\mathcal{S}_j} \alpha_{j,s}[t] > 0\,, \\ 0, & \text{otherwise,} \end{cases} \tag{10}$$

where an arrival in an MTC device 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 MTC devices.

In order to model this varying MTC traffic behavior, we leverage the two-state Markovian Arrival Process (MAP) framework to capture the interdependent and non-exponential inter-arrival times. The MAP, initially introduced in [16], 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 MTC 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 MTC device i, the convex combination of the matrices in the regular and event phase is considered with the aid of $\beta_i[t]$, as in [17]. Therefore, MAP is characterized by the rate matrices $\{\mathbf{D}'_0, \mathbf{D}'_1\}$ where

$$\mathbf{D}'_0 = (1 - \beta_{\text{i}}[t])\, \mathbf{D}_{0,\text{ regular}} + \beta_{\text{i}}[t]\, \mathbf{D}_{0,\text{ event}}, \quad (11a)$$
$$\mathbf{D}'_1 = (1 - \beta_{\text{i}}[t])\, \mathbf{D}_{1,\text{ regular}} + \beta_{\text{i}}[t]\, \mathbf{D}_{1,\text{ event}}. \quad (11b)$$

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

$$P_{i,j}(k,t) = \Pr(N_t = k, J_t = j | N_0 = 0, J_0 = i), \quad (12)$$

be the entry of a matrix $\mathbf{P}(k,t)$, where N_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 [16]

$$\frac{d}{dt}\mathbf{P}(0,t) = \mathbf{P}(0,t)\,\mathbf{D}'_0, \quad (13a)$$
$$\frac{d}{dt}\mathbf{P}(k,t) = \mathbf{P}(k,t)\,\mathbf{D}'_0 + \mathbf{P}(k-1,t)\,\mathbf{D}'_1,\ k = 1, \ldots, \quad (13b)$$

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

$$p_{\text{on}} = 1 - \sum_i \sum_j P_{i,j}(0,t), \quad (14)$$

where t corresponds to the duration of the LTE subframe (1ms). In the following section, we conduct a performance evaluation of our proposed mechanism in terms of achieved reliability.

IV. Numerical Results

To evaluate the performance of our proposed cell-planning and ZC root-sequence allocation mechanism, we consider a realistic scenario of power distribution automation where a high number of Intelligent Electronic Devices (IEDs) are uniformly deployed within a geographical area A. The IEDs are equipped with communication interfaces and generate event-based multicast traffic based on their input from voltage and current transformers/sensors. The random dropping model is used for the location of the IED transmitters whereas the location of a neighboring IED receiver is distributed according to a uniform distribution in a circular area around its associated IED transmitter. The MAP framework is used to capture the spatiotemporal correlation of the event-driven IED traffic and the well-studied expectation-maximization statistical framework [16] has been used for parameter $\{\mathbf{D}'_0, \mathbf{D}'_1\}$ fitting, based on the arrival traces of power automation traffic captured by a real-time digital simulator that implements the IEC 61850 GOOSE protocol.

Table II summarizes the basic parameters used in our simulations. A regular cell deployment is considered to provide coverage and the unsynchronized IEDs are assumed to contend for RACH access after a cascading power failure that affects the area A. An ACB scheme enhances the standard RACH procedure as an additional overload-control mechanism. Starting from a low-load scenario, new access requests generated by IEDs affected by the cascading events, appear progressively in the system until it is driven to overload. The contention-based RACH/ACB performance is then evaluated in terms of

TABLE II
Simulation Parameters

Parameter	Value
Preambles for contention-based access K	64
Coverage area A	100km$\times$100km
Range of cell radii $[r_{\text{min}}, r_{\text{max}}]$	[100m, 100km]
Transmit power	24dBm
Thermal noise power	-114dBm
Required preamble signal energy to noise ratio	18dB
Channel model	Suburban
Path loss coefficient	3.5
RACH configuration index	14
Barring/access backoff window sizes B, W (in ms)	20
Default barring rate b_{th}	0.5
Reliability threshold R_{th}	0.6
Preamble duration (in ms)	1
Max. allowed preamble transmission attempts L	10
RAR window size (in ms)	5
Contention resolution timer (in ms)	24
Master information block periodicity (in ms)	40
Time durations T_1, T_2, T_s, T_f (in ms)	{32, 16, 20, 1}

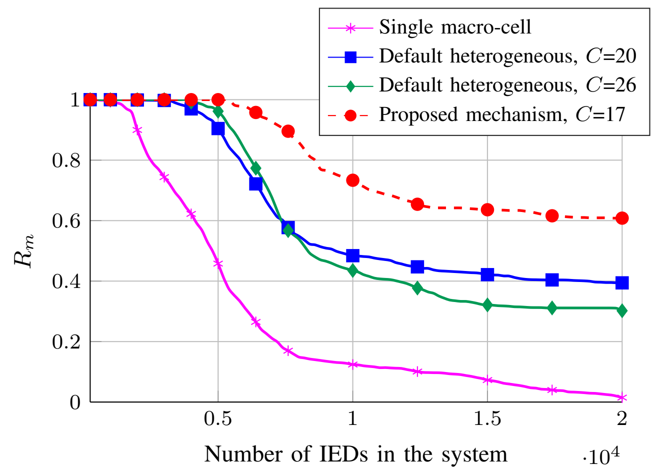

Fig. 4. Reliability achieved per IED for different cell-network deployments and ZC root-sequence allocation schemes.

reliability when the system operates close to its capacity limits. In particular, a comparative evaluation study of the achieved reliability R_m is performed among the following network-deployment options:

1) A single macro-cell deployment is used to provide coverage to the IEDs.
2) A default (traffic-unaware) heterogeneous deployment of multiple smaller cells with radii uniformly selected from the range $[r_{\text{min}}, r_{\text{max}}]$ and ZC root sequences randomly chosen among a set of N available roots in total.
3) A heterogeneous cell deployment based on our proposed mechanism where each cell radius is properly determined from $[r_{\text{min}}, r_{\text{max}}]$ to provide reliability guarantees for the IED traffic, according to the interference-aware ZC root-sequence allocation and the load-aware barring rate configuration, as described in Algorithm 2.

Fig. 4 illustrates the achieved reliability R_m per IED of a random cell m with increasing network traffic load. It can be observed that in the case of a single macro-cell deployment, the reliability level rapidly decreases with increasing traffic load, as the intra-cell interference becomes higher due to the orthogonality loss of the received preambles generated by different ZC root sequences. On other hand, for a default heterogeneous deployment of multiple smaller cells, the intra-cell interference is reduced due to the larger number of orthogonal preambles which leads to better preamble detection performance; however, since no reliability provisioning is considered for the cell size and the ZC root-sequence allocation, this improvement comes at the expense of increased inter-cell interference, especially when the number of cells required to provide coverage increases, as shown in Fig. 4. Therefore, the reliability gains for the default approach remain limited. Instead, in the case when our proposed mechanism is applied, reliability remains in higher levels even in the high traffic-load regime. The proper selection of the cell sizes and the spatial separation of the available ZC root sequences reduces the inter-cell interference since the allocation of the same roots among neighboring cells becomes less probable. In addition, the dynamic configuration of the ACB barring rate b_{th} provides reliability guarantees and relieves network congestion in high traffic-load conditions. It is also important to point out that, with our proposed cell-planning mechanism, a lower number of deployed cells is required to achieve the same reliability level as in the default cell-configuration case, which eventually leads to lower installation costs for the network operator.

V. Conclusions

The relation between the LTE cell radius and the number of available orthogonal preambles reveals an important limitation for cells with large radius due to the non-orthogonality of preambles generated by multiple ZC root sequences. On the other hand, root-sequence allocation needs to be properly performed among smaller cells to minimize inter-cell interference in the preamble reception. According to these limitations, in this paper, we introduce an interference- and load-aware cell-planning mechanism to provide reliable channel access for a high density of MTC devices. In addition, a realistic traffic model is proposed to accurately capture the spatiotemporal correlation of event-driven MTC traffic. The numerical evaluation of our mechanism demonstrates its superiority in terms of reliability with respect to benchmarking network-deployment schemes and useful insights can be drawn for the design of such cellular systems. Future work aims to enhance the proposed solution by studying the capture effect in the preamble reception and the trade-offs between MTC access latency and reliability.

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