LTE FDD Physical Random Access Channel Dimensioning and Planning

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***Abstract*—A User Equipment (UE) can only be selected for uplink transmission if it is time-synchronized, so that the Physical Random Access Channel (PRACH) becomes a key factor between non-synchronized UEs and the orthogonal LTE uplink access scheme. An appropriate design is essential to provide frequent enough random access opportunities and an accurate UE synchronization estimation to adapt to different cell ranges and network conditions without using unnecessary resources, which would lead to a decrease in uplink capacity. However, all these requirements make a robust design be a very complex procedure. This paper proposes a novel algorithm for LTE FDD PRACH dimensioning and planning that accurately estimates the required resources and assigns them minimizing the probability of wrong preamble detection by means of an uncoupled optimization process that can be efficiently applied by operators on real networks.**

I. Introduction

A User Equipment (UE) can only be selected for uplink transmission if it is time-synchronized. The main role of the Random Access (RA) procedure is to request for uplink resources, and to do so it is necessary to assure such time alignment for a UE which either has not yet acquired, or has lost its uplink synchronization due to a new connection request, a connection recovery, a handover, a tracking area update, etc. Therefore, the Physical Random Access Channel (PRACH) becomes a key factor between non-synchronized UEs and the orthogonal LTE uplink access scheme.

An appropriate PRACH design means providing frequent enough RA opportunities and an accurate UE synchronization estimation. Besides, PRACH must adapt to different cell ranges and network conditions, such as traffic, propagation delay, and UE mobility, but without using unnecessary resources, which would lead to a decrease in uplink channel capacity. All these requirements make a robust PRACH design be a very complex procedure.

There is a wide range of references about PRACH in LTE [1] mainly focused on providing a detailed explanation of 3GPP specifications [2]. There is also a contribution about self-optimization of PRACH power-related parameters [3]. However, literature lacks of relevant studies on PRACH design [4] oriented to facilitate network optimization. This paper proposes a novel algorithm for LTE FDD PRACH dimensioning and planning that can be efficiently applied by operators on real networks. As Figure 1 shows, the process is divided into a dimensioning stage, where resources for PRACH transmission are estimated, and a planning stage, where time-frequency resources and preambles are assigned in three optimization steps to decrease computational costs but without losing flexibility.

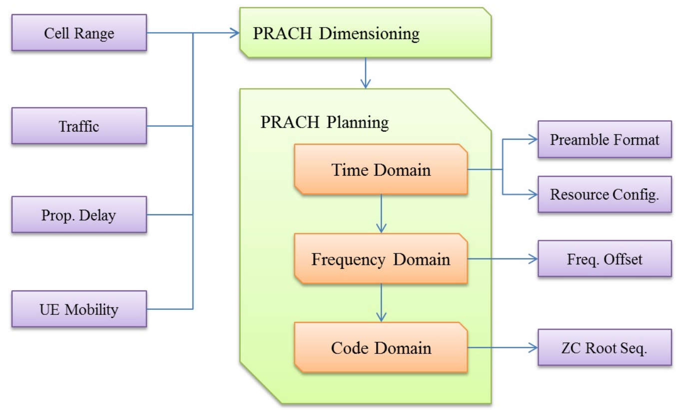

Fig. 1. PRACH design process, which is divided into two different stages: dimensioning and a planning.

The article is organized as follows: Section II briefly introduces PRACH specifications in LTE FDD. Section III provides a detailed description of PRACH dimensioning. Section IV explains the different stages of the PRACH planning algorithm. Section V states the field data assumptions and evaluates the performance of the proposed algorithm. Section VI summarizes the main conclusions from this study and gives some pointers regarding future work.

II. Physical Random Access Channel

PRACH [2] is transmitted over 6 consecutive Resource Blocks (RBs) during a variable number of sub-frames[1] to provide enough RA opportunities under different network conditions. If more than one UE tries to access to these time-frequency resources, collision is possible. In order to prevent so, there are 64 orthogonal preambles per cell, which allow up to 64 UEs to get simultaneously access. These preambles are split into (i) contention-free: used for critical situations such as handover, where there is a coordinated assignment of preambles so collision is avoided, and (ii) contention-based: the standard mode for network access, where preambles are selected in a random fashion so there is risk of collision.

[1]A sub-frame is transmitted during 1 ms.

Fig. 2. Structure of the different preamble formats.

A. Preamble Format

PRACH transmission is composed of a preamble sequence and a preceding cyclic prefix with four different formats, which determine the required number of sub-frames for PRACH. Multiple preamble formats are needed due to wide range of environments, as Figure 2 illustrates. For example, longer cyclic prefix allows higher delay tolerance due to multi-path or higher cell range. Configuration details are shown in Table I. So that collisions between sub-frames are avoided, there is a guard time T_G between the end of the PRACH transmission and the next sub-frame, which is calculated as:

$$T_G = T_{SP} - T_{CP} - T_{SEQ} \quad (1)$$

where T_{SP} is the PRACH period, T_{CP} is the cyclic prefix duration and T_{SEQ} is the preamble sequence duration.

B. Resource Configuration

In order to adapt to traffic conditions and provide enough RA opportunities without consuming unnecessary bandwidth, there are 16 resource configurations R_C for each preamble format. Table II shows, as an example, the set (and the number N_S) of sub-frames used for PRACH over two frames, i.e. 20 sub-frames, for preamble format 0. In case of other preamble formats, the table must be adapted considering that the PRACH period is longer than a sub-frame. Note that $R_C = [12, 13]$ are not valid if preamble format is 3, while $R_C = 14$ can be only used with preamble format 0.

C. Frequency Offset

As previously mentioned, PRACH transmission requires only 6 consecutive RBs, so if the carrier bandwidth is larger than 1.4 MHz different frequency allocation patterns may be available. These patterns are defined by the frequency offset, or index that determines the beginning of the PRACH allocation in frequency domain. In order to avoid partial overlapping, the number of frequency offsets N_{FO} is calculated as:

$$N_{FO} = int\left[\frac{N_{RB}}{6}\right] \quad (2)$$

where $int[X]$ refers to the integer part of X and N_{RB} is the number of RBs in the carrier. So each cell has a set of available frequency offsets F as below:

$$F = \{6 \cdot k\} \quad \forall k \in \{0, \ldots, N_{FO} - 1\} \quad (3)$$

TABLE I
PREAMBLE FORMAT

Format	$T_{SP}[ms]$	$T_{CP}[\mu s]$	$T_{SEQ}[\mu s]$	$T_G[\mu s]$
0	1	103.13	800	96.87
1	2	684.38	800	515.62
2	2	203.13	$2 \cdot 800$	196.87
3	3	684.38	$2 \cdot 800$	715.62

TABLE II
RESOURCE CONFIGURATION FOR PREAMBLE FORMAT 0

R_C	Sub-frames for PRACH Transmission	N_S
0	[1]	1
1	[4]	1
2	[7]	1
3	[1, 11]	2
4	[4, 14]	2
5	[7, 17]	2
6	[1, 6, 11, 16]	4
7	[2, 7, 12, 17]	4
8	[3, 8, 13, 18]	4
9	[1, 4, 7, 11, 14, 17]	6
10	[2, 5, 8, 12, 15, 18]	6
11	[3, 6, 9, 13, 16, 19]	6
12	[0, 2, 4, 6, 8, 10, 12, 14, 16, 18]	10
13	[1, 3, 5, 7, 9, 11, 13, 15, 17, 19]	10
14	[0 - 19]	20
15	[9]	1

D. Preamble Sequence

Zadoff-Chu (ZC) sequences are used to generate preambles due to their good correlation properties [2]. There are 838 ZC root sequences available for PRACH. Each of these roots can generate multiple preambles by shifting its ZC root sequence. The maximum shift, or Cyclic Shift (CS) offset, is related to the propagation delay, as described in Section III-C. A larger CS offset supports a larger delay but decreases the number of preambles that a root can generate. Considering that preambles obtained from shifting different ZC root sequences are not orthogonal, additional ZC root sequences should be used only when the required 64 preambles cannot be generated by shifting a single root. The number of required ZC root sequences N_R is calculated as below:

$$N_R = ceil\left[64 \cdot \frac{N_{CS}}{N_{ZC}}\right] \quad (4)$$

where $ceil[X]$ refers to the nearest integer greater than or equal to X, N_{CS} is the CS offset and N_{ZC} is the preamble length that equals 839. In order to adapt to different environments, there are 16 different CS offsets, as shown in Table III for normal-speed cells[2].

III. PRACH DIMENSIONING

Resources allocated for PRACH transmission must be dimensioned to assure an accurate synchronization with enough RA opportunities to have a reasonable probability of collision

[2]A similar analysis can be followed for high-speed cells [2].

TABLE III
CS CONFIGURATION FOR NORMAL-SPEED CELLS

CS Config.	N_{CS}	N_R
0	0	-
1	13	1
2	15	2
3	18	2
4	22	2
5	26	2
6	32	3
7	38	3
8	46	4
9	59	5
10	76	6
11	93	8
12	119	10
13	167	13
14	279	22
15	419	32

according to traffic conditions, cell range and UE mobility. However, a robust dimensioning must prevent from using unnecessary resources, which would not only lead to a decrease in uplink capacity, but would also increase the complexity of the planning process since there is lower flexibility for an optimal assignment.

A. Preamble Format

Preamble format must be chosen in accordance with the selected cyclic prefix so that it can neutralize multi-path and with a long enough guard time to deal with the maximum propagation delay, i.e. the round trip delay. Therefore, the time guard T_G must fulfill the next expression:

$$T_G \geq \frac{2 \cdot R}{v_c} \tag{5}$$

where R is the cell range and v_c is the speed of light that equals $3 \cdot 10^8\ m/s$. Figure 3 shows the preamble format selection flow-chart.

B. Resource Configuration

PRACH must be configured to adapt to different RA attempts intensities by dedicating more or less sub-frames. A collision between two or more UEs will occur when two or more UEs send the same preamble in the same sub-frame, so the probability of collision [5] depends on (i) the probability of arrival, which can be modeled as a Poisson distribution, and (ii) the probability of preamble collision, which can be computed as a classical combinational problem where each UE can select any preamble with equal probability. Therefore, the probability of collision P is written as below:

$$P(\varphi, \mu) = 1 - \left(\frac{\varphi + \mu}{\varphi}\right)^{\varphi} \cdot e^{-\mu} \tag{6}$$

where φ is the number of preambles dedicated to contention-based mode and μ is the arrival rate. This means that at least N_S number of sub-frames are required for PRACH

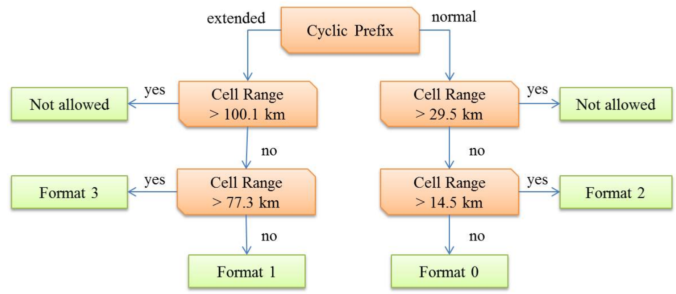

Fig. 3. Preamble format selection depending on cyclic prefix and cell range.

transmission every 20 ms, as shown below:

$$N_S \geq \frac{N_A}{50 \cdot \mu} \tag{7}$$

where μ is the arrival rate is calculated using eq. 6 for a certain probability of collision and number of preambles, 50 is the factor to move from 20 ms to a per-second window, and N_A is the number of attempts per second, which can be estimated as a function of the expected cell traffic in the cell, as below:

$$N_A = \frac{T}{\lambda} \cdot \rho \tag{8}$$

where T is the cell traffic (in Mbps), λ is the average data connection length (in Mb/connection) and ρ is the average number of attempts per data connection for a successful RA, including lost messages, handover, etc.

C. Cyclic Shift Offset

An eNodeB is able to distinguish the access from a UE, i.e. orthogonality is guaranteed, as long as the observed CS is smaller than the CS offset. This means that it is necessary to assure that the round trip delay plus a certain delay spread[3] D_S is smaller than the CS offset as described below:

$$N_{CS} \geq \left(\frac{2 \cdot R}{v_c} + D_S\right) \cdot \frac{N_{ZC}}{T_P} \tag{9}$$

where T_P is the preamble span that equals 800 μs.

IV. PRACH PLANNING

PRACH planning aims at assigning PRACH resources in a smart way so that probability of wrong preamble detection between neighboring cells is minimized. In order to facilitate the implementation but without losing flexibility, PRACH planning is divided into three different uncoupled steps.

A. PRACH Planning in Time Domain

As Table II illustrates, there are several resource configurations, which use different sub-frames for transmission. Considering that preambles transmitted on different sub-frames do not interfere, a planning in time domain can help avoid collisions and facilitate the following steps, i.e. PRACH planning in frequency and code domain. It is worth mentioning that time

[3] Delay spread equals 6.25 μs and 16.67 μs for normal and extended cyclic prefix respectively [1].

domain planning must be done per site basis, because cells from different sites are not synchronized, and collision-free cannot be assured by allocating disjoint sub-frames. The cost of selecting a certain resource configuration $R_C(i)$ and $R_C(j)$ for cells i and j from the same site is computed as the useless sub-frames due to collision over the total available sub-frames for this pair of cells, which can be written as:

$$C_{TD}(i,j) = \frac{crd[S(i) \cap S(j)]}{crd[S(i)] + crd[S(j)]} \quad (10)$$

where $S(i)$ and $S(j)$ are the set of sub-frames for PRACH transmission for $R_C(i)$ and $R_C(j)$ respectively, $crd[X]$ is the number of elements in X. Note that in case cells i and j belong to different sites $C_{TD}(i,j) = 1$. The time domain cost function can be calculated as the sum of the cost of adding each branch linking cells i and j of the site of study calculated in eq. 10. So, the planning algorithm consists of finding the resource configuration for each cell within a site that minimizes[4] such cost function.

B. PRACH Planning in Frequency Domain

OFDM sub-carriers are orthogonal, which means that allocation of PRACH on disjoint RBs avoids interference. So a frequency domain planning can help avoid collisions that time domain planning previously could not, and decrease complexity during PRACH planning in code domain. The cost function of selecting a certain frequency offset $F(i)$ and $F(j)$ for cells i and j respectively is calculated as:

$$C_{FD}(i,j) = \begin{cases} \dfrac{C_{TD}(i,j)}{L} & \text{if } F(i) = F(j) \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

where $C_{TD}(i,j)$ is the cost in time domain based on the already selected resource configuration index, L is the path-loss between cells i and j, so that larger inter-site distance leads to lower interference, and hence, lower contribution to the cost function. The expression above indicates that two cells may have the same frequency offset for PRACH transmission and avoid collisions by time domain diversity. This fact gives an extra grade of freedom to the planner to find an optimal frequency offset allocation. The frequency domain cost function can be calculated as the sum of the cost of adding the branch linking cells i and j calculated in eq. 11. So, the planning algorithm consists of finding the frequency offset for each cell that minimizes such cost function. Contrary to the planning in time domain, the optimization process in frequency domain is performed per network basis.

C. PRACH Planning in Code Domain

There are 838 ZC root sequences available to generate preambles. These roots must be assigned in a consecutive manner and in such a way that each cell can generate 64 preambles minimizing the probability of wrong detection. As explained in Section II-D, each ZC root sequence may generate different preambles depending on the CS offset. Let $\Phi[X,Y]$ be a function that returns the number of preambles generated by a set X of ZC root sequences selected for cell Y. If cells i and j have selected a set of ZC root sequences $Z(i)$ and $Z(j)$ respectively, the common ZC root sequences can be written as:

$$Z(i,j) = Z(i) \cap Z(j) \quad (12)$$

In that case the cost of such decision is computed as the amount of useless preambles due to collision as below:

$$C_{CD}(i,j) = C_{FD}(i,j) \cdot (\Phi[Z(i,j), i] + \Phi[Z(i,j), j]) \quad (13)$$

where $C_{FD}(i,j)$ is the cost in frequency domain computed on the previous step, and $\Phi[Z(i,j), i]$ and $\Phi[Z(i,j), j]$ are the number of preambles generated using $Z(i,j)$ in cells i and j respectively. This expression implies that two cells may have the same ZC root sequences, but avoid collision if there is no overlapping in frequency or time (the latter implicitly included). The code domain cost function can be calculated as the sum of the cost of adding the branch linking cells i and j calculated in eq. 13. So, the planning algorithm consists of finding the set of ZC root sequences for each cell that generates 64 preambles and minimizes such cost function.

V. Simulation Results

The performance of the PRACH dimensioning and planning algorithm is assessed on a LTE network based on a real European urban scenario. The layout consists of a sectorized network with 281 sites corresponding to 788 cells. The carrier bandwidth is set to 5 MHz providing 25 RBs for transmission. Normal cyclic prefix and normal-speed cell are assumed. Traffic per cell is set to 50 Mbps with connections of 4 Mb. The probability of collision is 1% and all 64 preambles are available for contention-based mode. Each UE requires 3 attempts for a successful PRACH access. Results presented in this article study the reliability of the proposed algorithm, as well as, quantify the benefits of a time-frequency planning prior to assign ZC root sequences.

A. PRACH Dimensioning

Before planning it is necessary to accurately dimension the required resources according to the network and traffic conditions. As shown in Figure 4(a), the cell range is below 1000 m at 90th percentile, which means that preamble format 0 can be assumed for all cells since cyclic prefix is normal. According to the chosen simulation setup and using eq. 6-8 a single PRACH attempt is enough to fulfill the traffic conditions, which means that four resource configurations [0, 1, 2 and 15] are available for time diversity. Besides extra freedom is given by the four potential allocations in frequency domain in a 5 MHz bandwidth. Finally, as Figure 4(b) illustrates, more than 75% of the cells will need only a single ZC root sequence for generating 64 preambles since the cell range is small enough to use the lowest CS configuration.

[4] The optimization process consists of an iterative algorithm following the guidelines in [6].

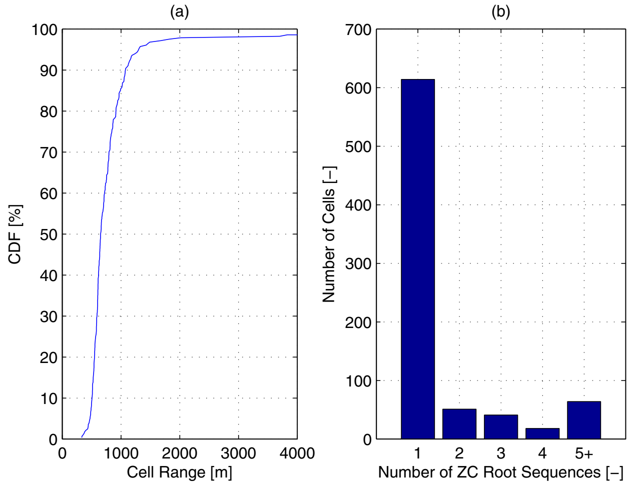

Fig. 4. Cell range CDF (a) and PDF of the number of required ZC root sequences per cell to generate 64 preambles (b).

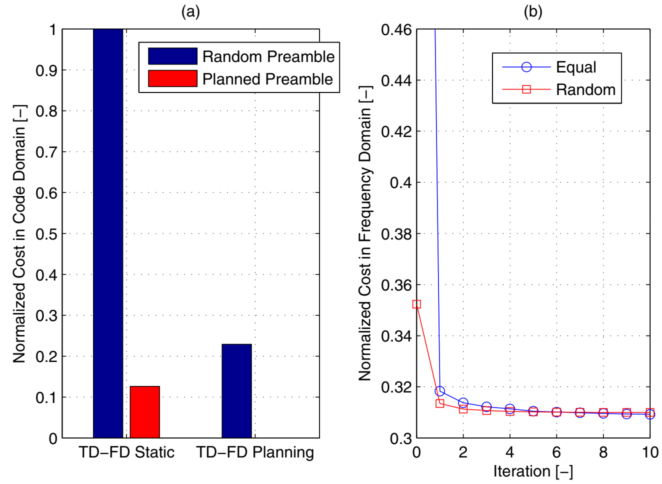

Fig. 5. Normalized cost in code domain (a) and frequency domain (b) under different scenarios.

B. PRACH Planning

The ultimate target of a PRACH planning algorithm is to smartly assign the different ZC root sequences minimizing wrong preamble detection between neighboring cells. However, time and frequency allocation provides extra flexibility that can facilitate this process. Figure 5(a) shows the normalized cost in code domain for a random and planned preamble assignment under two different scenarios: (i) planning in time and frequency domain is not considered, and hence, all cells share the same resources, i.e. TD-FD Static, and (ii) time and frequency planning is performed prior to preamble assignment, i.e. TD-FD Planning. The cost function can be seen as reuse factor indicator, so the lower the cost, the lower the probability of wrong preamble detection.

Results point out that performing a preamble planning instead of a simple random allocation of ZC root sequences sharply diminishes the cost function, i.e. around 90%. Besides, a time-frequency planning smooths the path for preamble selection, showing a decrease in the cost function of around 75%. In this simulation, it is even possible to fully avoid preamble collision between UEs when both a time-frequency and a code planning is performed. The need of a time-frequency planning depends on the network layout and number of cells, but it is expected to be more relevant in case of larger networks, where the total number of required ZC root sequences exceeds 838 by far, and hence, a preamble planning may not be enough for collision avoidance.

C. Algorithm Robustness

Each of the three steps of the planning process requires running an algorithm that minimizes the cost function to get the optimal assignment of resources. Convergence regardless of the initial network configuration is essential for reliable results. Figure 5(b) compares the cost in frequency domain on each iteration of the optimization process for (i) the most pessimistic initialization, i.e. all cells with the same frequency offset, and (ii) a random initial allocation. The figure corroborates the algorithm robustness since, on the one hand, both initial settings end up to a similar cost value, and on the other hand, more than 98% of the optimization benefit is reached in just one iteration.

VI. Conclusions and Future Work

This paper proposes a novel algorithm for LTE FDD PRACH dimensioning and planning that accurately estimates the required resources and assigns them minimizing the probability of wrong preamble detection by an uncoupled optimization process that can be easily applied by operators on real networks. As an outcome of this study it can be stated that, firstly, the algorithm manages to smartly configure PRACH so that probability of wrong preamble detection sharply diminishes, secondly, it is highly recommended to perform a time-frequency planning prior to assign ZC root sequences, getting a decrease in the cost function of around 75%, and finally, the optimization engine provides robust results, since they are not affected by the initial network setup. The next step is to quantify on a real network the benefits in terms of throughput, coverage, drop call rate, etc. of the proposed solution.

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