Handling Mission-Critical Communication in Smart Grid Distribution Automation Services through LTE

Charalampos Kalalas, Francisco Vazquez-Gallego and Jesus Alonso-Zarate
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain
E-mails: {ckalalas, francisco.vazquez, jesus.alonso}@cttc.es

***Abstract*—In this paper, a novel random access mechanism is introduced to enable the integration of smart grid distribution automation (DA) services in public LTE networks. The smart grid paradigm is anticipated to improve grid reliability through extensive and timely information exchange in the power distribution network. LTE appears as a promising communication technology for advanced distribution grid services since it supports extensive coverage, low latency, and quality-of-service differentiation. However, the standardized random access channel (RACH) mechanism of LTE has difficulties to meet the stringent requirements of such services in terms of access latency and reliability. This is the motivation for the contribution in this paper, where a representative DA scenario is considered and the achievable performance is evaluated on a system-level simulator. Extensive simulations of realistic overload scenarios demonstrate that our properly designed RACH mechanism can greatly improve the access performance of DA traffic with negligible impact on background traffic, i.e., human-type communication and smart metering data exchange.**

I. Introduction

The ongoing modernization of the electrical grid mainly relies on the evolution of the power distribution grid into a fully automated and interconnected electrical network in medium-voltage level. As smart grid capabilities expand dramatically, real-time monitoring, protection and control of distribution substations often involves the reliable transmission of mission-critical protection messages and/or massive amounts of monitoring information. Among various wireless communication alternatives, licensed-based cellular technologies, i.e., LTE and subsequent 3GPP releases, have been identified as promising technologies to meet the stringent Quality-of-Service (QoS) requirements of advanced distribution grid operations, e.g., Distribution Automation (DA) and fault location/restoration [1]. However, several challenges need to be addressed before LTE facilitates the upgrade of the aging distribution grid.

One of the key performance limitations refers to the network connectivity for a sheer scale of smart grid monitoring entities, i.e., Intelligent Electronic Devices (IEDs), in DA applications. In LTE, devices use the Random Access CHannel (RACH) to perform initial network association, request transmission resources, and re-establish a connection to the eNodeB, i.e., the base station. The RACH is formed by a periodic sequence of allocated time-frequency resources, reserved in the uplink channel for the transmission of access requests [2]. The random access procedure in LTE can be either contention-free or contention-based. In this paper, we focus on the contention-based random access operation, where LTE devices contend for network access by randomly selecting one of the available (up to 64) orthogonal preamble sequences to transmit over the random access slots. As shown in Figure 1, the eNodeB processes the received preambles and provides feedback in a Random Access Response (RAR) message informing the devices whether a collision was detected for their preamble. In case of collision, devices are signaled to perform a backoff time before the next contention attempt. The RAR also conveys information for successfully decoded preambles including the resource grant for devices to transmit a connection request.

Since LTE was not initially designed to handle efficiently the simultaneous access of numerous distribution grid devices, the standardized RACH mechanism suffers from congestion as the traffic load and number of access requests increase, due to a high probability of collision in the transmission of the preambles [3]. Besides the high density of devices requesting network access, the messages exchanged in DA applications, e.g., for real-time situational awareness, protection and control, are event-driven and require sporadic but time-critical data delivery [4]. In addition, the shared LTE network needs to support the human-type communication (HTC) generated by LTE subscribers and the access requests from smart grid metering devices conveying power quality measurements. Therefore, to achieve reliable communication within the distribution grid, LTE needs to be enhanced with advanced radio access mechanisms adapted to a complex range of network access requirements and smart grid traffic characteristics.

In this paper, we investigate the performance of the LTE RACH for the support of real-time automation services in large-scale distribution grid deployments. We present the technical challenges introduced by the data exchange among IEDs in DA operations and discuss the ability of LTE RACH to *i*) handle the traffic surge of simultaneous channel access requests and *ii*) meet the strict latency requirements of mission-critical messages. We focus on a representative DA application, namely a substation automation scenario, where a cascading power fault affects neighboring segments in the grid and triggers the transmission of notification alarm messages among geographically adjacent IEDs.

The main contribution of this work resides in the design of an efficient access mechanism to ensure the seamless operation of LTE RACH in network overload conditions. We address the shortcomings of existing random access solutions

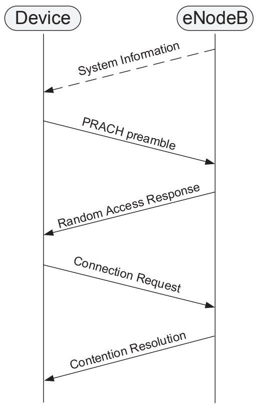

Fig. 1. Contention-based random access procedure in LTE normally involves a four-message handshake between the device and the eNodeB. Based on the system information broadcast by the eNodeB, mutually orthogonal preambles are used by the devices to contend in the available random access slots. An access request is completed if the four messages are successfully exchanged.

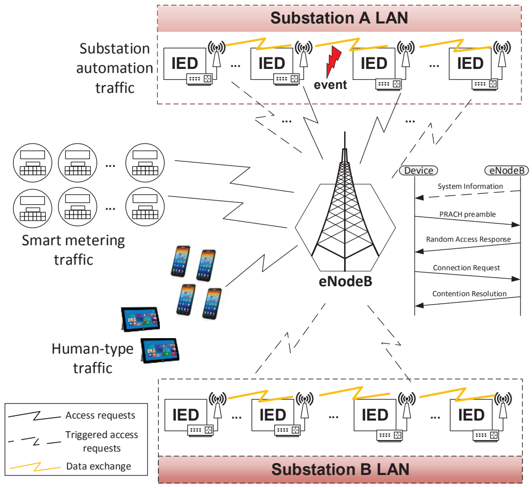

Fig. 2. Network architecture for the integration of LTE technology in the distribution grid and its system components. Substation automation services are achieved through extensive information-exchange among IEDs which contend for the shared access resources with LTE users and metering devices.

by proposing a novel mechanism, named Random Access for Distribution Automation (RADA), that consists of an adaptive integration of three individual schemes. In particular, based on the monitoring of the network loading state by the eNodeB, a flexible partition of the available preambles into different traffic classes is applied. In turn, in capacity overload conditions, a dynamic access barring scheme for delay-tolerant smart metering traffic is employed. RACH congestion is further relieved by a load shedding scheme that discards unnecessary preamble transmissions from neighboring IEDs. The RADA mechanism rigorously considers the stringent latency constraints imposed by DA traffic while guaranteeing the performance of contending network entities, i.e., cellular users and smart meters.

The structure of the paper is as follows. Section II provides an overview of related work. Section III describes the considered DA scenario, with LTE applied as the underlying communication technology. Section IV presents the implementation details of the RADA mechanism that enables a reliable integration with QoS guarantees for DA services over public LTE infrastructure. Section V validates the feasibility of RADA mechanism in overload through system-level simulations with ns-3 [5]. Our concluding remarks are presented in Section VI.

II. Related Work

Several methods have been proposed during the recent years to improve the contention-based RACH operation. Most of the available solutions are based on initial proposals compiled by the 3GPP, including separation of random access resources, access class barring schemes, and parameter optimizations in the medium access control (MAC) layer [6]. The separation of resources can be achieved either by splitting the available preambles or by allocating different random access slots to the traffic flows [7]. Despite reducing the resource contention among the competing entities, the performance of this mechanism tends to be worse when the traffic load increases. Thus, the benefits of this solution can be attained when applied in conjunction with an additional congestion-avoidance mechanism and resource partition is periodically adapted to the traffic conditions of the system [8].

Conventional access class barring schemes rely on the assignment of different barring parameters to traffic streams in an effort to alleviate network congestion [9]. However, when applied as standalone RACH solutions, they result in increased access latency that some delay-constrained devices cannot tolerate; hence, they are rendered insufficient for event-driven distribution grid operations where congestion may arise in a very short period of time. Solutions based on MAC parameter optimizations are generally use-case dependent. In most cases, an access network dedicated to machine-type communication is assumed and hence no resource contention with HTC is taking place [10], [11]. To the best of the authors' knowledge, there is no previous work on the design of an appropriate RACH mechanism for the accommodation of DA traffic in shared LTE networks.

III. System 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 time-critical message exchanges among neighboring IEDs for rapid diagnosis of system faults and initiation of control/isolation actions [4]. Figure 2 illustrates the network architecture for a substation automation deployment scenario. Moving beyond the state-of-the-art, we propose a system model that relies on peer-to-peer communications and decision making is distributed among the substations that coordinate through direct communications. In general, this network topology captures use cases where distributed event-driven communication is required. The IEDs, equipped with LTE communication interfaces, reside within the substation Local Area Networks (LANs) and can be seen as controllers that get their input from

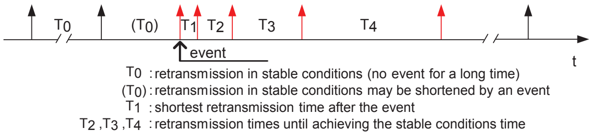

Fig. 3. GOOSE burst traffic pattern [12]. Under stable conditions, GOOSE messages follow a periodic traffic pattern, but are generated in bursts when an event occurs.

voltage and current transformers/sensors and provide their output (commands, status data), e.g., to circuit breakers. Via direct control signaling among IEDs attached on the distribution feeders and transformers, real-time situational awareness and supervision of the power equipment is possible [1].

According to the IEC 61850-8-1, Generic Object Oriented Substation Event (GOOSE) messages can be used for fast horizontal communication between IEDs within the same or different[1] substation LANs [12]. GOOSE messages allow for fast transmission of substation events and, assisted by the ubiquitous LTE coverage, can support inter-substation communication to prevent the extensive propagation of disturbances to the entire power system. As illustrated in Figure 3, under stable operating conditions, each IED periodically reports its application states via identical[2] GOOSE messages to neighboring IEDs, as a heart-beat function. In turn, the reception of a GOOSE message sequentially triggers the neighboring IEDs to transmit their own GOOSE messages, conveying the same information in a cascaded and redundant manner. When an event occurs and thus a status change is detected, the retransmission period of GOOSE messages is shortened (burst traffic) to ensure the timeliness of their delivery.

The cascading effect of the fast exchange of GOOSE messages among the neighboring IEDs results in a surge of network access attempts. The congestion problem may deteriorate in future distribution grids, where substation automation services require a dense deployment of IEDs within the substation LANs to improve observability and controllability. In addition, the time-sensitive nature of GOOSE messages renders the standard LTE random access mechanism insufficient for the reliable support of these services [1].

As shown in Figure 2, on top of DA traffic exchanged among IEDs, the shared LTE infrastructure accommodates a wide range of HTC services, e.g., web browsing, voice and video traffic, generated by regular LTE subscribers. Since our system model corresponds to a realistic distribution grid topology, smart metering traffic is also present in the network. In particular, following the IEC 61850 Manufacturing Messaging Specification (MMS), numerous smart meters periodically transmit their power quality measurements to data management systems at the utility end. Smart metering services typically require infrequent uplink transmissions of small-sized data packets and their latency requirements are relatively milder compared to DA functionalities.

[1]The need for wide-area monitoring and control of the distribution grid extends IEC 61850 to enable automation services beyond substation premises.

[2]Originally based on ”best-effort” switched Ethernet in the data link layer, GOOSE reliability is enhanced by transmitting multiple message copies.

Therefore, a significant challenge occurs for the shared LTE RACH on how to efficiently handle the simultaneous network access requests from a high number of smart grid entities, i.e., IEDs and smart meters, and HTC users. Due to the cascade effects of GOOSE traffic in the case of a power fault, the high number of neighboring IEDs attempting channel access results in an abrupt increase of the overall traffic load and hence in congestion issues for the standard RACH mechanism. Our objective is to address the implementation challenges so that LTE RACH can reliably support DA services and thus ensure the seamless operation of the power grid, as will be discussed in the following section.

IV. Proposed RADA Mechanism

In this section, we introduce RADA, our proposed LTE random access mechanism that enables time-critical data exchange in DA services. Since the shared LTE network should accommodate a wide range of human-centric and smart grid services, we apply traffic class differentiation via appropriate QoS provisioning, as an essential method for relieving the contention among the competing entities for network access. In an effort to leverage the advantages of various 3GPP RACH amendments when applied as standalone solutions, the RADA mechanism is comprised of an adaptive integration of three individual schemes:

1) A flexible partition of the random access resources by splitting the available preambles in subsets, each of them corresponding to each traffic class present in the system.
2) A dynamic access barring scheme for delaying the access to new arrivals originated from delay-tolerant traffic classes, i.e., MMS smart metering traffic.
3) A load shedding scheme based on the power levels of the received preambles from delay-critical GOOSE traffic generated by neighboring IEDs.

QoS provisioning allows for differentiated access handling in shared LTE networks and is achieved through the definition of new QoS traffic classes. In particular, we propose the extension of the standardized QoS-based LTE mechanism with the introduction of additional QoS classes for IEC 61850 GOOSE and MMS services [13]. Based on the latency and reliability requirements, the available preambles for contention-based network access are separated in three different subsets, namely: *i*) regular HTC, *ii*) delay-tolerant MMS, and *iii*) high priority GOOSE. The competing entities are then restricted to use the subset of resources according to their class.

The preamble partition is considered to be periodically broadcast by the eNodeB, as part of the master information block message[3] in the physical broadcast channel on downlink [9]. In case of channel access overload, the eNodeB appropriately reassigns the separation of preambles between HTC and GOOSE subsets, to cope with peak congestion levels. This can be achieved via a continuous monitoring of the loading state of the network by the eNodeB, based on a periodic calculation

[3]The master information block message includes a limited number of most frequently transmitted system information parameters [9].

of the average number of preamble retransmissions required to have a successful access request. Although the main goal resides in the support of the stringent performance constraints imposed by GOOSE messages, the preamble partition should be performed in a way that the performance degradation on conventional HTC is kept at a minimum level.

Based on the separation of the random access resources among the different traffic classes, the eNodeB is able to differentiate the origin of the received preambles and apply additional congestion-avoidance mechanisms depending on the traffic class. In particular, a dynamic access baring scheme is applied to MMS devices associated with delay-tolerant smart metering services. Similar to the previous scheme, the eNodeB can determine the congestion level of the RACH by calculating the average number of preamble retransmissions. In case of high traffic load detection, new access requests from MMS metering traffic are barred and MMS devices perform a random backoff time before scheduling their next preamble transmission. Thus, their access attempts are dispersed over time until channel contention conditions improve. The barring timer parameter is considered to be broadcast by the eNodeB along with the master information block message.

In an effort to alleviate the increased RACH congestion caused by neighboring IEDs when a power fault occurs, a load shedding scheme is applied based on the power levels of the received preambles associated with GOOSE traffic. As discussed in Section III, access requests for GOOSE messages conveying identical system fault data, are transmitted in a cascaded and redundant manner by neighboring IEDs to ensure that messages are eventually delivered. However, in cases of RACH capacity overload, we can exploit the spatial proximity of geographically adjacent IEDs to discard the unnecessary preambles with similar received power levels at the eNodeB[4], without adversely affecting the reliability of GOOSE services. Instead, RACH congestion is reduced since the preambles are more frequently available to IEDs and access latency for delay-constrained GOOSE traffic can be substantially improved.

The adaptive integration of the three schemes into the consolidated RADA mechanism aims at the support of the stringent performance constraints imposed by the time-critical GOOSE traffic while keeping the performance of the other access-competing entities, e.g., cellular users and smart meters, at a guaranteed level. In the following section, we evaluate the performance of the RADA mechanism.

V. Simulation Results

To evaluate the performance of the RADA mechanism, we consider realistic overload scenarios where LTE subscribers generate background HTC within the eNodeB macrocell coverage area and contend with the IEDs and MMS meters for the shared channel access. Such scenarios would arise in practice, if public LTE networks integrate distribution grid services that incorporate both DA and metering traffic. Starting from a medium-load scenario, new access requests from all traffic types appear according to a Poisson process with arrival intensities selected so as to drive the system to overload. The traffic mix among HTC, MMS and GOOSE classes, expressed as a percentage of the simultaneous access attempts, is kept at the same level. The RACH performance is then evaluated when the system operates close to its capacity limits. Table I summarizes the basic parameters used in our simulations.

TABLE I
Simulation Parameters

Parameter	Value
Preambles for contention-based access	54
PRACH configuration index[5]	6
Backoff indicator[5]	20ms
Preamble duration	1ms
Maximum preamble retransmissions[5]	10
RAR window size[5]	5ms
Contention resolution timer[5]	48ms
Master information block periodicity[5]	40ms
Barring factor b	0.4
Preamble partition {HTC,MMS,GOOSE}	{13,25,16}
Traffic mix {HTC,MMS,GOOSE}	{10%, 55%, 35%}
GOOSE interarrival time[5] T_0, T_1, $T_N, N \geq 2$	0.5s, 1ms, 2^{N-1}ms

[5] Standard values available in [2], [6], [12].

Two performance indicators have been used to assess the 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*) blocking probability, defined as the probability that a device reaches the maximum number of transmission attempts and is still unable to complete the access process. All results have been obtained through simulations with ns-3 discrete-event simulator. The RADA mechanism extends the standardized RACH implementation initially developed in [3]. GOOSE and MMS traffic modules have been implemented according to IEC 61850-8-1 specification and their integration with LTE radio protocol stack has been performed as in [13]. The existing LTE LENA modules [5] have been properly modified/extended when necessary.

A. Optimal operation parameters for RADA mechanism

As discussed in Section IV, the RADA mechanism relies on a dynamic integration of three individual schemes; hence, we first need to determine the parameter values, i.e., preamble partition and MMS access barring factor, that result in an optimal overall system performance, in cases of traffic overload. To this end, Figure 4 illustrates the average access delay experienced per IED and HTC device for different preamble partition subsets {HTC,MMS,GOOSE} in the RADA mechanism when the number of simultaneous access attempts is high. The delay for both traffic types increases with increasing traffic load due to the heavier contention. As expected, by allocating more preambles -originally oriented for HTC- to GOOSE traffic, the access delay for GOOSE messages decreases, whereas the HTC access delay increases due to the lack of adequate access opportunities. The optimal preamble partition $\{13, 25, 16\}$

[4] The spatial difference in the deployment of neighboring IEDs ensures that preambles are not constructively received by the eNodeB [3].

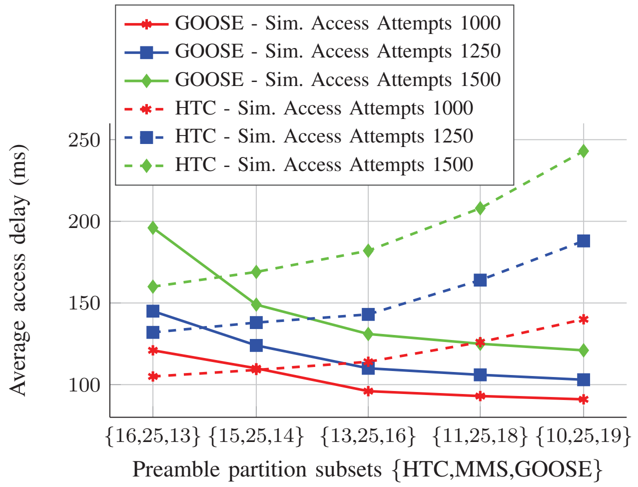

Fig. 4. Average access delay per IED (GOOSE traffic) and HTC device for different preamble partition subsets of RADA mechanism in traffic overload.

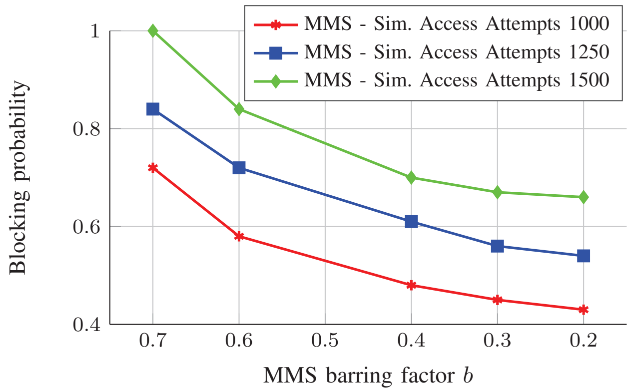

Fig. 5. Blocking probability per MMS metering device for different access barring factors of RADA mechanism in traffic overload.

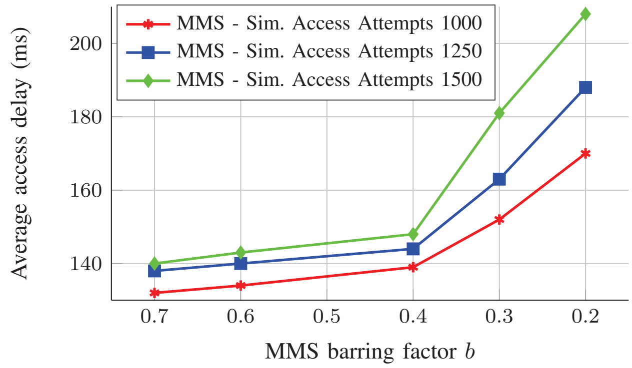

Fig. 6. Average access delay per MMS metering device for different access barring factors of RADA mechanism in traffic overload.

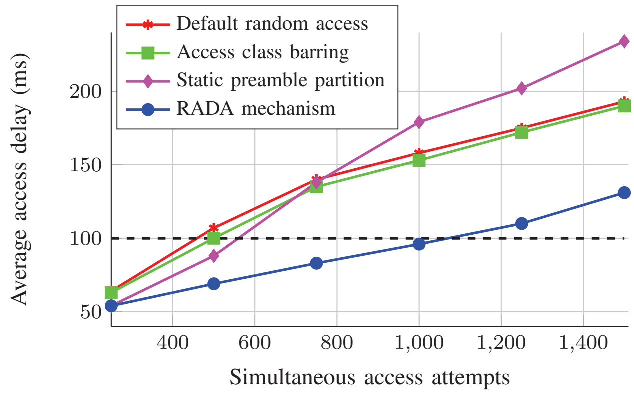

Fig. 7. Average access delay per IED (GOOSE traffic) for different random access mechanisms with increasing traffic load.

occurs before HTC performance starts to significantly degrade while GOOSE access delay tends to a common value.

To identify the optimal MMS barring factor for RADA, the blocking probability experienced per MMS metering device is evaluated for different access barring factors in traffic overload in Figure 5. In particular, the blocking probability decreases with decreasing access barring factor; when the barring factor is set to a more restrictive value, it is more likely that new MMS access requests are spread in time-subsequent attempts due to the backoff indicator. Although decreasing the barring factor may ease the congestion and improve access success probability, the average access delay for MMS traffic is increased, especially for high number of access attempts as depicted in Figure 6. Based on this tradeoff, the optimal barring factor value $b = 0.4$ is determined for MMS devices.

B. Comparison with other schemes

After identifying the optimal parameter values for the RADA mechanism in cases of traffic overload, its performance is compared with existing 3GPP RACH solutions for benchmarking purposes [6], [7], [9]. In particular, we perform a comparative study among the following:

1) Default random access scheme based on 3GPP standard, with no special handling for traffic types,
2) Access class barring scheme, with barring factor $b = 0.4$ applied to MMS traffic,
3) Static preamble partition $\{13, 25, 16\}$ for HTC, MMS and GOOSE traffic respectively,
4) RADA mechanism.

Figure 7 illustrates the average access delay experienced per IED for different random access solutions with increasing traffic load. The RADA mechanism outperforms the existing RACH schemes, especially in heavy contention conditions where the average access delay for mission-critical GOOSE messages remains in lower levels. In particular, even in the case of 1000 simultaneous access attempts, GOOSE average delay remains below 100ms, the upper delay bound for Type-1B data exchange in decentralized DA protection applications [14]. This is mainly due to the load shedding scheme applied to preambles from neighboring IEDs, which remain in contention for less time. The superior performance of the RADA is also quantified in terms of blocking probability experienced per IED in Figure 8, where lower figures are attained compared to existing RACH configurations.

Naturally, the performance improvement for delay-critical GOOSE traffic causes some performance degradation to HTC traffic. Figure 9 illustrates the average access delay experienced per HTC device for the different random access

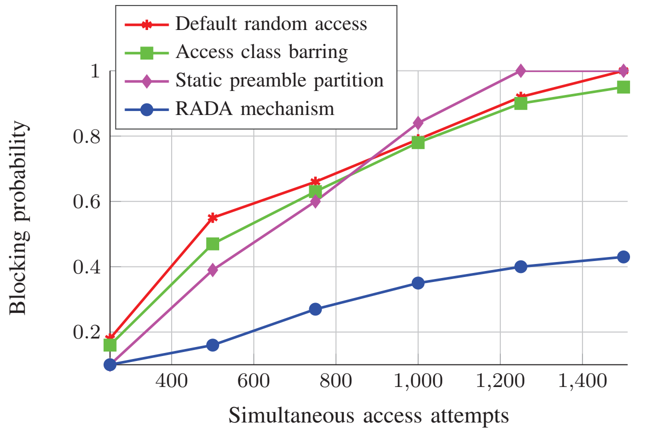

Fig. 8. Blocking probability per IED (GOOSE traffic) for different random access mechanisms with increasing traffic load.

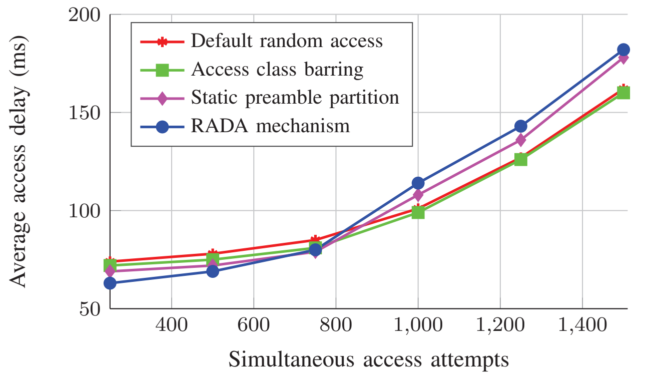

Fig. 9. Average access delay per HTC device for different random access mechanisms with increasing traffic load.

solutions with increasing traffic load. A slight increase in the experienced HTC access delay is observed for the RADA mechanism. However, HTC average delay remains less than 200ms in heavy contention conditions; hence it might not be noticeable by end users even for some real-time LTE services.

Figure 10 depicts the blocking probability experienced per MMS metering device for different random access solutions. Due to the dedicated preambles and the dynamic adaptation of the access barring factor in RADA mechanism, the blocking probability for MMS access requests remains in lower levels compared to other schemes, even in high traffic load.

VI. Conclusion

The support of advanced monitoring, protection and control operations in the distribution grid requires radical enhancements in the standard LTE RACH procedure to avoid performance degradation due to a high probability of collision in the preamble transmission. The limited random access opportunities compared to the increased resource demand render the standard access mechanism and its potential improvements highly susceptible to congestion for the support of DA services in shared LTE networks. In this paper, we proposed a novel LTE random access mechanism, named RADA, to resolve the contention and efficiently support mission-critical DA services with minimum impact on background traffic. Our

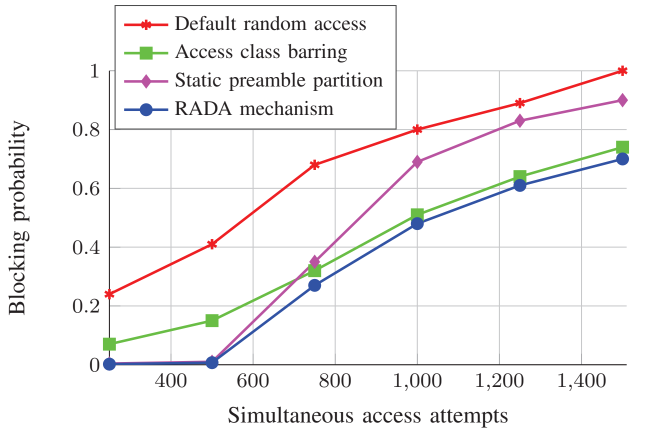

Fig. 10. Blocking probability per MMS metering device for different random access mechanisms with increasing traffic load.

extensive simulations in a system-level simulator demonstrate the superiority of RADA in terms of access delay and blocking probability compared to the existing 3GPP RACH solutions.

Acknowledgment

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References

[1] C. Kalalas, L. Thrybom, and J. Alonso-Zarate, "Cellular Communications for Smart Grid Neighborhood Area Networks: A Survey," *IEEE Access*, vol. 4, no. 1, pp. 1469–1493, Apr. 2016.
[2] 3GPP TS 36.211 V10.4.0, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation," Dec. 2011.
[3] A. Laya, L. Alonso, and J. Alonso-Zarate, "Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 4–16, Feb. 2014.
[4] IEC, "IEC 61850 Part 5: Communication requirements for functions and device models," Jan. 2013.
[5] The ns-3 network simulator. [Online]. Available: http://www.nsnam.org/
[6] 3GPP TR 37.868 v11.0.0, "Study on RAN improvements for Machine-Type Communications," Sep. 2011.
[7] K. D. Lee, S. Kim, and B. Yi, "Throughput comparison of random access methods for M2M service over LTE networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2011, pp. 373–377.
[8] J. P. Cheng, C. h. Lee, and T. M. Lin, "Prioritized Random Access with dynamic access barring for RAN overload in 3GPP LTE-A networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2011, pp. 368–372.
[9] 3GPP TS 36.331 V10.5.0, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC)," Mar. 2012.
[10] C.-H. Wei, R.-G. Cheng, and F. Al-Taee, "Dynamic radio resource allocation for group paging supporting smart meter communications," in *Proc. IEEE 3rd Int. Conf. Smart Grid Commun. (SmartGridComm)*, Nov. 2012, pp. 659–663.
[11] G. C. Madueño, N. K. Pratas, Č. Stefanović, and P. Popovski, "Massive M2M access with reliability guarantees in LTE systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 2997–3002.
[12] IEC, "IEC 61850 Part 8-1: Specific Communication Service Mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3," Jun. 2011.
[13] C. Kalalas, L. Gkatzikis, C. Fischione, P. Ljungberg, and J. Alonso-Zarate, "Enabling IEC 61850 Communication Services over Public LTE Infrastructure," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.
[14] IEC, "IEC 61850 Part 90-12: Wide area network engineering guidelines," Technical Report, Jul. 2015.