Physical Cell Identity Assignment in Heterogeneous Networks

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Abstract— **In order to meet the ever increasing demands for capacity in mobile networks, several technological solutions are being sought and one of them is heterogeneous networks. In heterogeneous networks, the pre-planned, relatively regular placed macro base stations are complemented with several low-powered base stations that might be deployed in a relatively unplanned fashion for both capacity and coverage enhancements. This can result in a large number of cells within a given area, making it difficult to assign non-conflicting cell identities from the limited number of available sets. In this paper, we analyze this problem in realistic deployment scenarios in a 3GPP LTE network that is enhanced with low power pico nodes. System level simulation results show that for deployment densities that can meet the anticipated traffic demands for up to 2020, the 504 cell identity limit in LTE is quite sufficient and cell identities can be reused efficiently among the pico nodes.**

Keywords- heterogenous networks,, LTE, LTE-Advanced, pico cells, physical cell identity (PCI), Self Organized Network (SON)

I. INTRODUCTION

The volume of global Internet traffic is increasing tremendously, mainly thanks to the popularity of peer-to-peer (P2P) networking and video traffic. With the proliferation of user friendly smart phones and tablets, the usage of high data rate services such as video streaming over the mobile network is becoming commonplace, greatly increasing the amount of traffic in mobile networks. Recent forecasts have predicted that traffic from wireless devices will surpass traffic from wired ones as early as 2015 [1]. Thus, there is a great urgency in the mobile network community to ensure that the capacity of mobile networks keeps up increasing with this ever-increasing user demand.

Research and development in improving the capacity and data rates of mobile networks traditionally focused on improving the spectral efficiency of the radio link, which resulted in the standardization of various mobile communication technologies. The latest systems such as Long Term Evolution (LTE), specially when coupled with interference mitigation techniques, have spectral efficiencies very close to the theoretical Shannon limit [2][3]. The continuous upgrading of current networks to support the latest technologies and densifying the number of base stations per unit area are two of the most widely used approaches to meet the increasing traffic demands.

Another approach to macro densification is to use Heterogeneous networks (HetNets) where the traditional pre-planned macro base stations (known as the *macro layer)* are complemented with several low-powered base stations that may be deployed in a relatively unplanned manner [4][5]. The concept of HetNets is not new and it has been considered for both GSM and CDMA systems ([6]), but it is only recently that it has started getting proper attention from standardization groups. 3GPP has incorporated the concept of HetNets as one of the core items of study in the latest enhancements of LTE known as *LTE-advanced* ([7]) and several low-powered base stations for realizing HetNets such as *pico* base stations, *femto* base stations (also known as home base stations or HeNBs), relays, and RRHs (remote radio heads) have been defined [8].

Fig. 1 illustrates an example HetNet deployment, where relays are used for coverage extension, picos offload the load of macro in hotspots and femtos are used for coverage/capacity enhancement in buildings. HetNets might offer a low cost alternative to macro densification and in some cases might be more effective as the deployment of the low power nodes can be made more focused towards hot spots and areas with coverage problems.

One of the important aspects of service provisioning in mobile networks is guaranteeing seamless handover of the user equipment (UE) from cell to cell. With heterogeneous networks, handover becomes even more important than in homogenous cellular networks as the total number of cells in the system becomes very large, which in turn increases not only the total number of handovers in the systems but also the number of handovers a user experiences per unit time.

In LTE, a handover is a UE-assisted, network-controlled procedure [9]. UEs send measurement reports containing the signal quality of the neighbor cells whenever the measurement configuration criteria (thresholds, timers, etc.) set by the serving cell are met. The serving cell can then decide to perform a handover based on these reports. In the measurement report, neighbor cells are identified by their Physical Cell Identity (PCI) and the carrier frequency they are using.

There are 504 unique PCI values defined in LTE, and a cell is assigned one of these values [10]. The limited number of PCIs leads to the reuse of the same PCI values in different cells that are using the same carrier frequency. If cells using the same PCI are within a close proximity of each other, confusion could arise regarding to which neighbor a UE has to be handed over, and this can result in handover failures. The PCI confusion problem is especially important in a HetNet scenario where the number of cells in a given geographical area can be

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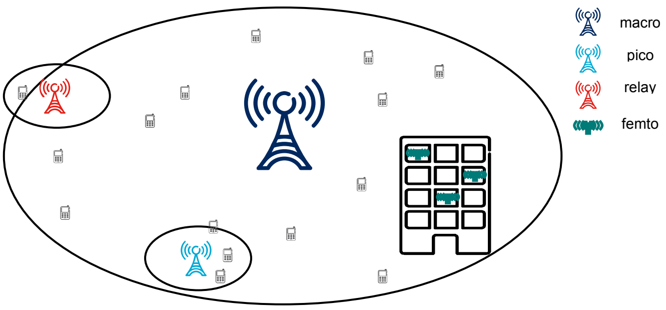


Figure 1: Heterogeneous network deployment

quite large and the low power nodes can be deployed without strict planning. The impact of small cell identification and PCI confusion has thus been identified as one of the items to be studied in the mobility enhancement work of LTE-Advanced HetNets [11].

In this paper, we address the issue of PCI assignment in a pico enhanced LTE HetNet. The rest of the paper is organized as follows. Section II discussed the issues of PCI assignment in more detail. In Section III, realistic deployment scenarios are identified and the resulting requirements on the number of PCIs for the identified cases are computed using system level simulations. Section IV discusses the findings of the simulations and their implications. Finally, concluding remarks are given in Section V.

II. ISSUES WITH PCI ASSIGNMENT

The PCI is an essential configuration parameter of a radio cell. It is used to generate (in a one-to-one fashion) the cell's synchronization signals, reference signals and their pseudo-random position in frequency, as well as the scrambling codes for most of the physical channels. PCIs are grouped into 168 unique physical layer cell identity groups, each group containing 3 unique identities. Thus, there are only 504 different PCIs altogether [10].

Limiting the number of PCIs makes the initial PCI detection by the UEs during cell search easier, as there is a one to one mapping between the reference symbols and the PCIs. However, the limited number of PCIs inevitably leads to the reuse of the same PCI values in different cells. Therefore, a PCI might not uniquely identify a neighbor cell, and each cell additionally broadcasts, as a part of the system information (SI), a globally unique cell identifier (CGI).

When a new base station is brought into the field, a PCI needs to be selected for each of its supported cells. The PCI assignment shall fulfill the following two conditions [13]:

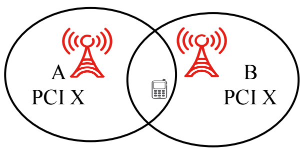
- *Collision-free:* The PCI is unique in the area that the cell covers for a given carrier frequency
- *Confusion-free:* a cell shall not have more than one neighboring cell with identical PCI that are using the same carrier frequency

The problems of PCI collision and confusion are illustrated in Fig. 2. Using an identical PCI for two neighboring cells creates collision (Fig. 2a). Such a collision means that a UE moving from one of the cells to the other fails to detect the candidate cell since it cannot disclose a new PCI. In fact, the reception situation is similar to the case when the UE receives multiple copies of a transmitted signal that has traveled along different paths. A PCI collision can be solved only by restarting at least one of the cells and reassigning it a different PCI, causing service interruption for all the UEs that were connected to it.

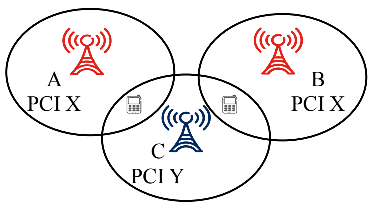
PCI confusion (Fig. 2b), on the other hand, occurs if the cells using the same PCI are not neighboring each other but have a common neighbor. Thus, handover measurements, which are based on the PCI, will become ambiguous leading to confusing measurement reports (for example, cell C will be not be sure whether to hand over a UE to A or B when getting measurement reports). This can lead to handover failures or even Radio Link Failure (RLF).

Traditionally, a proper PCI is derived from radio network planning and is part of the initial configuration of the node. The network planning tool calculates the possible PCIs for the new cell(s) based on estimated neighbor relations of the new cells, as estimated by cell coverage area predictions. However, prediction errors, due to imperfections in map and building data, and to inaccuracies in propagation models, have forced operators to resort to drive/walk tests to ensure proper knowledge of the coverage region and identify all relevant neighbors and handover regions. Even the accuracy of that is questionable as some factors such as seasonal changes (the falling of leaves or snow melting) can alter the propagation conditions. Also, the inaccuracy of cell coverage and neighbor relation assessment increases with time as the live network and its surroundings evolve. The use of such techniques is even further limited in a HetNet scenario as proper planning is almost impossible due to the sheer number of the nodes involved.

PCI confusion can be resolved by instructing the UEs to read the Cell Global Identity (CGI) of the concerned neighbor cell. A CGI uniquely identifies a cell and can have up to 2^{28} different values within one Public Land Mobile Network (PLMN) [12]. Cells transmit their CGI periodically in their broadcast channels. LTE supports a feature known as UE ANR (Automatic Neighbor Relations), which enables the serving base station to request the UE to decode and report the CGI



a) PCI collision



b) PCI confusion

Figure 2: PCI assignment problems

information associated with a reported PCI. And base stations maintain a neighbor relation table (NRT) for each of their cells, with detailed information about each neighbor.

UEs need to be assigned long enough idle periods (for example, using DRX configuration with long DRX cycles) in order to read the CGI from the broadcast channels of neighbor cells. Therefore, putting a PCI in use which causes confusion is highly undesirable as the UE might have to be requested to decode the CGI, which can cause service interruption from the serving cell during the CGI measurement duration.

In this paper, we investigate the problem of PCI assignment in the context of realistic pico cell deployment scenarios. First, preliminary analysis is made to determine the pico deployment density to meet future demands of mobile data users and then investigations are carried out to determine if the 504 PCI limit will create problems in these deployment scenarios.

III. PCI ASSIGNEMENT IN PICO ENHANCED LTE SYSTEM

A. *Required pico density*

The UMTS forum recently published a mobile traffic forecast, which predicted that the average daily data traffic from mobile handsets will increase from 10 MB in 2010 to 294 MB in 2020, while that of wireless dongles/tablets increases from 27 MB to 503 MB in the same period [14]. This translates roughly to 8 GB and 15 GB per month for the handset and tablet/dongle users, respectively. We took the estimate for the dongles, and added some margin, to consider data volumes of up to 20 GB/user/month for our studies.

System level simulations are performed to find the pico deployment density to satisfy the aforementioned requirements of 20 GB/user/month. An average density of 5400 UEs/km^2 is assumed based on a dense urban population density of 20,000 inhabitants/km^2, together with an overall service penetration level of 90%, and an operator market share of 30%. The UEs are dropped in such a way that 80% of them are in hotspots with a radius of 20m, and the rest 20% are uniformly distributed throughout the cell area. The picos are located as close as possible to the hotspot centers. Other important parameters used in the simulations are given in Table I.

TABLE I. PARAMETERS FOR SYSTEM LEVEL SIMULATIONS

Parameters	Value
Carrier Frequency	2GHz
Bandwidth	10MHz
Number of macro cells	21 (Seven 3-sectored eNBs)
Macro Tx Power	40W (46dBm)
Pico Tx Power	1W (30dBm)
Macro Inter-Site Distance	425m
Distance-dependent path loss	According to [8]
Wall loss	20dB
Shadow fading	Log-normal with std 8dB and 10dB to and from the macro and pico base stations, respectively

The number of picos per macro cell is varied, and the variation of the user downlink throughput for different loads is measured (please refer to [15] and [16] for the details of the methodology employed to calculate the throughput). Note that the simulations presented here are not meant to provide the exact number of pico cells needed for meeting future target traffic demands. Rather, the purpose is to estimate the order of magnitude of number of picos per macro cell.

Fig. 3 shows the results. As can be seen from the figure, with 10-30 picos per macro cell, we are able to fulfill the forecasted traffic demands in 2020. Also, the relative gains from adding more picos diminishes with the number of picos. The uplink results, which are not shown here for the sake of brevity, show similar patterns. Also, future LTE deployments will most likely employ bigger bandwidths than the 10 MHz assumed here, and in that case, the required number of picos will be even lower. However, to account for possible forecasting error in [14] and also for some of the simulation assumptions (such as the optimal placement of the picos and hotspot distribution), we have considered even larger number of picos (up to 75 per macro cell) for the PCI investigations. Though 75 picos per macro cell seems very impractical, we have chosen it to set a worst case scenario for the PCI allocation problem.

B. *Neighbor relations*

Now that we have identified the required pico density to satisfy future user demands, the next step is determining the number of neighbors a cell can have, as the probability of PCI collision and confusion is highly dependent on that. For a given UE, the Signal to Interference and Noise Ratio (SINR) of the received signals from all cells (both macros and picos) are calculated, and those cells that have SINRs of greater or equal to -7.5dB are identified as cells that will collide if they use the same PCI [16].

Doing this for all possible UE locations gives us all the neighbors of a given cell, i.e. all the cells that can be detected from a UE anywhere within the concerned cell and thus are possible handover candidates. The simulator employed for the study is a static simulator with no support for mobility, and as such several iterations consisting of two loops are performed to gather enough neighbor statistics. The outer loop varies the position of the pico cells, and the inner loop varies the locations at which the neighbor measurements are performed. 5000 locations are randomly selected in one iteration and the inner loop is repeated until the neighbor calculation converges for the particular pico cells realization as fixed by the outer loop. The choice of 5000 locations was based on trial and error to optimize simulation time and manage within the system memory limitations.

The dependence of the number of neighbors on the pico deployment density is depicted in Fig. 4. Note that only the neighbors that the macro cells see are shown because the neighbors seen by the picos is relatively unaffected by the density of the picos. Even with a super dense deployment

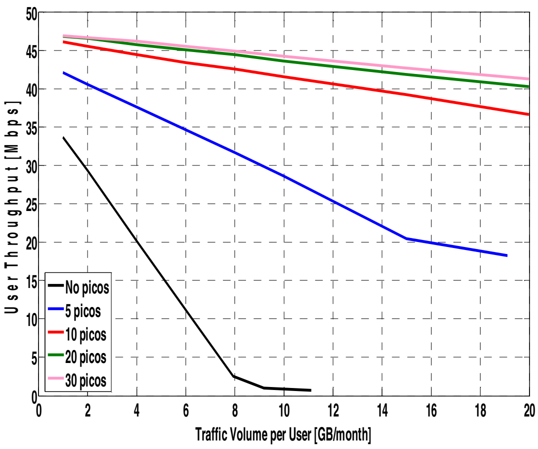


Figure 3: Mean downlink throughput dependency on pico cell deployment density

density of 75 picos per macro cell, the maximum number of neighbors seen by any macro in the system is below 200.

C. *PCI Assignment*

We use the following PCI assignment strategy to calculate the minimum number of PCIs needed for a given pico deployment density:

a) For each cell, determine its neighbors (as performed in the previous section)

b) Use the information from step (a) to determine the neighbors of neighbors of each cell

c) Sort the cells in descending order according to their number of neighbors of neighbors

d) Assign to the first cell in the list the lowest PCI that is not used by any of its neighbors of neighbors which already have a PCI allocated to them

e) Remove the cell that has just been assigned a PCI in step (d) from the list, and go back to step (d)

The above procedure is basically a graph coloring algorithm, where the vertices of the graph correspond to the cells, and the edges connect the cells that are neighbors and neighbors of neighbors to each other [18].

The outcome of the PCI assignment procedure is shown in Table II. Even in the case of super dense deployment of 75 picos per macro cell (225 pico nodes for each macro node), we need only 200 PCIs, less than half of the possible number of PCIs that could be assigned. As the density of the pico nodes increases, the additional PCIs required per pico for collision and confusion free allocation decreases. This is mainly due to the fact that the higher the deployment density of the pico, the larger percentage of the cells in the system will be pico cells and the number of neighbors of the picos is not changed that much for the considered cases. Thus, there is a high likelihood of PCI reuse among the picos that are not located within the same macro cell.

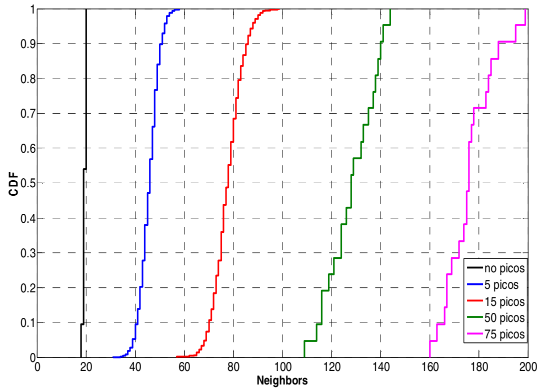


Figure 4: Dependency of the number of neighbors of macro cells on the pico deployment density

IV. DISCUSSION

From the results shown in the previous sections, it can be concluded that the number of PCIs needed in a heterogeneous network with a realistic pico deployment density is well within the 504 limit of LTE. The algorithm we used to evaluate this assumes that information about the neighbors of each cell is available, and as such is well suited to be implemented in a centralized Operations and Management (O&M or OaM) entity that oversees the management of both the macros and picos.

However, there are considerable differences between the pico and macro cases when it comes to PCI management. There will be relatively more picos than macros to manage and the deployment of the picos can take a longer time span (for example, few picos added every now and then). Due to this it might be hard to do proper planning and also some picos can end up being used on a need basis and can be turned on and off more frequently than macros (for example, a pico that is supposed to increase the capacity in a stadium that is turned on only when there are matches). These make it hard to assign the PCIs of the picos in the traditional ways such as drive tests used for macros and thus a more dynamic way of assigning PCIs is needed.

Self-Organizing Network (SON) has been one of the core focuses of 3GPP for LTE and LTE-Advanced, where decentralized solutions are sought to automate tasks that currently require significant planning efforts [13]. In relation to PCI assignment, there has been several SON based proposals where mobile assisted measurements (UE ANR) are used to continuously update the neighbor relation information of the cells in the network which then is employed to allocate collision and confusion free PCIs when a new base station is brought into the field and also to quickly resolve any PCI conflicts that might arise [19][20]. These solutions are shown to provide good performance and fast convergence and can be readily used in the case of a HetNet with picos.

TABLE II. REQUIRED NUMBER OF PCIS VS . INCREASING PICO DEPLOYMENT DENSITY

Picos / macro cell	**Total picos**	**Max neighbors**	**PCIs required**	**Picos per additional PCI**
0	0	20	20	N/A
5	105	58	66	2.3
15	315	99	106	2.97
50	1050	144	145	7.2
75	1575	199	200	7.9

A pico, when it becomes operational, can spend some time in a UE mode, sniffing for PCIs it can detect, and can choose a PCI that is not in conflict with these detected PCIs. However, this does not guarantee that there will be no PCI confusion, as there might be picos located within other macro cells or even in the same macro cell but farther away than the new pico that are using the same PCI. Another alternative is for the O&M entity to assign the new pico a PCI that is not used at the moment. For example, for the cases of 75 picos per macro cell discussed in the previous section, PCI 201 can be assigned for the new pico. However, if we continue this way, we will run out of PCIs very soon.

A more efficient method will be to assign this new PCI only temporarily, and to start updating the neighbor information changes of other cells due to the introduction of this new node. When enough neighbor information has been gathered, the O&M can then be able to reassign the new node a PCI that is most likely is already being used somewhere else in the network, and recover the unique PCI for future picos. In case the pico is deployed for capacity enhancement, it can be restarted promptly. On the other hand, if the pico is deployed for coverage extension, the restart might have to be postponed till the pico is very lightly loaded in order to ensure that not many UEs will be affected by the PCI re-assignment.

The results and discussion so far have been about pico deployment, but they equally apply for open access femtos. For closed subscriber group (CSG) femtos, which allow access only to UEs that have CSG membership, the situation is quite different because there might be hundreds of femtos even within one macro cell (for example, there can be several big apartment buildings in close proximity). As such, PCI confusion is unavoidable. However, this will not be very problematic due to several reasons. To begin with, only the UEs that have CSG access will be measuring and reporting the CSG femtos. Additionally, in the current standards, the use of proximity detection is specified, and it is recommended to be followed up by CGI and CSG-ID reading before accessing the CSG cells [9].

V. CONCLUSIONS

Heterogeneous networks, also known as HetNets, where several low-powered base stations are deployed on top of the macro base stations, are one of the proposed network deployment mechanisms to meet the ever increasing capacity demands of mobile networks. One of the challenges of HetNet deployments is to ensure that the multitude of cells in the network have PCIs that will not cause collision or confusion. This problem is addressed in this paper, and system level simulation studies have been performed to analyze the issue in realistic deployment scenarios. The results show that even in the case of super dense pico cell deployments, the current limit of 504 possible cell identities is quite sufficient as PCIs. The assignment of the PCIs can be performed quite efficiently if there is a common O&M that oversees the PCI management of both picos and macros.

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