Extended Synchronization Signals for Eliminating PCI Confusion in Heterogeneous LTE

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***Abstract*— Heterogeneous long term evolution (LTE) networks evolve as a possible solution to accommodate the exponential growth of mobile data. However, the heterogeneity introduces several design challenges such as increasing interference and mobility overhead. In this paper, we propose Extended Synchronization Signals (ESS) to eliminate the unavoidable physical cell identity (PCI) confusion problem in dense heterogeneous LTE deployments. The ESS is also designed to reduce signaling overhead and handover delay. Our analysis shows a handover delay reduction of 65% can be realized. Additionally, we show that PCI confusion probability can be practically eliminated in case of centralized planning and a reduction of five order of magnitude in confusion probability can be attained in case of distributed planning.**

I. Introduction

The deployment of heterogeneous long term evolution (LTE) cellular systems represents a very promising approach to accommodate the exponential growth in mobile data [1]. In heterogeneous deployment, a macrocell tier typically provides full coverage using base stations (BS) with large footprints while other BSs with smaller footprints, such as relay BSs and femto-BSs, are implemented to improve or extend the coverage in their locality. This heterogeneous deployment, especially femtocells, not only boost the system spectral efficiency and enables traffic offloading from the congested macro-tier but also increases the average revenue per user, extends the mobile terminal (MT) battery life and enhances the customer loyalty.

The introduction of femtocells introduces several design issues including but not limited to interference mitigation, mobility overhead, and self-organization aspects. Typically, femtocells increase the rate of cell crossing in the system and consequently increase signaling overhead for location update and handover. Additionally, LTE standards define three access modes for femtocells [2] including closed access, open access, and hybrid access. Closed access cells are restricted to a set of users. Hence, additional signaling overhead may be incurred if a MT tried to camp on a cell that it has no right to access.

On performing handovers, the MT provides the serving BS with a measurement report including the signal strength and a PCI for each detected cell. If the serving BS has two or more neighbors having the same PCI, it would not be able to determine the MT target BS. This problem is known as PCI confusion [3]. In the heterogeneous deployment, the PCI confusion problem seems to be unavoidable due to the expected large number of femtocells and the limited range of PCI in LTE standards. Typically, the PCI is derived from two physical layer signals known as the primary synchronization signal (PSS) and the secondary synchronization signal (SSS). The PSS and SSS have a short transmission time interval of $0.5ms$ to speed the cell search process. Additionally they are used to derive the cell scrambling codes. Hence, every BS should have a unique PCI in its neighborhood.

In this paper, we present a framework for eliminating the PCI confusion problem in heterogeneous LTE using our novel concept of extended synchronization signals (ESS). The ESS extends the basic synchronization signals (BSS) by embedding additional information about the femtocell. Based on ESS, we propose a centralized PCI planning algorithm that practically eliminates the PCI confusion possibility. Additionally, we show that ESS reduces both signaling load and handover delay when compared to existing design alternatives. Furthermore, the proposed design enables the the MT to identify the femtocell access mode leading to a further reduction in the overall system signaling overhead as well as the MT battery consumption.

The rest of this paper is organized as follows. In Section II, we present an overview for background and related work. In Section III, we present our framework that tackles PCI confusion design issues in heterogeneous deployments followed by our performance evaluation in Section IV. Finally, we conclude and present future work in Section V.

II. Background and related Work

This section first briefly introduce LTE access procedure after which a brief overview for femtocell access modes is then provided. PCI relevant topics are the presented presented in the last subsection.

A. LTE Access Procedure

In order to communicate with LTE system, a MT should first acquire synchronization with the cell and then receive and decode cell system information. The synchronization process is known as cell search and is performed on powering up the MT and is repeated whenever the MT is interested in using a new BS. During the cell search, the MT searches for the PSS and SSS within LTE frames. Each LTE frame spans 10ms and is divided into 1ms sub-frames which are further subdivided into two slots containing six or seven OFDM symbols. In frequency division duplexing (FDD) LTE, the PSS

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is transmitted within the last symbol of the first slot of subframes 0 and 5, while the SSS is transmitted within the second last symbol of the same slot. On locking the PSS and SSS, the MT should have identified the frame timing and the cell PCI. The PCI is obtained by direct mapping from the PSS (which represents one of three possible cell identities) and the SSS (which represents one of 168 cell-group-identities).

Once MT synchronizes with a new cell, the MT can acquire the reference signal, which enables the MT to determine the received signal strength for mobility purposes and decode the broadcast transport channel for obtaining relevant system information. The system information includes a Master information block (MIB) and System information blocks (SIBs). The MIB contains limited information and is transmitted over the broadcast channel (BCH) while the SIBs contain more detailed information and are transmitted over the downlink shared channel (DL-SCH). It is worth noting that for reading DL-SCH, the MT has to first acquire MIB whose transmission time interval (TTI) is 40ms. SIB-1 contains information about the access rights of the BS and has a typical TTI of 80ms. Other SIB (SIB2-SIB13) contains other relevant information and are typically transmitted at longer TTIs [4].

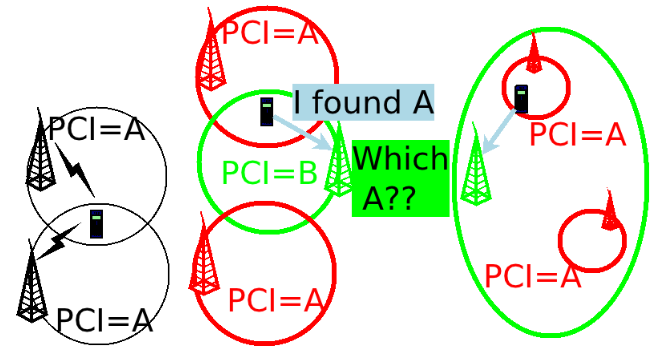
B. Femtocell Access Modes

The LTE standards define three different access modes [2] including closed, open, and hybrid. Closed access femtocells are restricted to a specific set of users; open access femtocells can be used by any MT; and hybrid access femtocells can be accessed by any MT with a prespecified set of users holding higher access priorities. In 3GPP standards, the concept of closed subscriber group (CSG) is introduced to define the group of users with specific access rights to a closed or hybrid access femtocells.

The identification of the femtocell access mode is required to avoid unnecessary signaling sent by MTs requesting camping to femtocells that they do not have the right to access. For example, a MT that has no subscription with any CSG would not be interested in accessing closed access femtocells. Note that femtocell access requests are forwarded by the serving BS to the network core where such requests are processed. Hence, such unnecessary requests cause significant signaling and processing overhead. In order to avoid such overhead, a combination of a CSG indicator (one bit flag) and a CSG identifier are broadcasted in the SIBs to identify the access mode. However, this approach is expensive in terms of the associated delay, which is critical for active users having ongoing real-time applications.

Another alternative to avoid this expensive delay is to split PCI range into groups corresponding to open access[1], hybrid access and closed access BSs. Hence, the MT can identify the type of the femtocell by the end of the cell search phase. However, the limited range of PCI in each cluster would magnify the PCI confusion problem.

[1]Open access BSs include macro and open access femtocells.



(a) PCI Collision (b) PCI Confusion

Figure 1: PCI Problems

C. PCI

Typically, the PCI should represent a *local* unique identifier in the serving cell neighborhood as it is directly mapped from the synchronization signals and is used in the derivation of the cell scrambling codes. Hence, there exist two typical PCI planning requirements including *collision-free* medium and *confusion-free* medium. The former requirement mandates that any two neighbor cells, i.e. cells with coverage overlap, *should not* have the same PCI. If a PCI collision occurs, the MT located in the common coverage of the two cells may not be able to decode the channels of the serving base station as illustrated in Figure 1a. The second requirement mandates that any two cells having the same PCI *should not* share a neighbor. In case of PCI confusion, the serving cell would not be able to identify the target cell on receiving a measurement report for handover purposes as illustrated in Figure 1b.

Two approaches are proposed in the literature to avoid PCI confusion for femtocells. The first solution is based on including an additional identifier with the PCI in the measurement report. The global cell identifier (GCI) is a typical identifying parameter. The GCI in LTE consists of two parts [5]:

- PLMN Identity: The identity of the Public Land Mobile Network.
- CIPL: Unique Cell Identity for a cell within a PLMN.

This approach is a delay critical solution, especially for active MTs, because GCI would not be available until the MT reads the SIBs. The second approach is to send conditional handover messages to all cells having the same PCI in the serving cell neighborhood. The latter approach leads to a significant signaling and processing[2] load increase especially in dense femtocell deployment.

PCI planning plays a role in reducing the PCI confusion problem. Two approaches are proposed for PCI allocation in LTE including centralized and distributed mechanisms. In the former, a central entity typically located in the evolved packet core would collect the initiating femtocell information and assign it a new PCI based on a wider overview for the system, while in the latter each femtocell allocates its PCI based on the local collected information. Note that in macro-tier, the base

[2]Note that all femtocell signaling has to to go through the network core due to the independent nature of its implementation.

stations can communicate to each other using X2 interface to collect information about neighbor cells. On the contrary, femtocells only depends on the sensed information due to its deployment nature. In [6] and [7], the authors present PCI allocation under centralized and distributed settings for macro-tier. In [8], the authors propose a PCI allocation algorithm for incremental network growth with minimal overhead using graph coloring as a typical tool for such type of planning problems. In [9], the authors propose a centralized PCI assignment function entity that collect information form initiating femtocells and then assign the femtocell a suitable PCI. This information may include a list of sensed neighbors, the configured access mode information (including the CSG ID), and previously assigned PCI if applicable.

III. ESS Framework

In this section, we first present the concept of extended synchronization signal (ESS). Second, we present the ESS-based PCI planning strategy in centralized and distributed deployments.

A. Extended Synchronization Signals

Both PSS and SSS are based on Zadoff–Chu (ZC) sequences [4]. The PSS and SSS are respectively transmitted in the last and second-last symbols of sub-frame 0 and 5. The PSS uses a 63-bit ZC sequence (only 62 bits are used after dropping the middle bit) that is transmitted in both PSS symbols. The SSS uses two 31-bit ZC sequence that are interleaved before transmission in the assigned slots; i.e two versions of SSS are transmitted in the defined OFDM symbols. This shift will allow the MT to acquire complete frame timing by detecting the PSS and one of the SSSs. The synchronization ZC sequences are typically padded with five zeros before and after the synchronization signals resulting in a 72-bit sequence that is passed to the OFDM modulator.

In the proposed extended synchronization signal design, the padding zeros are replaced by additional information bits that can be used for different purposes. Typically, eight 5-bit groups (totaling forty padding bits) can be used before and after the synchronization signals within each LTE frame. However, the synchronization signal is extended with only twenty bits since the cell search process is concluded by locking one PSS and one SSS within this frame. These twenty bits are split into four five-bit groups denoted G1-G4. These groups are transmitted as shown in Figure 2 . As shown in the figure, G1 and G2 are respectively transmitted before and after PSS Zadoff-Chu codes. Similarly, G3 and G4 are respectively transmitted before and after SSS Zadoff-Chu sequences.

Note that only femtocells would advertise such additional information bits. Hence, once a MT decodes the symbols of the synchronization signals, it can identify it as a macrocell if all the information bits are set to zero. Additionally, these bits can be defined in different ways to obtain additional information about the femtocell. One possible design for such additional information bits is

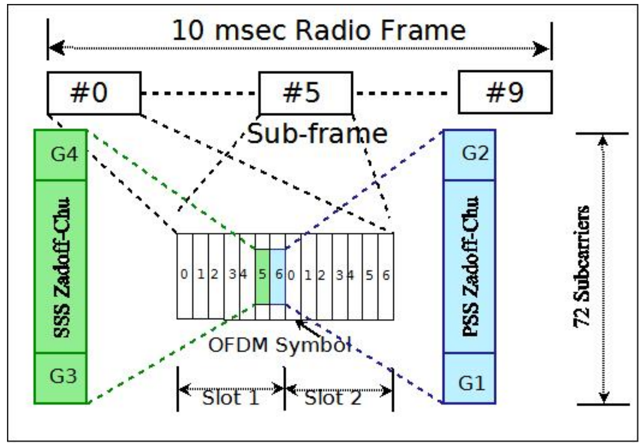


Figure 2: Extended Synchronization Signal Structure (FDD LET)

- The most significant bit is used to determine the access mode of the femtocell. On decoding one in this bit, the MT would identify the femtocell as a closed access cell; while on decoding it as zero, the MT would identify the femtocell as an open or hybrid access. Hence, if a MT is not interested in CSG cells, it would not proceed with detecting the reference signal and can dismiss this cell. Additionally, it may start looking for another cell instantaneously. Consequently, this bit is considered as an early stage filtering rule that reduces the MT battery consumption, speeds mobility function, and reduces overall signaling.
- The remaining information bits are taken from one of the femtocell identifiers. For example, the least significant bits of the GCI. This identifier would be sent within the measurement report together with the PCI to the serving BS. This additional identifier would not only significantly reduce the PCI confusion probability but will also improve the handover performance, especially for real-time applications, by reducing the time required for measurement gaps as presented in Section IV.

To this end, it is worth noting that ESS is compatible with legacy devices that can only send PCI in their measurement report or employ measurement gaps to obtain the GCI. However, these legacy devices would not enjoy the benefits of ESS due to the higher probability of PCI confusion.

B. PCI Planning

1) Centralized PCI Planning : By employing centralized PCI planning and ESS concept, the PCI confusion can be practically eliminated for heterogeneous LTE systems. In this section, we assume that the macro-tier is PCI confusion free and we focus on eliminating PCI confusion and collision problems at the femto-tier as well. In order to achieve this, the following PCI sets are defined

- Ω_s : a set of sensed PCIs at the download link (DL) of the initiating femtocell.

- Ω_n: a set of PCIs of the sensed neighbor BSs. These cells are determined by the PA-function according to the information provided in the Ω_s.

- Ω_{nn}: a set of PCIs of the neighbors of neighbors. This set is determined through the information read from the SIBs and information stored in the PA-Function.

- Ω_a: the set of all possible PCIs. This set typically includes the 504 PCI defined in the standard. If the PCI range is split to define different ranges for various femtocell access modes, this set would include the corresponding PCI range for the type of the initiated femtocell.

- Ω_{id} : the set of PCIs of femtocells that have both a common overlaying macrocell and identical ESS information bits to the initiating femtocell. For eliminating the PCI confusion, the initiating femtocell should not be assigned a PCI from Ω_{id}.

- Ω_c: the set of the candidate PCIs. This set includes all the possible PCIs after excluding all the PCIs that can cause a PCI collision or confusion problems, i.e. $\Omega_c = \Omega_a/[\Omega_n \bigcup \Omega_{nn} \bigcup \Omega_{id}]$.

Once the Ω_c is determined, a PCI is selected and assigned to the initiating femtocell according to the adopted PCI selection policy. This policy can be selecting a random PCI from the list or choosing the least used PCI or any other policy.

2) Distributed PCI Planning: In distributed PCI planning, the process is mainly dependent on sensed information in the initiating femtocell DL. In enterprise implementations, the femtocell may be able to communicate with other femtocells peers connected to the same communication backbone to collect more information about femtocells in the local neighborhood. Hence, Ω_s, Ω_n, Ω_{nn}, and Ω_{id} are all based on locally sensed or collected information. The allocated PCI is chosen randomly from the calculated Ω_c. Hence, the probability of PCI confusion is a non-zero probability. However, by including the ESS information in the measurement report, this probability is far less than the probability or PCI confusion in systems using basic synchronization signals (BSS).

IV. Performance Evaluation

A. Handover Delay Analysis

The handover delay, denoted as d_{ho}, in LTE has several components including

- the cell search delay, denoted as d_s, required for locking PSS and SSS. Since the TTI of synchronization signals is 5ms, the time required to lock the PSS is $2.5ms$ on average. The following SSS would be transmitted after 5ms. Hence, the cell search delay is expected to be $7.5ms$.

- measurement delay, denoted as d_m, required for reading the reference signal which is transmitted in every resource block withing any sub-frame. Hence, d_m is estimated as $0.25ms$.

- reading system information delay, denoted as d_i, required for obtaining GCI of femtocells from system information blocks. This delay include the delay required for reading MIB ($20ms$ on average) and SIB-1 ($40ms$ on average) totaling $60ms$ on average[3].

- total handover messages propagation delay, denoted as d_l, required for message propagation in between the serving and target BSs in the access part and the involved entities in the network core such as the mobility management entity (MME) and the femto-gateway (F-GW). In any handover involving a femtocell, two round trips are required. One way delay is required for submitting the measurement report to the evolved packet core network to check access rights and decision taking. Assuming the MT has the right to access the target cell, a round trip delay is required to forward the handover request to target BS and receiving the target BS confirmation. Finally, another one way delay is required to send the handover acknowledgment to the MT. For more details about the handover procedure and signaling, the reader is referred to [3]. In [10], one-way delay is estimated as 5ms. Hence, the expected d_l equals $20ms$.

- processing delay, denoted as d_p, which includes processing at MT, macro-BS, femto-BS, and involved core network entities. This delay is common between both BSS and ESS and is approximated to $0.5ms$ per involved entity. Hence, the total processing delay at different involved entities is approximately assumed to be $5ms$, i.e. $d_p = 5ms$.

The summation of these delay components provides an estimate for the required handover delay. Yet, the main difference between BSS- and ESS-based handover is eliminating the time required for reading the system information. Hence, the handover delay for BSS-based system, d_h^{BSS} can be estimated as

$$d_h^{BSS} = d_s + d_m + d_i + d_l + d_p \approx 92.75ms.$$

The handover delay for ESS-bases system, d_h^{ESS} can be estimated as

$$d_h^{ESS} = d_s + d_m + d_l + d_p \approx 32.75ms.$$

Hence, the proposed concept of ESS leads to a reduction of 65% in handover delay in comparison to BSS-based system that depends on reading system information to avoid PCI confusion. Additionally, adopting ESS would also prevent introducing any transmission gaps required for reading system information. Hence, using ESS would improve the handover performance of real-time applications such as voice and video communications.

B. Access Mode Identification

Identifying the femtocell access mode without reading the system information is a required design feature. This feature not only reduces the battery usage of the MT [2] but also enables avoiding transmission gaps required for reading the system information for active MTs. ESS realizes this goal without compromising other system configurations by including an access mode indicator in the most significant bit of the ESS. Hence, by adopting ESS, if a MT is only interested in open access or hybrid access femtocells, the MT will instantaneously ignore closed access femtocells. Note that the other design alternative is to adopt PCI slicing into ranges dedicated for different access modes. Clearly, the latter approach will magnify the PCI confusion problem especially if BSS is used. It is worth noting that, both PCI range slicing and ESS can be used together and in this case, the entire 20 bits can be used for the additional identifier.

[3]It is worth noting that the MIB and SIB are transmitted several times within their TTIs. Depending on the the signal to interference and noise ratio, users would be able to decode the information blocks after different number of block reception.

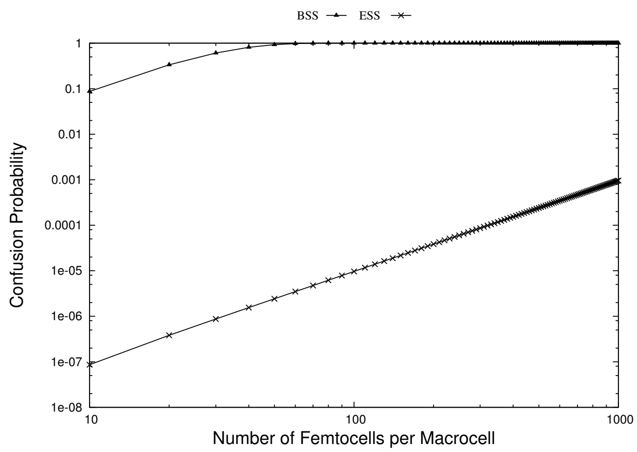


Figure 3: PCI confusion probability for BSS and ESS

C. PCI Confusion Probability

In this section, we compare the probability of PCI confusion, denoted as P_c, of BSS and ESS for distributed PCI allocation. On using BSS, the PCI confusion would occur if two or more femtocells use the same PCI under the same macrocell coverage. Note that we assume no confusion would take place in the same tier since this type of confusion can be avoided using self-healing mechanisms, which are based on femtocell reconfiguration according to user measurement reports. We also assume that the PCI is selected randomly from the estimated candidate set Ω_c. Let n_f denotes the number of femtocells installed in a specific macrocell and n_c denotes the number of candidate PCI. Note that n_c equals the cardinality of Ω_c. Hence, P_c for BSS can be expressed as $P_c = 1 - \overline{P_c}$, where $\overline{P_c}$ represents the probability of no PCI confusion. On using BSS, $\overline{P_c^{BSS}}$ can be derived as

$$\overline{P_c^{BSS}} = \left\{ \begin{array}{cc} \frac{{}^{n_c}P_{n_f}}{n_c^{n_f}} & , n_f \leq n_c \\ 0 & , n_f > n_c \end{array} \right\},$$

where ${}^{n_c}P_{n_f}$ represents the n_f permutations.

On using ESS, a PCI confusion would occurs if two or more femtocells have the same PCI, the same access mode bit and identical 19 least significant bits of GCI. Hence, the $\overline{P_c^{ESS}}$ can be derived as

$$\overline{P_c^{ESS}} = \left\{ \begin{array}{cc} (\alpha^2 + (1-\alpha)^2)\frac{{}^{(n_c n_{id})}P_{n_f}}{(n_{id} n_c)^{n_f}} & , n_f \leq n_c n_{id} \\ 0 & , n_f > n_c n_{id} \end{array} \right\},$$

where α represents the probability that a femtocell access mode is closed and n_{id} represents the number of possible combinations of the 19 least significant bits of the GCI; i.e. $n_{id} = 2^{19}$.

Figure 3 plots the confusion probability for BSS- and SSS-based systems versus the number of femtocells per macrocell with $\alpha = 0.5$. The figure clearly shows that the confusion probability in BSS-based systems is very high. On using ESS, the PCI confusion probability significantly drops to about five order of magnitude less in comparison to BSS-based systems.

To this end, it is worth noting that P_c in systems with centralized allocation function is deterministic and can be expressed as

$$P_c|_{centralized} = \left\{ \begin{array}{cc} 0 & , n_f \leq n_l \\ 1 & , n_f > n_l \end{array} \right\},$$

where n_l respectively equals n_c and $n_c n_{id}$ for BSS- and ESS-based systems. Hence, using ESS would practically provide a PCI confusion free system as the number of femtocells within an LTE macrocell will not practically approach $n_c n_{id}$ even in 3d realizations.

V. Conclusion

The dense deployment of femtocell in LTE cellular networks introduces several design issues to the system. PCI confusion is one of the most critical mobility management challenges in heterogeneous LTE networks. The existing solutions would either lead to an increase in handover delay or the signaling and processing overhead in the network core and backhaul. The proposed ESS represents a novel practical framework to eliminate PCI confusion in heterogeneous deployment. Additionally, the presented ESS design provides a means that enables the MT to identify the femtocell access mode without reading the system information. Hence, ESS not only improves the handover performance for active MTs but also reduces the battery drainage and signaling load required for some essential mobility functions for both active and idle devices.

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