PRACH Power Control Mechanism for Improving Random-Access Energy Efficiency in Long Term Evolution

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***Abstract*—The Random Access (RA) procedure is one of the most frequently used and energy consuming operations in LTE User Equipment (UE) devices. However, little attention has been given to its energy-efficient operation in the literature. In this paper, we propose two Physical Random Access Channel (PRACH) power control mechanisms for improving the energy efficiency of the overall RA procedure. Our proposals increase the preamble transmit power based on special characteristics of the UE energy consumption behavior. By doing this, the number of transmitted preamble per successful RA procedure decreases, thus obtaining important energy savings. Our simulation results show that our proposals can reduce up to 41 percent the energy consumption of the RA procedure when compared to the standardized PRACH power control mechanism with power ramping.**

***Keywords*—LTE/LTE-A networks, random-access procedure, PRACH power control and power ramping.**

I. Introduction

The energy awareness of wireless communications technologies has become a central aspect of their design, especially for battery-driven devices such as smartphones. The growth in the device data rates as well as its overall complexity is remarkably faster than the advancements in the battery capacities [1], leading the battery lifetime to be one of the main bottlenecks for the spread of heavily data demanding applications. Although while convening the Long Term Evolution (LTE), the Third Generation Partnership Project (3GPP) focused on dealing with these high data rate demands, less attention was given to the energy drawbacks of the complexity added in the device.

From the LTE User Equipment (UE) perspective, the Random Access (RA) procedure is one of the most energy consuming operations. This procedure is used to establish initial network connection, provide uplink synchronization, perform handover and request uplink resources. The RA is a multistep procedure whose initial step is the transmission of a *preamble sequence* on the Physical Random Access Channel (PRACH). A power control mechanism is used to adapt the preamble transmit power to the variable conditions of the radio propagation channel, which is subject to pathloss, shadowing, multipath and interference, etc. Nonetheless, the widely used 3GPP model for the preamble transmission success probability shows that the first preamble transmission success rate can be as low as 63 % [2]. When a RA attempt fails, the PRACH power control includes a power ramping technique, which increases the transmit power up to 6 dB for every new preamble transmission attempt, thus increasing the preamble detection probability. This technique was designed to compensate for uncertainties in the signal quality caused by sudden spatiotemporal changes in the environment and the non-reciprocity between the uplink and downlink channels in Frequency Division Duplexing (FDD) systems. However, multiple transmissions of the preamble increases the duration of the RA procedure.

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There is a limited literature studying the energy aspect of the RA procedure [3][4], mainly focusing on Machine-to-Machine (M2M) communications in which preamble collisions are the main driver of its energy consumption. Laya *et al.* [3] study the energy consumption of the RA procedure under massive M2M communications scenarios. They show that a massive number of M2M devices trying to access the network can negatively impact the device energy efficiency.

The work in [4] studied the effect of the use of the power ramping in contention-based RA procedure over an M2M scenario. In this scenario, most RA failures are not caused by enough transmission power but by preamble collisions. Since the naive traditional power ramping has no way to gauge the reason of the failure, it may increases the transmit power unnecessarily, thus increasing the UE energy consumption of the preamble transmission. Authors then address this problem by proposing a mechanism that triggers the power ramping based on the probability of preamble transmission failure, modeled as being inversely proportional to the Received Signal Strength Indicator (RSSI). Thus, the proposed mechanism triggers the power ramping less frequently, reducing the overall energy footprint of the RA procedure.

In [5], authors explore the efficiency of the RA procedure over highly loaded M2M scenarios, taken into consideration Packet Downlink Control Channel (PDCCH) constraints. They show that power ramping is beneficial to the probability of RA success for networks under low and medium traffic loads and that a high number of preamble retransmission may lead to more frequent RA collisions.

The manipulation of the PRACH transmit power level is explored in [6] to differentiate transmission from two different devices classes (i.e., Human-to-Human (H2H) and M2M devices) during the RA procedure. Since the preamble power threshold for H2H devices is higher, it is possible to prioritize them, with the counterpart of demanding a higher transmit power from H2H devices. However, none of the above-reviewed studies addresses the PRACH power control and its impact on the energy efficiency of the RA procedure.

In this paper, we propose a PRACH power control mechanism for energy-efficient RA procedure execution based on UE power consumption modeling. Our proposal focuses on increasing the effectiveness of preamble transmission through a more aggressive power allocation, while counterbalancing it with the awareness of the energy expenditure. In this way, the proposed mechanism reduces the number of unsuccessful preamble transmissions and the total UE energy consumption.

The rest of the paper is organized as follows. Section II briefly introduces the standardized RA procedure and PRACH power control mechanism with power ramping. Section III presents the proposed mechanism for making preamble transmission power decisions. Section IV assesses the performance of the proposed solution via extensive simulations and discusses the results. Finally, Section V concludes the paper.

II. LTE Background

This section introduces some concepts in LTE to the understanding of the proposal presented in this paper.

A. The LTE random-access procedure

The LTE has two operation modes available for the RA procedure: *contention-free* mode, which is used for downlink synchronization and handover; and *contention-based* mode, which is used when the UE establishes network connection, requests uplink resources or losses uplink synchronization. In both modes, the UE sends a preamble (MSG_1) to the evolved NodeB (eNB). Particularly, in the contention-based mode, this preamble is randomly chosen by the device from a set of valid preambles periodically updated by the eNB. If the preamble sequence is correctly detected by the eNB, it answers with a Random Access Response (RAR), also known as MSG_2, on the Physical Downlink Shared Channel (PDSCH) containing the timing advance command, the temporary Cell Radio Network Temporary Identifier (C-RNTI) and an uplink grant for the next step. The eNB informs where the MSG_2 is located in the PDSCH through a control message on the PDCCH addressed to the RA-RNTI. The PDCCH is monitored by the UE since the preamble is sent until MSG_2 is received or MSG_2 timer expires. In case of failure, a new RA attempt can be performed after a backoff period for a given maximum number of times.

The correct reception of the MSG_2 by the UE allows the device to send the MSG_3 on the Packet Uplink Shared Channel (PUSCH) based on the grant provided in MSG_2. The MSG_3 contains information associated to the purpose of the RA procedure triggering (e.g., the UE identity, connection request). Once the MSG_3 is correctly received by the eNB, it answers with the MSG_4, concluding the contention-based RA procedure. Note that, as the preamble does not carry any UE-related information and its detection is based on a power threshold, if more than one UE choose the same preamble in a given RA opportunity, the preamble transmission may still be detected. Nonetheless, as the procedure continues, the MSG_3 may collide (since the MSG_2 is received by more than one UE), affecting the correct reception of MSG_3. After a certain number of MSG_3 retransmissions the RA procedure restarts for all UEs involved in the collision.

B. The standardized PRACH power control mechanism

The Radio Resource Management (RRM) in wireless communication systems is challenging due to the various phenomena that can affect the quality of the transmitted signal, including (*i*) *pathloss*, which is the attenuation in signal strength due to the propagation distance through the wireless medium (*ii*) *slow fading*, which is the signal strength fluctuation due to object obstruction (also known as *shadowing*); (*iii*) *fast fading*, which is the signal strength fluctuation originated by multipath propagation of the signal (both destructive and constructive wave interference); and (*iv*) *co-channel interference*, which is the degradation of the channel quality due to modification or disruption of the intended signal caused by the interaction with other users due to reuse of the spectrum forced by its scarcity and high cost.

The uplink transmit power control in such systems is a key RRM function to face the above-mentioned impairments by providing sufficient link quality to a transmission while minimizing the energy consumption of the battery-constrained wireless devices. Unlike transmission on data channels, for which LTE can apply open- and close-loop power control since the UE is in the Radio Resource Control (RRC) connected state, transmission on PRACH typically occurs when the connection is not yet established or the device is not known by the base station. Thus, an open-loop scheme is the only option available for PRACH power control. The PRACH transmit power (P_{PRACH}) for a given preamble transmission is defined in [7] and given by:

$$P_{PRACH} = min\{P_{UE}, P_{TARGET} + PL\}; \quad (1)$$

P_{UE} is the maximum UE transmit power, PL is the path-loss factor estimated by the device, and

$$P_{TARGET} = P_{INITIAL} + \Delta P_{TYPE} + (I - 1) \cdot S, \quad (2)$$

where $P_{INITIAL}$ is the expected power to be received at eNB, ΔP_{TYPE} is a constant associated with the preamble type defined for the cell, I is the index of this preamble transmission, and S is the power ramping step value [7].

The parameters used by the UE to perform the RA procedure, including the above-mentioned $P_{INITIAL}$ and S for PRACH power control, are sent by the eNB in the System Information Block 2 (SIB2) [8], while the PL is locally estimated by the UE calculating the difference between the Received Signal Reference Power (RSRP) and the eNB reference signal transmission power in the Downlink (DL) (value also included in the SIB2). This PL value, however, is not an estimation of the *pathloss* only, but a measure including all signal impairments, such as shadowing, multipath, and co-channel interference. Note that this estimation is made in an instant preceding the actual transmission and on the downlink channel. Thus, this estimation is prone to errors and one of the main reasons of PRACH failures under normal conditions.

III. PRACH Power Control Mechanism for Energy-Efficient Random-Access Procedure

This section describes the proposed GrEen Random Access (GERA) approach for performing preamble transmit power control. Our proposal opportunistically increases the preamble transmit power by exploring the UE power consumption model

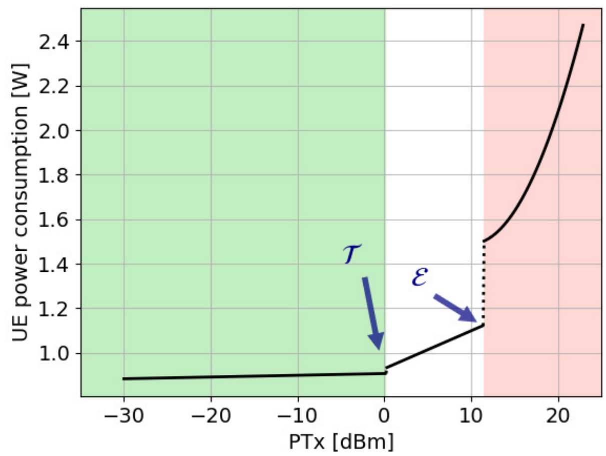


Figure 1. Lauridsen *et al.*'s model for UE power consumption as a function of PUSCH transmit power [9].

recently provided by Lauridsen *et al.* [9], which evinces the non-linearity between the transmit power and the energy consumption. This controlled gain of the preamble transmit power increases the success probability of the preamble reception at the eNB without an expensive counterpart in UE energy consumption, reducing the overall RA procedure duration and increasing its energy efficiency.

A. UE energy consumption models and the PRACH

As the energy efficiency of the network interface has become more and more relevant, more accurate UE energy consumption models have been developed. Even though every device model of each manufacturer may have a particular energy consumption signature, the overall shape of the curves tends to be similar. The first LTE UE power consumption model available in the literature was proposed by Nokia in 2007, during the standardization phase of the 3GPP release 8 [10]. This model specifies a fixed power consumption value for the reception state, and other communication interface states. This model was extended in [11] to include the transmission state as well. Lauridsen *et al.* [9] propose a more accurate empirical model that takes into consideration both the uplink and the downlink power levels and data rates, as well as the idle and connected Discontinuous Reception (DRX) modes. Moreover, in respect to DRX, Lauridsen *et al.* have shown that for a 1 ms ON period, the device stays with the interface activated, on average, more than 30 ms due to hardware limitations and protocol procedures (such as synchronization) required every ON period in the LTE interface. This model evinces that short sleep periods during multistep procedures in LTE (e.g., the Random Access), are still not viable.

Power consumption models for transmissions on the PUSCH considers the transmit power as the main driver of the energy consumption [9]. Since there is no model including the PRACH power consumption, we use the PUSCH model as an approximation for the PRACH. This is a reasonable assumption since the preamble is sent in the same frequency spectrum, uses similar modulation and coding scheme as the PUSCH [12], and employs common hardware (*e.g.*, power amplifier). Although this is a fair approximation for the preamble transmit energy consumption, the RA is a multistep procedure and during the interval between messages, particularly from preamble transmit to MSG_3 transmission and during the backoff period, the LTE interface cannot go to sleep and the energy consumption is high during the entire procedure. Therefore, targeting the duration of the RA procedure, shortening it by reducing the number of preamble retransmissions and, consequentially, shortening the length of the RA procedure can have a significant impact on the energy consumption.

B. The GrEen Random Access (GERA) PRACH power control

One of the major energy consuming components in a wireless communication interfaces is the power amplifier [9]. As the required transmission power surpasses a given limit, the power amplifier enters on the high gain mode, severely increasing the energy required to perform a transmission. Figure 1 shows the UE power consumption as a function of the transmit power based on the model described in [9]. It indicates that when transmit power surpasses $\mathcal{E} = 11.4\,\mathrm{dBm}$, the device enters in the *exponential region*, where the energy consumption is huge. The region between $\mathcal{T} = 0.2\,\mathrm{dBm}$ and $\mathcal{E}$ is labelled *linear region* and the region below $\mathcal{T}$ is designated *constant region*, where the derivative is nearly zero.

The traditional PRACH open-loop power control applied by the UE follows (1), leading to a P_{PRACH} value which is expected to compensate all power losses. This value can lie over any one of the three above-mentioned power consumption regions. Note that a overcompensation within the constant region (up to $\mathcal{T}$) results in an insignificant increasing in the energy consumption, hence this power escalation is straightforward. On the other hand, if P_{PRACH} lies over the linear region, the trade-off between a power escalation to $\mathcal{E}$ and energy saving is dubious. Thus, we propose two slightly different PRACH power control algorithms for RA energy efficiency based on the UE energy consumption modeling to better explore the previous mentioned tradeoff.

The first (GERA $\mathcal{E}$, in Algorithm 1) escalates the transmit power calculated by the open-loop power control directly to $\mathcal{E}$, if the standardized P_{PRACH} value lies over the constant or linear regions. The second (GERA $\mathcal{T}$-$\mathcal{E}$, in Algorithm 2) makes an intermediary step and escalates the transmission power to $\mathcal{T}$ if the standardized P_{PRACH} value lies over the constant region or to $\mathcal{E}$ if it lies over the linear region. In both algorithms, in the case of an unanswered preamble transmissions, the retransmission will occur with the same power as before if the standardized P_{PRACH} value lies over the same region since the power ramping is not substituted, but encapsulated in our proposal.

Different from other systems, the orthogonal characteristic of the LTE PRACH in relation to the uplink data channels and to the PRACH transmissions from other users in the cell allows

Algorithm 1 GERA $\mathcal{E}$

Input: $I, PL, \mathcal{E}$

$P_{TARGET} \leftarrow P_{INITIAL} + \Delta P_{TYPE} + S \cdot (I - 1)$

$P_{PRACH} \leftarrow min\{P_{UE_{MAX}}, P_{TARGET} + PL\}$

if $P_{PRACH} < \mathcal{E}$ **then**

  $P_{PRACH} \leftarrow \mathcal{E}$

return P_{PRACH}

Algorithm 2 GERA $\mathcal{T}$-$\mathcal{E}$

Input: $I, PL, \mathcal{T}, \mathcal{E}$
1: $P_{TARGET} \leftarrow P_{INITIAL} + \Delta P_{TYPE} + S \cdot (I - 1)$
2: $P_{PRACH} \leftarrow min\{P_{UE_{MAX}}, P_{TARGET} + PL\}$
3: **if** $P_{PRACH} < \mathcal{T}$ **then**
4: $\quad P_{PRACH} \leftarrow \mathcal{T}$
5: **else if** $P_{PRACH} < \mathcal{E}$ **then**
6: $\quad P_{PRACH} \leftarrow \mathcal{E}$
7: **return** P_{PRACH}

to increase the preamble transmit power without affecting other users' transmissions, for instance, by using the power ramping technique [13]. For single-cell scenarios and multi-cell scenarios using different root sequences, the low correlation among those root sequences also allows for increasing the PRACH transmit power without significantly affecting other users [13]. In the case of different PRACH configurations in neighboring cells, the difference in the transmission technique between the PRACH and PUSCH avoid high interference between the PRACH transmissions in a cell and the PUSCH transmission in its neighbouring cells. In addition, some inter-cell interference coordination techniques are also available to avoid interference from neighbouring cells or to reduce its effect [14].

IV. Performance Evaluation

In this section, we analyze the performance of the GERA proposal by using an extended version of the *LTE-Sim* simulator [15], [16]. Its performance is compared to that of the traditional PRACH power control mechanism standardized by the 3GPP. The following metrics are considered for the analysis: (*i*) average preamble transmit power and its distribution; (*ii*) average number of transmitted preambles per successful RA procedure; and (*iii*) average energy consumption per successful RA procedure. The Lauridsen *et al.*'s energy consumption model [9] was used and the energy consumption of the RA procedure was calculated as the total energy spent between the first preamble transmission and the end of the RA procedure (*i.e.*, the MSG_4 reception in case of success, or, in case of failure, when the maximum number of preamble retransmission is achieved). Figures presented in this section show mean values with confidence intervals corresponding to 95 % confidence level derived using the independent replication method.

A. Simulation Model and Setup

The simulation scenarios comprise a 5 MHz bandwidth cell served by an eNB in the Frequency Division Duplexing mode located at its center. Scenarios considers two different propagation models and different cell radius: Urban-Macrocell at 2.0 GHz with cell radius of 0.25 km, 0.5 km and 1 km and Rural-Macrocell at 900 MHz with cell radius of 1 km, 2 km and 1 km [17]. To focus only on the impact of the PRACH transmit power control on network performance, the scenarios were designed to have a reduced number of preamble collisions. Thus, 500 UEs are uniformly distributed around the cell considering either indoor or outdoor locations. Each UE triggers the RA procedure only once following a uniform distribution within 10 s, which is also the total simulation duration. It is assumed that all configuration parameters have already been received by the UEs at the beginning of the simulation.

TABLE I. Simulation Parameters

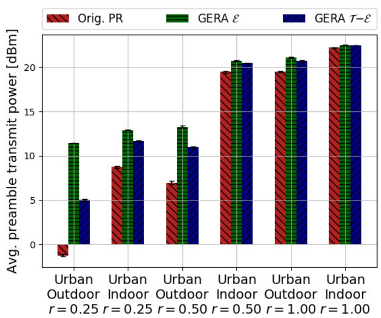
Parameter	Value
System type	Single cell
System bandwidth	5 MHz
Cell radius (urban)	250 m, 500 m, 1 km
Cell radius (rural)	1 km, 2 km, 4 km
PRACH configuration index	6
RA preamble format	0
Contention-based preambles	52
# of UL grants per RAR message	3
# of CCEs allocated for the PDCCH	16
# of CCEs per used per UEs	4
Backoff period	20 ms
preambleTransMax	10
RAR Window Size (W_{RAR})	5 ms
Contention Resolution Timer	48 ms
maxHARQ-MSG3Tx	5
P_{UE}	23 dBm
Preamble Received Target Power ($P_{initial}$)	-110 dBm
Power Ramping Step (S)	2 dBm
α	1.0

A preamble is detected by the eNB only when its received Signal-to-interference-plus-noise Ratio (SINR) is equal to or higher than the Preamble Received Target Power value (Table I) [17]. The detection of each preamble transmission at the eNB is performed after applying pathloss, shadowing and fast fading to the transmitted signal. Moreover, the interference from various preambles being received over the same channel is considered to be negligible as in [5].

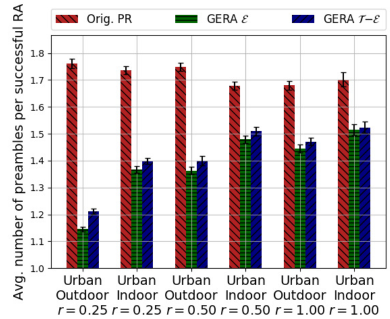
Although contention-free RA was not simulated, some preambles are reserved for this purpose, leaving 52 for the contention-based RA procedure. The contention resolution timer is set to 48 ms and the UE can retransmit the preamble 10 times at most. The main configuration parameters used in the simulations are summarized in Table I.

B. Simulation Results and Discussion

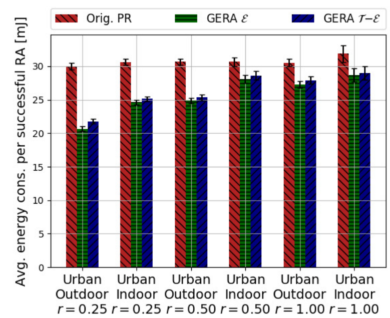
The GERA approach increases the average preamble transmit power (Fig. 2(a) and 3(a)) when compared to the traditional PRACH power control scheme with power ramping. While the Cumulative Distribution Function (CDF) of the preamble transmit power for the traditional power control scheme is a continuous function, the ones for the GERA approach are similar to a staircase function, with one step at $\mathcal{E}$, and one at $\mathcal{T}$ for the GERA $\mathcal{T}$-$\mathcal{E}$ algorithm, followed by a curve similar to the one of the traditional scheme beyond $\mathcal{E}$ (Fig. 4). This is a direct consequence of the transmit power escalation promoted by the proposed approach at $\mathcal{E}$ and $\mathcal{T}$. Also, note that our proposal does not modify preamble transmit power that surpasses $\mathcal{E}$ with the standardized mechanism. However, the portion of preambles transmitted with power level higher than $\mathcal{E}$ can slightly vary depending on the algorithm used (Fig. 4(a), 4(c) and 4(d)) because of the variation in the total number of preambles transmitted (Fig. 2(b) and 3(b)). Given the intermediate power level $\mathcal{T}$ used by the GERA $\mathcal{T}$-$\mathcal{E}$ algorithm, the average preamble transmit power given by that algorithm is slightly lower than that of the GERA $\mathcal{E}$ algorithm in all scenarios.



(a) Average transmit power per RA procedure

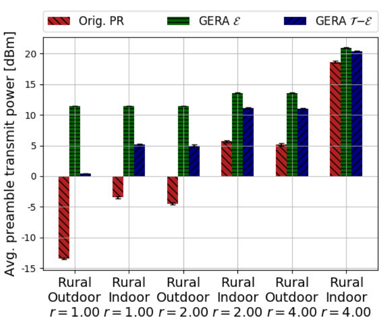


(b) Average number of preambles sent per successful RA procedure

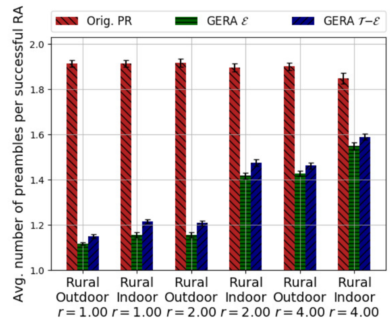


(c) Average energy consumption per successful RA procedure

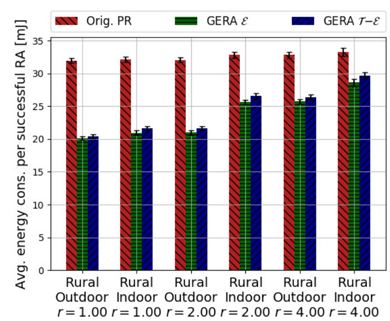
Figure 2. GERA performance evaluation for urban scenario



(a) Average transmit power per RA procedure

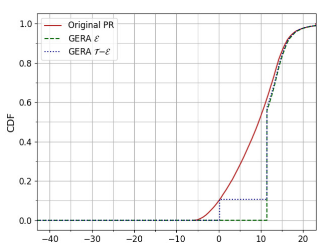


(b) Average number of preambles sent per successful RA procedure

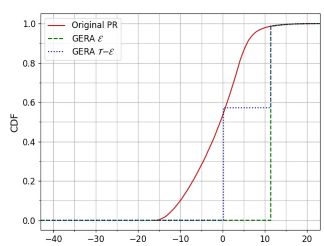


(c) Average energy consumption per successful RA procedure

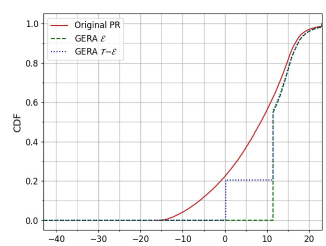
Figure 3. GERA performance evaluation for rural scenario



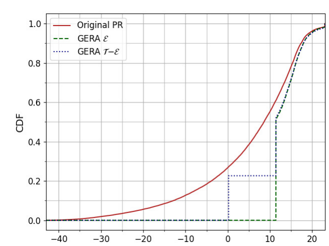
(a) 250m indoor urban scenario



(b) 250m outdoor urban scenario



(c) 500m outdoor urban scenario



(d) 4km outdoor rural scenario

Figure 4. Cumulative distribution function of the preamble transmit power for different scenarios

The comparison between Fig. 4(a) and 4(b) evinces the impact of the UE location (either indoor or outdoor). The indoor scenario cause a decreasing in the portion of preamble transmissions affected by our algorithms from 98 % to 58 % in relation to $\mathcal{E}$, and from 58 % to 11 % in relation to $\mathcal{T}$. Moreover, the start point of the traditional scheme curve for indoor scenario is 10 dBm higher than that for outdoor scenarios (Figures 4(b) and 4(c)). This is because the signal power degradation due to wall loss. Furthermore, the rural scenario (Fig. 4(d)) presents a start point 30 dBm lower than that of the urban scenarios as a consequence of the good channel conditions experience in those scenarios.

The increasing in preamble transmit power induced by the GERA approach yields lower average number of transmitted preambles per successful RA procedure when compared to the traditional PRACH power control scheme (Fig. 2(b) and 3(b)). This reduction is particularly accentuated for scenarios in which the difference between the average transmit power given by our proposed approach and the traditional scheme is substantial, namely cells with a short radius and UEs in outdoor environments. In these cases, the average number of preambles of our proposal when compared to the traditional scheme is reduced 31 % (GERA $\mathcal{T}$-$\mathcal{E}$) to 35 % (GERA $\mathcal{E}$) in urban scenarios and 40 % (GERA $\mathcal{T}$-$\mathcal{E}$) to 42 % (GERA $\mathcal{E}$) in rural scenarios. On the other hand, scenarios in which the preamble are frequently transmitted with high power, such as large urban cells and outdoor environments, can still take advantage of the GERA approach. In those scenarios, users with good to moderate channel quality are the ones that benefit from the power escalations but this gain is veiled by UEs operating near the maximum UE transmit power (e.g., UEs at the cell edge), which generally performs multiple preamble retransmissions.

The decreasing in the number of preamble transmitted produced by the proposed approach yields lower UE energy consumption for the whole RA procedure when compared to the traditional scheme in all scenarios (Fig. 2(c) and 3(c)), achieving up to 41 % of energy saving. With the traditional power control scheme, even though different mean preamble transmit powers are observed (Fig. 2(a) and 3(a)), the energy consumption per RA procedure is quite similar for different scenarios. This behaviour indicates that the preamble transmission itself is not the dominant part of the energy consumption during the RA procedure. The RA is a multistep procedure and the interface remains active almost during the entire RA procedure. Particularly, if a preamble is not detected, the interface needs to stay active from the preamble transmission until the end of the RAR window size, which can take up to 12 ms [18]. After that, a backoff period of 20 ms or less [18] is typically applied before trying a new preamble transmission, during which the interface is also not able to go to sleep as previously explained.

Therefore, the reduction in the number of transmitted preambles induced by or proposal allow the device to spend less energy during the RA procedure. At the same time, our efficient transmit power escalation makes its impact to be fully compensated by the consumption of the entire RA procedure because of the latency reduction. The GERA approach is able to reduce the energy consumption for all scenarios studied, showing that there is a strong correlation between the average number of preambles per successful RA and the energy consumption per successful RA ($r = 0.97$ with $p < 0.0001$). Although, the results show no statistic difference between GERA $\mathcal{E}$ and GERA $\mathcal{T}$-$\mathcal{E}$ algorithms related to the energy consumption, GERA $\mathcal{T}$-$\mathcal{E}$ has the advantage of having a lower impact on the SINR for users in other cells, since its average transmit power is smaller than that of the GERA $\mathcal{E}$ algorithm.

V. Conclusion

In this paper, we propose GERA, a new PRACH power control approach for reducing the energy consumption of the overall RA procedure in LTE UE devices. Our proposal opportunistically escalates the preamble transmit power in order to obtain energy savings. This increasing in transmit explores particular characteristics found in recent smartphone power consumption models. This power escalation increases the preamble detection probability, thus decreasing the number of preamble transmission per successful RA procedure and the overall RA procedure latency. Simulation results shows that the GERA approach reduces the energy consumption of the entire RA procedure up to 41 % when compared to the standardized PRACH power control with power ramping.

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