# Performance Evaluation of the Contention-Based Random Access of LTE under Smart Grid Traffic

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**Abstract.** Power distribution networks are often widely distributed to accommodate electrical power feeds to dense cities while monitoring and control systems typically require extensive information exchange among numerous intelligent electronic devices. Using the existing network infrastructure, cellular technology appears as a key enabler for the support of large-scale metering deployments and wide-area monitoring systems. In this paper, we evaluate the performance of the contention-based random-access mechanism of LTE networks for real-time monitoring and metering applications. In particular, the impact of smart grid traffic is investigated in terms of access delay and outage probability under different network configurations and traffic characteristics. Simulations of realistic network-overload scenarios demonstrate that the random-access channel of LTE/LTE-A is prone to congestion when a high number of smart grid devices attempt for network access, while the bursty nature of monitoring traffic results in even higher performance degradation.

**Key words:** LTE, random-access channel, smart-grid traffic, metering, monitoring, Markov-modulated Poisson process

## 1 Introduction

The ongoing modernization of the electrical grid mainly relies on the evolution of the distribution grid into a fully automated and interconnected network. A wide variety of communication technologies and network protocols have been proposed to support advanced distribution-grid operations. Among various communication alternatives, cellular networks based on 3GPP Standards, emerge as a promising solution to enhance the observability and controllability of the distribution network [1]. However, cellular technology was not initially intended for distribution-grid applications and smart grid traffic characteristics are fundamentally different from regular human-type communication. Thus, significant challenges arise for the current structure of cellular networks.

In LTE/LTE-A, the devices use a random-access procedure to request a dedicated communication channel in several cases, e.g., initial network association, transition from idle to connected state, radio-link failure, handover, and uplink synchronization. Cellular networks were designed to support a moderate number of users per base station; thus, the simultaneous channel access attempts of numerous distribution-grid devices render the standard random-access mechanism highly susceptible to congestion, due to the scarce random-access resources compared to the increased demand [2]. Besides the high density of devices requesting channel access, the messages exchanged in monitoring applications are generally event-driven and involve sporadic and time-critical data delivery.

Several methods have been proposed during the recent years to improve the random-access procedure of LTE networks [3–5]. Most of the available solutions are based on initial proposals compiled by the 3GPP, including separation of random-access resources, access class barring (ACB) schemes, and parameter optimization in the medium access control layer [6]. A reliability analysis for smart grid monitoring traffic is performed in [7] based on a developed analytical framework for the ACB scheme. The authors in [8] propose an enhancement of the standard access mechanism by proactively estimating the anticipated network load (alarm reports, periodic measurements) to determine the required random-access opportunities. An adaptive random-access mechanism is introduced in [9] to enable the integration of IEC-61850 communication services in public LTE networks, based on a continuous monitoring of the network loading state by the eNodeB.

Unlike the majority of existing literature where delta traffic or simple Poisson models are used to represent the aggregate smart grid traffic, in this work we leverage the Markov-Modulated Poisson Process (MMPP) framework [10] to capture the bursty behavior of monitoring traffic in event-driven distribution-grid operations. Focusing on two representative scenarios of distribution-grid services, i.e., wide-area monitoring and large-scale metering, we assess the performance of the standard random-access mechanism of LTE for different network configurations and traffic characteristics. We further investigate the impact of the random-access parameters and traffic-load conditions on the access delay and outage probability and several insights can be drawn for the feasibility of the standard random-access procedure when handling massive smart-grid traffic.

The structure of the paper is as follows. Section 2 provides an overview of the random-access mechanism in LTE/LTE-A. Section 3 describes the considered communication scenarios, with LTE applied as the underlying communication technology for wide-area monitoring and metering services. Section 4 provides a performance evaluation of the standard random-access mechanism under smart-grid traffic in network-overload conditions with system-level simulations in ns-3 framework. Our concluding remarks are presented in Section 5.

## 2 The Random-Access Mechanism in LTE Networks

In LTE/LTE-A, the physical Random-Access CHannel (RACH) is used by the devices to request transmission resources or re-establish a connection to the eNodeB [11]. The RACH is formed by a periodic sequence of time-frequency resources, reserved in the uplink channel for the transmission of access requests. The RACH periodicity is determined by the *RACH configuration index* and may

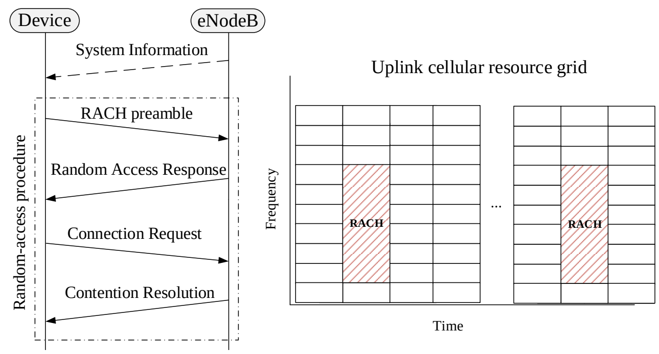



Fig. 1: Overview of the contention-based random-access procedure in LTE/LTE-A. Connection establishment normally involves a four-message handshake between the device and the eNodeB. An access request is completed if the four messages are successfully exchanged.

vary from once in every subframe (1ms) to once every two frames (20ms). Either a contention-based or a contention-free scheme can be used for the random-access procedure, depending on the purpose [2]. This paper focuses on the challenging contention-based mode, which consists of a four-message handshake between the device and the eNodeB, as shown in Fig. 1. In particular, the following messages are sequentially exchanged between the device and the eNodeB:

1. *RACH preamble*. The first step of the random-access procedure is the transmission of a random-access preamble. Based on the system information broadcast by the eNodeB, each device randomly selects one of the available (up to 64) preamble sequences for contention-based access and transmits it using the RACH. More than one device can possibly choose the same preamble in the same random-access resource, resulting in a preamble collision. In this case, a contention-resolution process is required.
2. *Random-Access Response (RAR)*. After receiving the preambles in a specific random-access resource, the eNodeB replies with a RAR message to all the devices with preamble transmission on this resource. In particular, the RAR message includes an identifier of each successfully decoded preamble, timing information for synchronization, a temporary device identifier and an uplink resource grant for devices to transmit a connection request. In case a device receives a RAR without the identifier of the preamble it used, it is signaled, via a backoff indicator attached to the RAR, to wait for a random time until the next preamble transmission attempt. A preamble collision might remain undetected, when devices are located at a similar distance from the eNodeB and their preambles are constructively received. In this case, the contention is resolved in the next step.
3. *Connection Request*. After receiving the RAR, the device transmits a connection-request message conveying the device identifier and the establishment cause, using the resource granted by the eNodeB in the previous step. A

retransmission mechanism is enabled to ensure the message delivery. In case of undetected preamble collision in the previous step, more than one device will transmit in the same uplink resource; the eNodeB will not then reply with an acknowledgment and each device will retransmit the message.

4. *Contention Resolution.* The final step of the random-access procedure involves the transmission of a contention-resolution message from the eNodeB to the device. Any contention due to multiple devices attempting channel access using the same random-access resource, is now resolved. The completion of this step renders the random-access attempt successful. Otherwise, if the message is not received by a device within a predefined time window, the random-access procedure is declared as failed and the device needs to restart from the first step until the allowed preamble retransmissions are reached.

As the traffic load and the number of access requests increase, the standard LTE random-access mechanism suffers from congestion due to the high probability of collision in the transmission of the available preambles. Therefore, RACH congestion constitutes a significant challenge in large-scale distribution grid deployments with a high number of communicating entities, as will be described in the following section.

## 3 Smart Grid Communication Scenarios and Traffic Modeling

As the distribution grid evolves towards more complex loads and decentralized generation, distribution planning may need to account for more dynamic and faster changes to the distribution grid through *i*) the extensive installation of intelligent electronic devices (IEDs) for *wide-area monitoring* purposes and *ii*) the large-scale *smart-metering* (AMI) deployments. Two representative communication scenarios in cellular-enabled distribution grids are depicted in Fig. 2. We provide the details in the following.

### 3.1 Wide-Area Monitoring Systems

Distribution automation deals with system automatic functionalities that involve communication from numerous IEDs installed along the distribution network [12]. The emergence of distributed energy resources results in a growing need for real-time monitoring and quasi-real-time analysis of the grid behavior to enhance the observability and controllability of the distribution network. As illustrated in Fig. 2, in this paper we focus on wide-area monitoring systems, where IEDs -equipped with LTE communication interfaces- transmit monitoring information for situational awareness and supervision of the distribution equipment.

Besides the periodic transmission of monitoring information, we consider a scenario where event-driven IED communication is required to detect out-of-step conditions (e.g., excessive/increasing phase angle), issue alarms and initiate control actions to rectify the fault and/or isolate the system. In order to capture

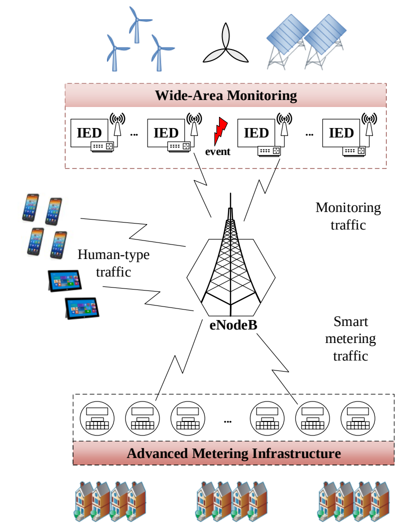



Fig. 2: LTE networks as the underlying communication technology for advanced distribution grid applications, e.g., distribution automation and advanced metering infrastructure.

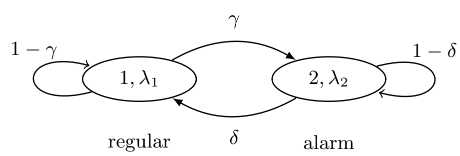



Fig. 3: The state diagram of an IED traffic generation modeled with an MMPP.

the bursty characteristics and varying behavior of IED traffic, we may model each IED traffic generation using a two-state Markov Modulated Poisson Process (MMPP) [10]. In particular, the MMPP can be viewed as a superposition of the two Poisson processes with an underlying two-state Markov chain modeling the transition between the processes. As illustrated in Fig. 3, the first state corresponds to the regular IED operation, modeled as a Poisson process with rate $\lambda_1$; the second state represents the alarm IED operation where the generation of a traffic burst is also modeled as a Poisson process with rate $\lambda_2 > \lambda_1$, to account for the higher arrival intensity of the alarm traffic.

Let $P$ be the state-transition matrix that incorporates the transition probabilities between the states of the Markov chain. Then,

$$P = \begin{bmatrix} 1-\gamma & \gamma \\ \delta & 1-\delta \end{bmatrix}, \tag{1}$$

where $\gamma$ is associated with the frequency of a burst occurrence and $\delta$ is related with the duration of each burst. Let also $\pi = \{\pi_1, \pi_2\}$ be the stationary distribution vector. Then, from the steady-state equations $\pi = \pi P$ and $\pi_1 + \pi_2 = 1$, we derive the stationary distribution $\pi$ of the chain and the overall rate $\lambda_g$ of the MMPP as

$$\pi = \left\{ \frac{\delta}{\gamma + \delta}, \frac{\gamma}{\gamma + \delta} \right\} \quad \text{and} \quad \lambda_g = \sum_{i=1}^{2} \lambda_i \pi_i \,, \tag{2}$$

respectively.

### 3.2 Advanced Metering Infrastructure Systems

In the case of metering-data delivery, a typical AMI system uses smart meters to communicate information between consumers and power utilities for operating and billing purposes. The enhanced coverage offered by LTE/LTE-A networks allows smart-metering deployments to span over vast areas and remote end-points to be connected into the same management network. As illustrated in Fig. 2, in this communication scenario, spatially distributed smart meters transmit consumer-meter information from a large number of customer/industrial premises at the utility end for data processing. The AMI systems require infrequent uplink transmissions of small-sized data packets and traffic generation is assumed to follow a Poisson process with an aggregate arrival rate $\lambda_0$.

In both communication scenarios, the channel-access attempts of numerous distribution grid devices, i.e., IEDs in wide-area monitoring and smart meters in dense AMI deployments, render the standard access mechanism of LTE highly susceptible to congestion due to the limited random-access opportunities compared to the increased resource demand. Therefore, RACH scalability constitutes a significant challenge especially for the dynamic environment of the future distribution grid where the number of devices joining the network rapidly evolves, i.e., frequent entry/re-entry [12]. In the following, we evaluate the RACH performance under different network settings and smart grid traffic characteristics.

## 4 Performance Evaluation

To evaluate the performance of the LTE random-access scheme for monitoring and metering traffic, we consider realistic network-overload scenarios in ns-3 discrete-event simulator where each traffic type is solely present in the system. The standard RACH implementation initially developed in [2] is extended with the traffic modules of Section 3 and the integration with LTE radio protocol stack is performed as in [9, 13]. In the simulation setup, numerous IEDs or smart meters generate traffic within the eNodeB coverage area and contend for channel access. Starting from a medium-load scenario, new devices appear in the system according to a Poisson process with arrival intensities based on the traffic modeling described in Section 3. The MMPP parameters are selected to closely match the traffic behavior of IEC-61850 automation services [13]. As the simultaneous channel attempts progressively drive the system to overload, the RACH

Table 1: Simulation Parameters

| Parameter | Value |
|---|---|
| Preambles for contention-based access | 54 |
| RACH configuration index[1] CI | $\{3, 9\}$ |
| Backoff indicator[1] | 20ms |
| Preamble duration | 1ms |
| Max. allowed preamble transmissions[1] | 10 |
| RAR window size[1] | 5ms |
| Contention resolution timer[1] | 24ms |
| Arrival rates $\lambda_0$, $\lambda_1$, $\lambda_2$ (in attempts/ms) | $\{10^{-3}, 2 \cdot 10^{-3}, 0.5\}$ |
| Traffic model transition probabilities $\gamma$, $\delta$ | $\{0.5, 0.3\}$ |

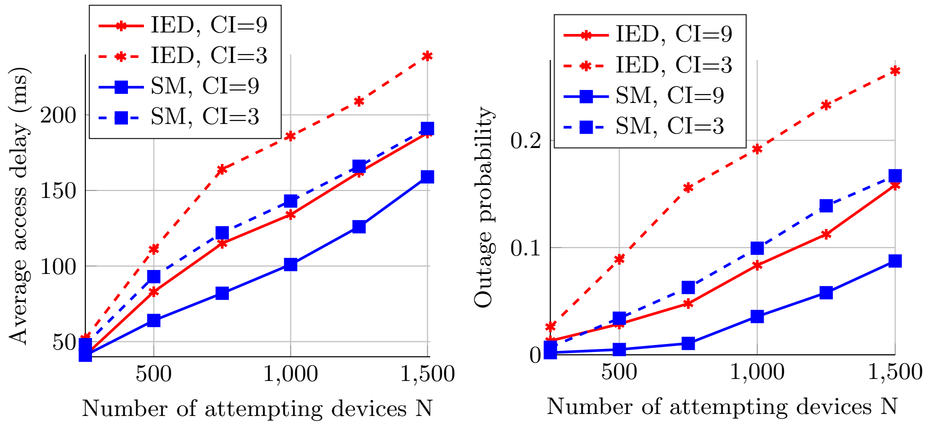
[1] Standard values available in [6, 11].

performance is evaluated under different network configurations and traffic characteristics when the system operates close to its capacity limits.

Two performance indicators have been used to assess the RACH performance, namely: *i*) average access delay, defined as the time elapsed between the first preamble transmission until the contention-resolution message reception from the eNodeB, and *ii*) outage probability, defined as the probability that a device reaches the maximum number of transmission attempts and is still unable to complete the random-access process. Table 1 summarizes the basic parameters used in our simulations.

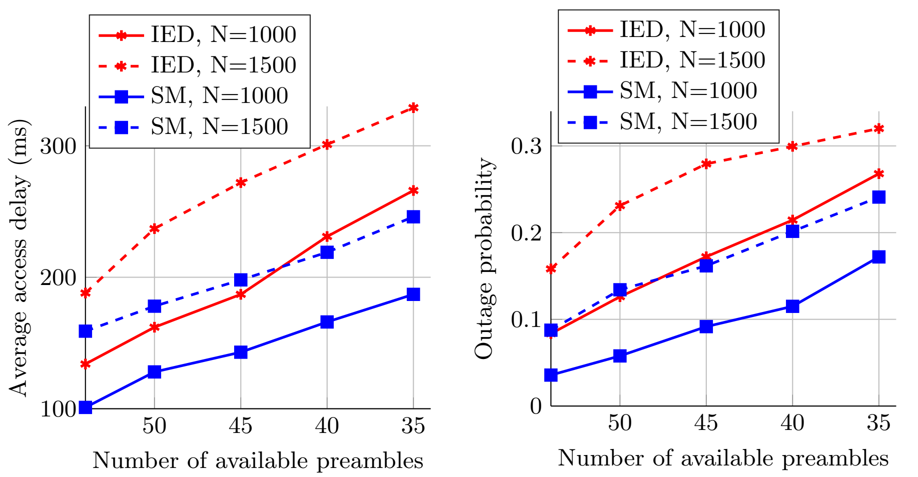
The impact of RACH configuration index (CI) on the average access delay and outage probability is illustrated in Fig. 4, for both monitoring (IED) and metering (SM) traffic. In particular, as shown in Fig. 4a, the average access delay experienced per IED/smart meter increases with increasing monitoring/metering traffic load since contention becomes heavier. A greater value of CI corresponds to a more frequent recurrence of random-access opportunities per time frame; i.e., the index CI = 3 corresponds to one random-access slot per frame whereas for CI = 9 each frame has three random-access slots. Thus, when CI is configured to a higher value, we observe that the average access delay is reduced. In addition, as shown in Fig. 4b, the outage probability experienced per IED/smart meter also decreases with a greater CI. In both figures, the average access delay and outage probability are higher for monitoring traffic compared to the metering traffic, due to the bursty traffic nature of IEDs and the higher arrival rates.

The impact of the number of available preambles for contention-based access on the average access delay and outage probability is illustrated in Fig. 5 for both types of smart grid traffic and a high number of attempting devices. In use cases where the RACH resources are shared with the conventional LTE users, a dedicated set of preambles needs to be allocated to smart grid traffic given the aimed quality-of-service requirements. In particular, as shown in Figs. 5a and 5b respectively, the average access delay and outage probability experienced per IED/smart meter increase as the number of dedicated preambles decreases due to the lack of adequate random-access opportunities. As it can be observed, the




(a) (b)

Fig. 4: Impact of the RACH configuration index (CI) on (a) average access delay and (b) outage probability for monitoring (IED) and metering (SM) traffic with increasing number of attempting devices.




(a) (b)

Fig. 5: Impact of the number of available preambles for contention-based access on (a) average access delay and (b) outage probability for monitoring (IED) and metering (SM) traffic in network-overload conditions.

performance degradation is higher for the monitoring traffic compared to the metering traffic, due to the more aggressive arrival rate of monitoring messages.

In the case of monitoring traffic, the impact of the traffic characteristics $\gamma$, $\delta$ on the average access delay and outage probability is depicted in Fig. 6 for a high number (i.e., 1000) of attempting devices. As defined in Fig. 3, $\gamma$ is

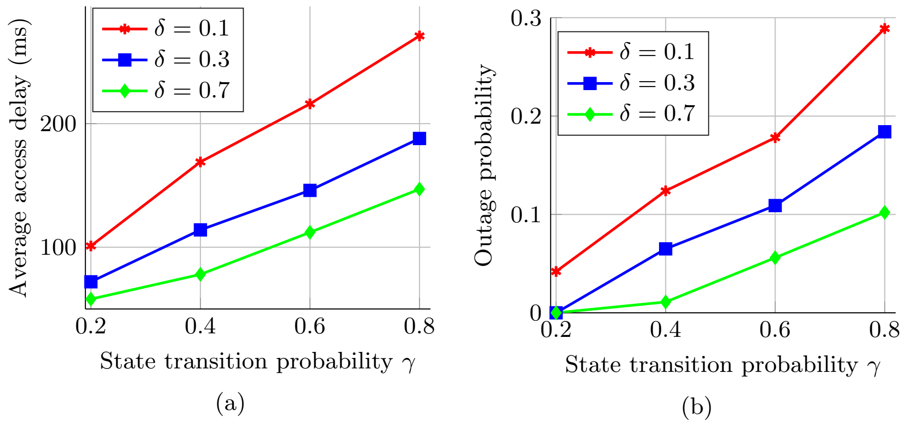



Fig. 6: Impact of the traffic characteristics $\gamma$, $\delta$ of the monitoring IEDs on the (a) average access delay and (b) outage probability in network-overload conditions.

associated with the frequency of a burst occurrence and $\delta$ is related with the burst time duration. In Fig. 6a, it can be observed that as the frequency of a burst increases, or equivalently $\gamma$ increases, the average access delay increases due to the higher attempt rate in the alarm state which leads to a surge of channel access attempts. Similarly, due to the heavier contention, the outage probability in Fig. 6b increases with increasing $\gamma$ since it is more possible for an IED to reach the limit of the allowed preamble retransmissions without a successful attempt. In addition, as the length of each burst increases, or equivalently $\delta$ decreases, the average access latency and outage probability increase since the IEDs remain longer in the alarm state and RACH becomes more prone to congestion.

## 5 Conclusions

In this paper, we conduct a performance evaluation of the contention-based random access in LTE networks under monitoring and metering traffic for emerging distribution-grid applications. We investigate the impact of different network configurations and smart grid traffic characteristics on the standard random-access procedure of LTE and LTE-A. Our feasibility study aims to reveal the performance limitations and signaling bottlenecks of the RACH when a high number of smart grid entities attempt for channel access in a highly-synchronized manner. The simulation results of realistic network-overload scenarios illustrate that the standard LTE mechanism becomes highly susceptible to congestion while the bursty nature of monitoring traffic results in even higher performance degradation. Radical enhancements are thus required for the efficient accommodation of a high density of smart grid devices in future cellular networks.

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