On the Impact of LTE RACH Reliability on State Estimation in Wide-Area Monitoring Systems

Achilleas Tsitsimelis, Charalampos Kalalas, Jesus Alonso-Zarate, Carles Antón-Haro
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), Barcelona, Spain
E-mails: {achilleas.tsitsimelis, ckalalas, jesus.alonso, carles.anton}@cttc.es

***Abstract*—The realization of advanced electrical grid functionalities, e.g., phasor measurement unit (PMU) information acquisition in wide-area monitoring systems (WAMS), requires a scalable and reliable underlying communication technology. Cellular networks, e.g., LTE/LTE-A systems, appear as a promising option to facilitate the smart grid evolution. However, the effect of LTE communication constraints on power system state estimation (SE) has not been thoroughly addressed in the literature. In this paper, we investigate the impact of the LTE random access channel (RACH) reliability on the transmitted PMU measurements and, consequently, on the SE accuracy. In particular, we assess the SE performance based on the achieved reliability per PMU attained with *i*) increasing number of contending devices, i.e., smart meters and PMUs, and *ii*) varying cell coverage range. Numerical results demonstrate that, under different network and traffic configurations, SE accuracy can be significantly affected by the RACH reliability levels. Useful insights can thus be drawn for a reliability-aware design of a power system state estimator in LTE-based WAMS.**

***Index Terms*—LTE, phasor measurement units, power system state estimation, random access channel, reliability, WAMS.**

I. Introduction

The ongoing modernization of the electrical grid into a smart grid, e.g., through the introduction of distributed energy sources, results in a growing need for real-time monitoring and quasi-real-time analysis of the grid behavior. In this context, State Estimation (SE), i.e., the determination of the system state variables (voltage magnitude and angles) at all the buses of the electrical network from a set of remotely-acquired measurements, becomes a cornerstone for the monitoring of the electrical grids [1]. The increasing use of Phasor Measurement Units (PMUs), capable to provide synchronized measurements, is expected to enhance the SE accuracy and improve the situational awareness of the power system. However, in order to exploit the PMUs as inputs for an efficient SE solution, a robust communication technology is required to support reliable PMU data exchange in future Wide-Area Monitoring Systems (WAMS).

Among various communication technologies, cellular networks, e.g., LTE/LTE-A systems, appear as a promising solution to enhance the observability and controllability of WAMS, mainly due to the extensive coverage and low latency characteristics. However, cellular technology was not initially designed to handle efficiently the near-simultaneous access of numerous grid devices. As the WAMS extend over large geographical areas, a shared LTE network needs to accommodate the channel access attempts originated from a large number of measurement devices ranging from PMUs to massive-scale smart meter infrastructure. In particular, the LTE Random Access CHannel (RACH) procedure, where devices perform initial network association by randomly selecting one of the available preambles to transmit over the random access slots, suffers from congestion when the number of access requests increases. The concurrent transmission attempts of a large number of devices results in a high probability of collision in the transmission of the preambles. Besides the scalability problem, as the radius of an LTE cell increases, the number of orthogonal preambles available for contention in RACH decreases; this relation imposes an additional challenge for the reliable PMU data exchange in WAMS since the non-orthogonality between preambles generated from different root sequences results in decoding failures at the base station [2].

In this paper, we focus on the reliable PMU information exchange in WAMS when LTE is applied as the underlying communication technology. Unlike the majority of existing literature where communication constraints are either absent [3], [4] or limitedly considered [5] in power system functionalities, here we present a numerical study on the impact of communication reliability deficiencies on SE quality. In particular, we evaluate the effect of the achieved LTE RACH reliability levels per PMU on the accuracy of the SE algorithm under different traffic and network configurations. To this end, we consider two representative scenarios, namely *i*) a shared LTE network, where PMUs contend for the shared random access resources along with a high number of smart metering devices, and *ii*) a dedicated LTE network, where the selected range of an LTE cell that provides coverage solely to PMUs, determines the availability of the orthogonal random access preambles. In both cases, we demonstrate that the SE accuracy performance critically depends on the achieved RACH reliability levels for PMU communication. Therefore, useful design insights can be drawn for SE schemes when the problem of estimation is coupled with the reliability challenges in information acquisition.

Organization: The rest of the paper is organized as follows. Section II provides an overview of the power system state estimation model. In Section III, the access mechanism in LTE-based systems is presented along with the analytical expression of the achieved reliability. A performance assessment of the SE accuracy based on the reliability attained in various network and traffic LTE configurations is presented in Section IV. Finally, Section V concludes the paper.

II. STATE ESTIMATION SYSTEM MODEL

Consider a power system which spans over a specific geographical area. This electrical network is supervised by a control center which has the responsibility and the ability to perform control and protection actions based on the monitoring of the network. The latter hinges on the reliable data acquisition from remote points that are assumed to record the system footprint at a specific time instant.

Mathematically, the power system is composed of N buses represented by the graph $\mathcal{G} = (\mathcal{V}, \mathcal{B})$, where $\mathcal{V}$ denotes the set of buses with cardinality $|\mathcal{V}| = N$; and $\mathcal{B}$ stands for the set of edges that describes their interconnections (branches), with cardinality $|\mathcal{B}|$. The complex current injections at the buses, i.e., $\mathbf{i} = [I_1, \ldots, I_N]^T$, satisfy $\mathbf{i} = \mathbf{Y}\mathbf{v}$, where $\mathbf{Y} \in \mathbb{C}^{N \times N}$ is the nodal admittance matrix [3] and $\mathbf{v} = [V_1, V_2, ..V_N]^T \in \mathbb{C}^N$ stands for the complex voltages of measurements at selected buses and branches. Power system state estimation aims to determine the complex voltages in all the buses of the system from a number of measured variables in selected buses and branches, as illustrated in Fig. 1.

Defining the Cartesian representation of the system state, $\mathbf{x} = [\Re\{V_1\}, \Im\{V_1\}, \ldots, \Re\{V_N\}, \Im\{V_N\}]^T \in \mathbb{R}^{2N}$, the measurement model can be defined as:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{e}\,, \tag{1}$$

where $\mathbf{z} \in \mathbb{R}^M$ stands for the corresponding measurement vector, $\mathbf{h}(\mathbf{x})$ denotes a non-linear function of $\mathbf{z}$ on $\mathbf{x}$ in compliance with the AC power flow model and $\mathbf{e} \in \mathbb{R}^M$ stands for zero-mean Gaussian noise with known covariance matrix $\mathbf{R_e}$. It is worth noting that, typically, we have $M >> 2N$. According to Eq. (1), the conventional state estimator is given by the solution to the following non-convex optimization problem:

$$\hat{\mathbf{x}} = \arg\min_{\{\mathbf{x}\}} \ \|\mathbf{z} - \mathbf{h}(\mathbf{x})\|_2^2 \,. \tag{2}$$

Traditionally, problem (2) is solved via gradient-based schemes [6]. Other efficient solutions based on convex relaxations [7], [8] and graphical models have been also proposed during the latest years [9].

As discussed before, a crucial element in order to improve the monitoring quality of the system is the phasor technology. The deployment of the PMUs, providing linear measurement functions, can significantly improve the accuracy of the SE via precise and synchronized measurements. In this case, the following linear model holds:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}\,, \tag{3}$$

and, hence, SE becomes a convex (least-squares) optimization problem:

$$\hat{\mathbf{x}} = \arg\min_{\{\mathbf{x}\}} \ \|\mathbf{z} - \mathbf{H}\mathbf{x}\|_2^2 \,, \tag{4}$$

where $\mathbf{H} \in \mathbb{R}^{M \times 2N}$ stands for the corresponding measurement matrix, and $\mathbf{w}$ denotes zero-mean Gaussian noise with known covariance matrix $\mathbf{R_w}$. When $\mathbf{H}$ is full-rank, i.e., observability via PMUs is achieved [6], the least-squares problem has the unique solution $\hat{\mathbf{x}} = (\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{z}$.

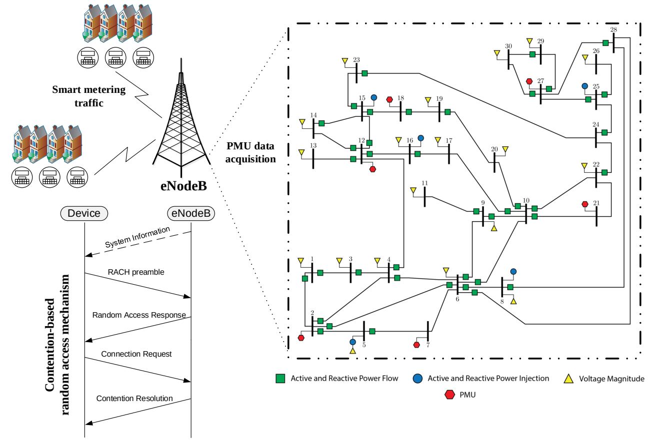

Fig. 1. The IEEE 30 bus test case including possible measurement devices in specific buses and branches (adapted from [1]). Cellular communication via the installation of LTE base stations is provided where the PMUs may contend for the shared random access resources with smart metering devices.

However, problem (4) refers to the idealistic case where $\mathbf{z}$ includes a full measurement set corrupted only with i.i.d. Gaussian noise with low standard deviation. In a more realistic scenario, the efficient and timely data transmission relies on the reliability of the respective communication technology that each power utility leverages. Hence, in what follows, we incorporate the imperfect PMU data exchange in LTE-based systems as a consideration for the accuracy of the transmitted measurements.

III. ACCESS MECHANISM IN LTE-BASED SYSTEMS

In this section, the random access procedure in LTE networks is described, followed by the analytical expression of the achieved reliability as a function of the PMU traffic characteristics and the network parameters.

A. Overview of the LTE random access procedure

As illustrated in Fig. 1, in the contention-based random access procedure, each device initiates a four-message handshake with the base station to request an allocation of a radio resource for data transmission or achieve uplink time synchronization. In this mechanism, a preamble signature is randomly chosen by each device and transmitted over a specific resource in the RACH. Since more than one devices may simultaneously transmit the same signature, a collision occurs[1] and a subsequent contention-resolution process is performed. The time-synchronized nature of PMU access attempts along with the massive presence of smart meters renders the LTE RACH mechanism highly susceptible to congestion, due to the scarce random-access resources (up to 64 preambles) compared to the increased demand. Therefore, the required reliability levels for accurate state estimation may be compromised.

[1]In this work, we assume no capture effect in the collided preambles.

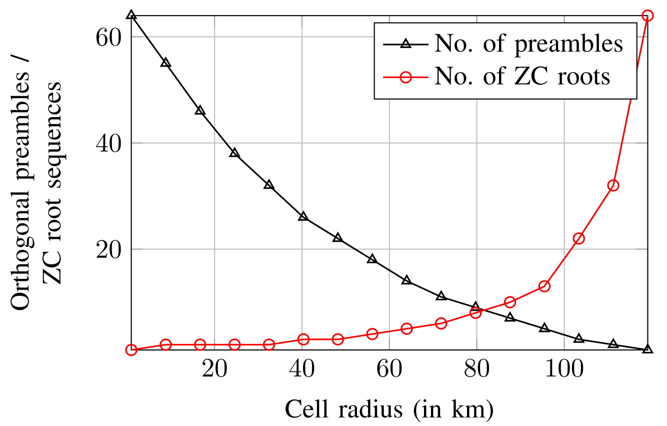

Fig. 2. Relation among the cell size, the availability of orthogonal preambles per ZC root sequence and the number of ZC root sequences required to generate 64 preambles in a single LTE cell [11].

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. The 3GPP has included the Access Class Barring (ACB) scheme to provide an additional control mechanism and prevent access failures [10]. In case of network overload, the base station broadcasts to the devices a set of parameters related to ACB, as part of the system information; this includes a barring rate factor and a barring timer for backoff. Each device then performs a Bernoulli trial to determine whether it is barred or not, based on the barring rate value.

According to the LTE preamble design principles, the random access signatures are generated by one or several Zadoff-Chu (ZC) root sequences and their cyclic shifts [12]. The ZC sequences satisfy a constant-amplitude zero-autocorrelation property, which implies that orthogonal preambles can be generated from the same ZC root by means of cyclic shifts. On the other hand, preambles obtained from cyclic shifts of different ZC sequences are not orthogonal and induce intra-cell interference in the preamble reception. Therefore, orthogonal sequences obtained by a single root sequence should be favoured over non-orthogonal sequences. However, additional ZC root sequences need to be used when the required number of preambles cannot be generated by cyclic shifts of a single root sequence.

The cyclic shift dimensioning is important for the design of the preamble sequence. Its value (lower bound) depends on the selected cell size [12]. In particular, the larger the cell radius, the larger the cyclic shift required to generate orthogonal preambles, and consequently, the smaller the number of orthogonal preambles constructed by a single ZC root. Thus, for large cells, a higher number of ZC root sequences is necessary to provide the 64 required preambles in LTE. This relation is illustrated in Fig. 2. Since the zero cross-correlation property of a root sequence only exists among cyclic shifts of the same root, using a single root for all preambles results in less intra-cell interference and better detection performance at the base station. Therefore, the RACH is more prone to congestion in cases related to widespread deployment of PMUs in an area covered by a single macro cell [2].

The discussion presented above reveals that *i*) the number of contending devices in an LTE cell and *ii*) the selected cell coverage affect the RACH preamble detection performance and, consequently, the reliability levels achieved in LTE-based WAMS. In the following, we present the analytical expression of the RACH reliability per PMU based on the preamble collision probability in a single LTE cell.

B. *Reliability expression*

In the contention-based random access procedure, the reliability is defined as the probability that a device successfully completes a channel access attempt before exceeding the maximum allowed preamble transmissions. In [13], we derive an analytical expression for the achieved reliability per cell based on a generalized Markov chain model of the LTE random access. The finite state space of the Markov chain includes the *idle* state where a device expects a packet arrival, the *random-access* states where preamble transmission occurs, the *backoff* states due to unsuccessful access attempt and the *success*/*fail* states. An ACB scheme with the corresponding *barring* states is further considered as an overload-control mechanism.

Let D be the number of contending devices in the LTE cell and L the maximum allowed preamble transmission attempts per device. Based on the analysis in [13], the reliability, R, can be expressed as

$$R = 1 - p_c^L, \tag{5}$$

where p_c denotes the preamble collision probability experienced by a contending device in the cell. For the calculation of R, we first need to determine the expression for p_c.

Let K be the number of available preambles for contention-based access. Given that a device selects one of the K_z preambles generated by the ZC root sequence z, $z = 1, \ldots, N_s$, the collision probability, p_c, is defined as the probability that at least one of the i contending devices (from the remaining D-1), selects the same preamble of the orthogonal K_z preambles or selects a non-orthogonal preamble generated by a ZC root sequence other than z. We assume that there is 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 base station (worst case). Then, p_c is given by the conditional probability in Eq. (6), where τ denotes the probability that a device attempts a channel access. By applying the normalization condition of the Markov chain in [13] and assuming that a preamble transmission holds for 1ms, the expression of τ is given in Eq. (7) as a function of the collision probability p_c, the traffic generation probability, p_{on}, and the random-access/barring parameters. Table I summarizes the definitions of the parameters included in Eqs. (6)–(7).

Note that p_c in Eq. (6) depends on both the number of contending devices in the cell and the number of orthogonal

$$p_c = \sum_{i=1}^{D-1} \binom{D-1}{i} \tau^i (1-\tau)^{D-1-i} \left[\frac{K_z}{K} \left(1 - \left(1 - \frac{1}{K_z} \right)^i \right) + \left(1 - \frac{K_z}{K} \right) \right]. \tag{6}$$

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

TABLE I
NOMENCLATURE FOR EQS. (6)–(7)

Notation	Definition
p_c	Preamble collision probability
τ	Access attempt probability
p_{on}	Traffic generation probability
q	Probability of barred access
D	Number of devices in the cell
K	Preambles for contention-based access
N_s	Number of required ZC root sequences
K_z	Orthogonal preambles from ZC root z
L	Maximum allowed preamble transmissions
B	Barring backoff window size
W	Random access backoff window size
W_{off}	Average holding time of the *idle* state
T_1	Average elapsed time from first access attempt until the end of contention-resolution timer
T_2	Average elapsed time from first access attempt until the reception of contention-resolution message
T_s	Average holding time of the *success* state
T_f	Average holding time of the *fail* state

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Preambles for contention-based access K	64
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
Barring rate factor	0.5
Preamble duration (in ms)	1
Max. allowed preamble transmission attempts L	10
Contention resolution timer (in ms)	24
Time durations T_1, T_2, T_s, T_f (in ms)	{32, 16, 20, 1}

preambles per ZC root sequence, which in turn depends on the selected cell size. The expressions of the preamble collision probability p_c in Eq. (6) and the probability τ of attempting a random access in Eq. (7) form a system of non-linear equations that can be solved via an iterative numerical method [11]. By plugging the obtained value of p_c in Eq. (5), the value of R can be calculated.

In the following section, we evaluate the impact of the achieved reliability levels per contending PMU on the accuracy of a SE algorithm in LTE-based WAMS.

IV. NUMERICAL RESULTS AND DISCUSSION

In order to study how RACH reliability affects the SE performance in LTE-based WAMS, we consider realistic network scenarios where PMUs, equipped with LTE communication interfaces, reside within the coverage of a single LTE cell. The PMUs provide direct measurements of voltage and current phasors collected over multiple substation local area networks to provide situational awareness of the power system state. A simple periodic traffic model has been used to generate the time-synchronized RACH attempts of the PMUs. Table II summarizes the basic network parameters used in our simulations.

The SE performance has been assessed via computer simulations, solving the optimization problem in (4). We have considered both the IEEE 30 and 118 bus test cases where we have guaranteed system observability with PMUs according to the number and location of devices proposed in [14]. Using Monte Carlo approach, 500 random measurement sets have been generated and the values have been corrupted with additive white Gaussian noise of standard deviation $\sigma = 10^{-4}$. The SE accuracy is given in terms of normalized [2] error, i.e., $\|\hat{\mathbf{x}} - \mathbf{x}\|^2 / 2N$, where $\hat{\mathbf{x}}$ denotes the estimated power system state and $\mathbf{x}$ the actual one, averaged over realizations. For power flow simulations we have used Matpower [15].

In order to independently quantify the impact of the *i*) the number of contending devices in an LTE cell and *ii*) the selected cell coverage range on the achieved SE accuracy, we consider the following scenarios:

1) *Shared* LTE network, where a large number of smart metering devices generate background traffic within the coverage area of the base station and compete with the PMUs for the available RACH preambles. Such scenarios would arise in practice, if public LTE infrastructure was shared by smart metering deployments and grid monitoring equipment. Given a cell coverage range, we quantify the degradation of the achieved reliability and SE accuracy when an increasing number of smart meters is generating channel access requests.
2) *Dedicated* LTE network, where only PMU traffic is accommodated in the system. This scenario corresponds to the use case when a utility-dedicated communications infrastructure is deployed by the mobile network operator. In this case, our interest is focused on how the SE accuracy performance evolves for different cell

[2] Notice that the error is normalized to the number of elements in the state vector (and, hence, it does not depend on the number of buses in the electrical network).

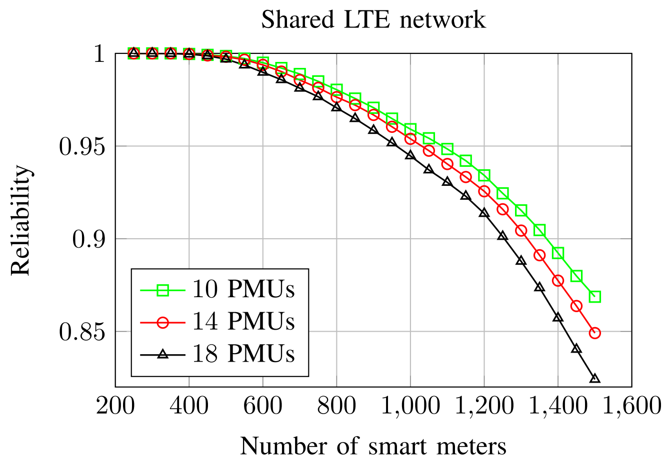

Fig. 3. Reliability experienced per PMU vs. number of smart meters generating background traffic.

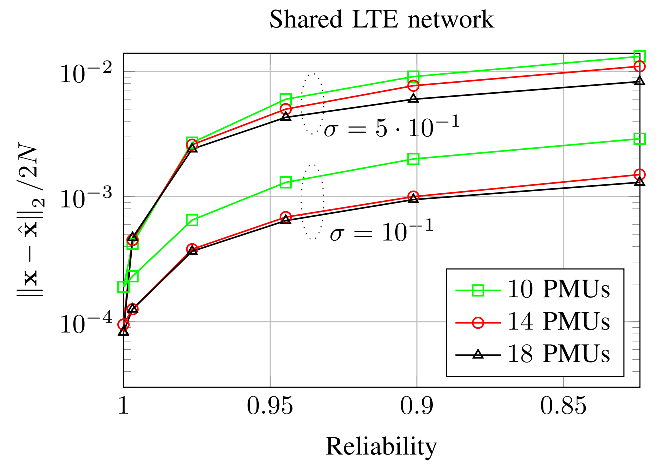

Fig. 4. Normalized error associated to the estimated state vector with respect to reliability achieved for varying smart metering traffic load.

coverage range. As discussed in Section III-A and shown in Eq. (5), the cell radius is related with the number of orthogonal preambles and, in turn, affects the achieved reliability per PMU.

In both scenarios, whenever a RACH attempt for a synchrophasor measurement fails, after exceeding the maximum number of retransmissions, it is replaced by a pseudo-measurement with higher standard deviation, i.e., $\sigma = 10^{-1}$ or $\sigma = 5 \cdot 10^{-1}$, in the measurement vector $\mathbf{z}$.

A. Shared LTE network

Fig. 3 illustrates the reliability per PMU with increasing number of smart meters coexisting as background traffic in the shared LTE network. In particular, starting from a medium-load scenario, new access requests from smart meters appear progressively in the system until it is driven to overload. The contention-based RACH performance is then evaluated in terms of reliability when the system operates close to its capacity limits. It can be observed that as the number of contending smart meters increases, the reliability experienced per PMU decreases due to the heavier contention in RACH. It is also noted that reliability performance further deteriorates when a higher number of PMUs is considered.

Based on the reliability levels attained with increasing smart metering traffic load and PMUs, we evaluate the error performance of the SE algorithm in Fig. 4. In particular, as the figure reveals, the lower PMU reliability figures achieved due to the increasing number of smart meters, leads the SE algorithm to performance degradation. However, it can be observed that the SE accuracy improves when a higher number of PMU devices is considered. Although increasing the PMUs leads to heavier contention and slightly-degraded reliability, as shown in Fig. 3, the benefits in SE accuracy are higher when the number of PMUs increases. Moreover, as expected, the choice of the standard deviation value, σ, for the pseudo-measurements has significant impact on the SE performance.

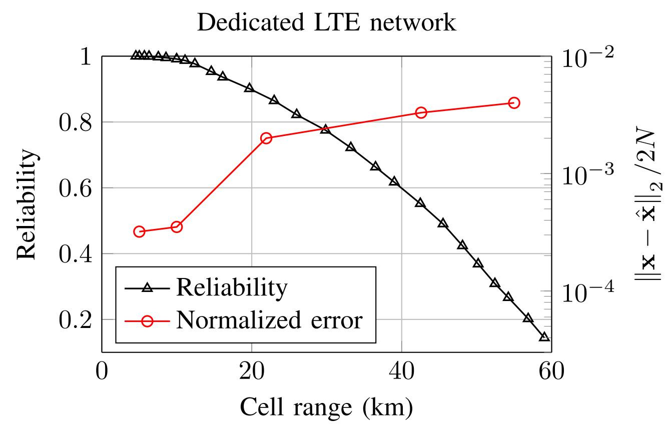

Fig. 5. Reliability experienced per PMU (y-axis on the left) and normalized error associated to the estimated state vector (y-axis on the right) vs. cell coverage range.

B. Dedicated LTE network

The reliability per PMU with increasing cell coverage range is illustrated in Fig. 5. As the cell radius increases, the number of available orthogonal preambles decreases and thus more ZC root sequences are required to generate the total number of 64 random-access preambles. In turn, this results in a degradation of the reliability performance due to the orthogonality loss for preambles generated from different roots. In addition, as shown in Table III, when the cell coverage increases, the minimum number of PMUs required to provide full observability of each power subsystem increases, resulting in a degradation of the achieved reliability since additional contending devices are requesting network access.

Based on the reliability levels achieved with increasing cell coverage range, we evaluate the error performance of the SE algorithm in Fig. 5. In particular, five different power systems have been considered for assessment where each cell coverage rage corresponds to a respective subsystem of the IEEE 118 bus test case. For instance, as illustrated in Table III, the

TABLE III
RELIABILITY AND SE PERFORMANCE ASSESSMENT FOR VARYING CELL COVERAGE RANGE

Subsystem of interest	No. of buses in subsystem	Cell range in km	Orthogonal preambles	PMUs	Reliability	Normalized Error
1	15	4.54	22	9	1	3.2×10^{-4}
2	41	9.98	11	24	0.9914	3.51×10^{-4}
3	72	22.99	5	30	0.8645	2×10^{-3}
4	98	45.51	3	39	0.4903	3.3×10^{-3}
5	118	59.03	2	48	0.1441	4×10^{-3}

first coverage range under concern corresponds to a 15-bus subsystem of the original network while the last one represents the whole system. Consequently, each case-subsystem includes a higher number of buses and accordingly PMUs. The red curve in Fig. 5 depicts that the estimation error increases with increasing cell radius. In stark contrast with the previous scenario, the respective increased number of PMUs included in the larger coverage, does not improve the SE accuracy. As indicated in Fig. 5, the PMU reliability severely degrades with the increasing cell radius, leading to a SE performance degradation that cannot be counterbalanced by the higher number of available synchronized measurements.

V. CONCLUSIONS

The utilization of PMUs in the monitoring, protection and control of power systems has become increasingly important in recent years. As such, the communication reliability for these critical measurements nodes becomes a significant issue. In this paper, the impact of the RACH reliability on the SE performance in LTE-based WAMS is investigated. Unlike existing literature where the reliability limitations imposed by the underlying communication technology are decoupled from the SE problem, we demonstrate how the number of contending devices and the cell coverage range critically affect the SE accuracy in LTE-based WAMS. The numerical evaluation of realistic network scenarios that involve acquisition of PMU information using LTE systems reveals that reliability constraints introduce significant SE accuracy limitations. The consideration of imperfect communication can thus provide useful insights for the design of reliability-aware state estimators for WAMS.

Future work aims to enhance the presented study by considering the optimal PMU placement problem under communication reliability constraints. In particular, we aim to determine the minimum number of PMUs along with their optimal locations while ensuring full observability of the power system as well as acceptable reliability levels due to the varying wireless channel conditions.

ACKNOWLEDGMENT

This work has been funded by projects ADVANTAGE under Grant 607774 and P2P-SmarTest under Grant 646469.

REFERENCES

[1] M. Cosovic, A. Tsitsimelis, D. Vukobratovic, J. Matamoros, and C. Anton-Haro, “5G Mobile Cellular Networks: Enabling Distributed State Estimation for Smart Grids,” *IEEE Commun. Mag.*, accepted for publication, Oct. 2017, Available: https://arxiv.org/pdf/1703.00178.pdf.

[2] A. Laya, L. Alonso, and J. Alonso-Zarate, “Efficient Contention Resolution in Highly Dense LTE Networks for Machine Type Communications,” in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1–7, Dec. 2015.

[3] V. Kekatos and G. B. Giannakis, “Distributed Robust Power System State Estimation,” *IEEE Trans. Power Syst.*, vol. 28, pp. 1617–1626, May 2013.

[4] M. Gl and A. Abur, “A Fast Decoupled State Estimator for Systems Measured by PMUs,” *IEEE Trans. Power Syst.*, vol. 30, pp. 2766–2771, Sep. 2015.

[5] J. Zhang, S. Nabavi, A. Chakrabortty, and Y. Xin, “ADMM Optimization Strategies for Wide-Area Oscillation Monitoring in Power Systems Under Asynchronous Communication Delays,” *IEEE Trans. Smart Grid*, vol. 7, pp. 2123–2133, Jul. 2016.

[6] A. Abur and A. G. Exposito, *Power System State Estimation: Theory and Implementations*. CRC Press, 2004.

[7] H. Zhu and G. B. Giannakis, “Power System Nonlinear State Estimation Using Distributed Semidefinite Programming,” *IEEE J. Sel. Topics Signal Process*, vol. 8, pp. 1039–1050, Dec. 2014.

[8] J. Matamoros, A. Tsitsimelis, M. Gregori, and C. Antón-Haro, “Multi-area state estimation with legacy and synchronized measurements,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, pp. 1–6, May 2016.

[9] M. Cosovic and D. Vukobratovic, “Distributed state estimation in power system using belief propagation: Algorithms and performance,” *CoRR*, vol. abs/1702.05781, 2017.

[10] 3GPP TR 37.868 v11.0.0, “Study on RAN improvements for Machine-Type Communications,” Sep. 2011.

[11] C. Kalalas and J. Alonso-Zarate, “Efficient Cell Planning for Reliable Support of Event-Driven Machine-Type Traffic in LTE,” in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1–7, Dec. 2017, Available: https://cloud.cttc.es/index.php/s/mX0AcW9uqov0AGQ.

[12] S. Sesia, I. Toufik, and M. Baker, *LTE: The UMTS Long Term Evolution from theory to practice*. John Wiley & Sons Ltd., 2009.

[13] C. Kalalas and J. Alonso-Zarate, “Reliability analysis of the random access channel of LTE with access class barring for smart grid monitoring traffic,” in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, pp. 724–730, May 2017.

[14] N. M. Manousakis and G. N. Korres, “A weighted least squares algorithm for optimal pmu placement,” *IEEE Trans. Power Syst.*, vol. 28, pp. 3499–3500, Aug 2013.

[15] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, “Matpower: Steady-state operations, planning, and analysis tools for power systems research and education,” *IEEE Trans. Power Syst.*, vol. 26, pp. 12–19, Feb 2011.