On the Limits of PCI Auto Configuration and Reuse in 4G/5G Ultra Dense Networks

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***Abstract*—Increased demand for higher user throughput has led to deployment of multi-layer networks commonly called heterogeneous networks (Hetnets). Therein, small cells are deployed alongside traditional macro cells, in many cases on the same spectrum. Such scenarios complicate the configuration of network parameters such as the Physical Cell Identity (PCI). A number of approaches have as such been proposed to automate the allocation of PCIs in such scenarios. These approaches seek to address the two conflicting objectives for PCI assignment in a hetnet scenario: 1) the need for optimal performance by avoiding conflicts, against 2) the requirement to separate the different layers and avoid any need to share knowledge among the layers. However, as the density of small cells increases evolving the Hetnets into what are called Ultra Dense Networks (UDN), these approaches reach their limits. In this paper, we study the performance of the current PCI allocation strategies in such UDN scenarios and evaluate their break down points. Our results show that these strategies do not adequately address PCI allocation for the UDN scenario. Specifically, we observe that PCI assignment in one layer requires knowledge of the assignments in the other layer, otherwise the consequence is a very high count of PCI confusions.**

Keywords: Physical Cell Identity; PCI; Hetnet; UDN

I. INTRODUCTION

Demand for higher user throughput has motivated the rollout of heterogeneous networks (Hetnets) having small cells alongside traditional macro cells. However, deploying small cells, whether micro, pico or femto cells, increases the complexity of Network Management(NM). To counter this, self organization has been proposed to automate the NM processes [1] [2], including the assignment of PCIs.

Although seemingly simple, PCI assignment is not a trivial problem, owing to the limited number of PCIs [3] and the need to minimize PCI conflicts among cells. For Hetnets, we need to find a compromise between two conflicting objectives: 1) to separate the layers such that there is no need for sharing knowledge among the layers which would otherwise require advanced features in the small cells or their element management systems; 2) to ensure optimal performance such that any PCI conflicts are minimized as much as possible.

Some studies have been undertaken on the Hetnet PCI assignment problem, most concluding that it is possible to assign PCIs in an automated and conflict free manner. However, in dense urban environments, the small cell density is expected to continue growing at least in the foreseeable future. This results into extremely dense cell deployments, generally called Ultra Dense Networks (UDNs). Then, the original assumptions made about the network deployment (and subsequently used in the PCI assignment studies) cease to be true. For example, as we describe in sections II and III, many of the approaches considered only the major constraints - PCI collisions and confusions - but not the other constraints related to interference among reference signals. This implies that the exact break down points for these approaches are unknown, especially when all practical constraints are considered.

Effectively, the degree of densification that can practically be achieved, which depends on the interconnectivity among the cells, is unknown. This paper seeks to determine these limits. We model a generic UDN and evaluate how well these current approaches would be applicable in such a UDN scenario.

The rest of the paper is structured as follows: Section II summarizes the PCI assignment problem while Section III reviews and classifies the approaches into two generic strategies. Sections IV and V respectively present the study scenario and the performance results of applying the strategies in Section III. Our results clearly highlight the suspected limits and the need for rethinking the PCI-values space and /or the assignment strategies. Finally, Section VI concludes with a general summary and an outlook to our expected future work.

II. PCI ASSIGNMENT REQUIREMENTS

A. *PCIs, Synchronization Signals and Reference Signals*

The PCI is the primary configuration parameter for the cell and aids in differentiating the signal of one cell from that of another. It has a one-to-one mapping with the cell's synchronization signals; reference signals (RS) and their pseudo-random position in frequency, as well as with the scrambling codes for most of the physical channels [4]. There are 504 unique PCIs grouped into 168 unique physical-layer cell identity groups (PLIGs, N^1_{ID}), each group having three unique physical-layer cell identities (PLIs, N^2_{ID}) [3]. A cell's PCI is thus the combination of the Cell's PLIG, and its PLI i.e.

$$PCI = 3 \cdot N^1_{ID} + N^2_{ID} \quad (1)$$

The cell's PCI is related to the synchronization signals used by the UEs for cell search. Every $5ms$, the cell transmits two synchronization signals- the primary synchronization signal (PSS) and the secondary synchronization signal (SSS). The PSS is generated from a frequency-domain Zadoff-Chu sequence whose root index has a one-to-one mapping to the PLI N^2_{ID}. The SSS is a concatenation of two sequences both of which are characterized by two indices m_0 and m_1. The indices are derived from the PLIG according to (2) [3]:

$$m_0 = m' \ mod \ 31$$
$$m_1 = \left(m_0 + \left\lfloor \frac{m'}{31} \right\rfloor + 1\right) mod \ 31$$
$$m' = N_{ID}^1 + q(q+1)/2$$
$$q = \left\lfloor \frac{N_{ID}^1 + q'(q'+1)/2}{30} \right\rfloor \quad ; \quad q' = \lfloor N_{ID}^1/30 \rfloor \qquad (2)$$

Besides the synchronization signals, the PCI is also related to the cell's Reference Signal (RS) and serves as a resource allocator parameter for both the downlink and uplink signals. Downlink RSs are allocated in a time-frequency grid, always transmitted in the same OFDM symbol in the time domain. In the frequency domain however, each cell has a different RS frequency shift whose index u_d given by Equation (3).

$$u_d = PCI \ mod \ 3; \ SISO \ scenario$$
$$u_d = PCI \ mod \ 6; \ MIMO \ scenario \qquad (3)$$

If neighboring cells' PCIs have different shifts (u_d), the cells' RSs do not overlap in frequency resulting in less interference on UE channel estimation. This is critical for intra-eNB cells.

The uplink demodulation RS sequence is defined by a cyclic shift of a base sequence $r_{u,v}$. Sequences $r_{u,v}$ are divided into 30 groups ($u = 0, 1, ..., 29$) each having one ($v = 0$) or two ($v = 0, 1$) sequences [3]. To minimize RS interference, neighboring cells should be assigned different base sequences. This requires that $PCI \ mod \ 30$ is different among such cells, although more complex schemes have been proposed [5].

B. PCI Assignment Objectives

Owing to the limited PCIs, some PCIs must be reused in different cells. Methods have been proposed for extending the PCI range, e.g. using the time synchronization between the cells [6], but they have not been extensively studied and thus not included in the standards. Consequently, we can only use the limited PCIs targeting the following objectives:

1) *Minimize the number applied PCIs:* A smaller number of PCIs ensures that during cell search, the initial detection of PCIs by the UEs is easier as there is a one-to-one mapping between the reference symbols and the PCIs.
2) *Avoid PCI collision:* A collision occurs if two neighboring cells A and B are assigned the same PCI as shown in Fig. 1a. The implication is that a UE coming from cell A towards the second cell B can not detect the new candidate cell since the candidate cell is also using the same PCI as the current serving cell.
3) *Avoid PCI confusion:* A confusion occurs if two cells C1 and C3 that are both neighbors to a cell C2 are assigned the same PCI (Fig. 1b), resulting in C1 and C3 handover measurements being ambiguous in C2. C2 is then confused whether to trigger handover to C1 or C3.
4) *Avoid (or minimize) m_0 and m_1 confusion:* For two PCIs P1 and P2, it is possible that one of the SSS root indices (m_0 or m_1) is the same, e.g., PCIs [1, 31, 60, 88, ...] all with m_0=1, or PCIs [5, 34, 62, 89, ...] all with $m_1 = 6$. If two neighbor cells C1 and C2 have PCIs P1 and P2 with the same m_0 or m_1, part of the SSS will be similar. Then, In low SINR conditions, a UE may not be able to differentiate the SSS (and the PCIs), resulting in a long synchronization time for the UE.
5) *Avoid (or minimize) RS Interference:* Cells for which either of $PCI \ mod \ 3/6/30$ is equal (Fig. 1c) will have increased co-interference among each other. As such good PCI assignment should ensure, when possible, that $PCI \ mod \ 3$ and $PCI \ mod \ 6$ are dissimilar among cells on the same Base Station (BS) and that $PCI \ mod \ 30$ is dissimilar among any two potentially interfering cells. Ensuring dissimilarity of $PCI \ mod \ 3$ and $PCI \ mod \ 6$ among cells on two neighboring BSs is practically hard to achieve, especially in hetnet scenarios and is thus not considered going further.

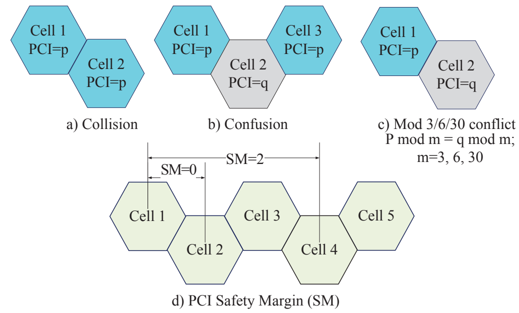

Fig. 1. Critical PCI conflicts and the safety margins (SM)

The degree of occurrence of the conflicts, especially PCI collisions and confusions, can be reduced by ensuring an adequate separation of cells with the same PCI. A safety margin (SM), shown in Fig. 1d, defines the number of cells between two cells C1 and C2 that are assigned the same PCI. For example SM=0 implies that the same PCI is allocated to two direct neighbor cells. Meanwhile SM=2, which is the minimum required to guarantee confusion free assignment (at least within one layer), leaves a space of two cells between the cells C1 and C2. One could imagine that a SM=2 is adequate in all scenarios, but it is sometimes necessary to have a bigger safety margin. For example, in scenarios where more cells are expected to be added to the network after the initial deployment, which will be the case for most UDNs, a bigger SM allows a PCI to be assigned to the new cell without changing the assignments of the existing cells.

III. PCI Sssignment Strategies

A. State of the Art Approaches

The PCI assignment problem has been fairly widely studied both for single layer scenarios, where it is fairly trivial, as well for the more challenging hetnet scenarios. The majority of the solutions, including [4], [7] [8], apply some degree of graph coloring to solve the problem. However, variations such as [9] and [10], which typically focus on the specific problem of introducing a new cell/eNB in an already operational network, do exist.

The shortcoming with all the solutions so far is that they have not considered potential UDN scenarios for the PCI assignment. They considered either the traditional single layer scenarios (e.g. in [5] [7] [10]) or the currently deployed hetnet scenarios, (e.g. [8]) where a macro cell network underlays a few small cells (up to 3 small cells/macro) and typically in a few hot-spots. Other solutions e.g. [7] consider PCI assignment in the pico layer but with the macro layer completely ignored. Moreover, even where the macro layer is considered, the assumed density of macro cells is also low - typically 3 sectors per macro e.g. in [4]. In practice the realistic deployment scenario is such that the macro network is densified with up to 6 cells/macro before the small cell layer is introduced. Another critical challenge is that all solutions we found have not considered the effects of m_0 and m_1 conflicts or the effects of RS shifts; all of which, as described in Section II, have significant effects on users' quality of experience.

In this study we wish to apply all the practical constraints as described in II-B to evaluate the likely UDN scenarios that consider a dense pico cell layer as well as dense macro cell layer. It is only then that we can truly conclude if the 504 PCIs are adequate for the dense networks that are expected to be deployed in the near future.

B. Derived Generic Strategies

In general, the proposed solutions show that PCI assignment is a graph coloring problem. For hetnet scenarios however, the solutions can be generalized into two strategies:

1) **Single PCI range**: In this case the entire PCI range, as shown in Fig. 2a, is used to assign PCIs in each and in every layer. This strategy includes all approaches that were studied in single layer networks such as those in [7], [10] and [5] as well as hetnet approaches like in [4]. To accurately assign the PCIs requires that each layer has full information about the PCI assignment in the other layer(s). This, however, is in practice not desirable since each layer may be provided by a different vendor and the small cells may typically not have X2 interfaces to directly query their direct neighbors for the outer neighbor relations (NRs). Nevertheless, allocating each layer independently would be inaccurate as the same PCI may be assigned to two cells that are neighbors to one another. Therefore, although it is not desirable, we assume the case of full information across layers, even if only as a reference case against which the other approach is measured.
2) **Range separation**: This approach, proposed in [8], splits the entire PCI range a priori into subranges, allocating a subrange to each layer (Fig. 2b). All cells in a given layer can only be assigned PCIs from the specific layer's subrange regardless of the applied assignment scheme. The main advantage here is that PCIs can be independently assigned in the different layers without sharing any knowledge across the layers. The drawback, however, is that the PCI ranges cannot be adjusted at runtime (i.e the value of x in Fig. 2b can not be adjusted at runtime). This implies that PCIs could easily be exhausted in one layer while they are underutilized in the other layer. Moreover, even though the assignment may be confusion free in each layer, there is no guarantee of the same confusion freeness across layers. These challenges will be investigated further in our study.

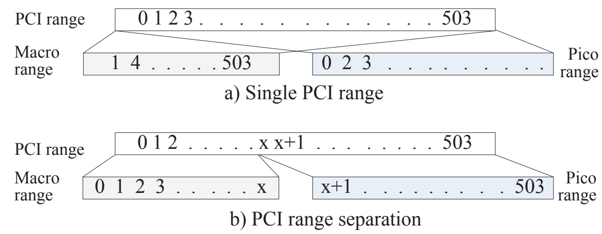

Fig. 2. PCI assignment Strategies

The two generic approaches represent the two conflicting desires in the PCI assignment problem for a hetnet environment. On the one hand, we would like to assign PCIs in each layer independently, i.e. without any concern as to what PCIs have been assigned in the other layer. This, addressed by range separation, would be important in the scenario where each layer is supplied by a different vendor and the vendor, for example, has a different SON solution for PCI assignment. This is also desirable since the macro network is likely to be stable for a long time while the pico layer is likely to change over time. On the other hand, independently assigning PCIs leaves the possibility that PCIs assigned in one layer conflict, to some degree, with the PCIs assigned in the other layer. The resulting effects are expected to be more pronounced in the UDN scenario and would thus require each layer to have full knowledge of the other layer. We therefore investigate these effects and determine the points at which each strategy breaks down in a UDN scenario. The next section describes our modeling of such a UDN scenario which we use in the evaluation in Section V.

IV. Generic UDN Scenario

As stated earlier, there are currently no UDN deployments. UDN related studies must as such only be evaluated through simulations. Meanwhile, a network level study with no direct implications for the UE (such as PCI assignment), does not require a full radio simulator or demonstrator. The critical requirement is that the demonstrator appropriately models the network entities (cells in this case) as well their interconnections (the NRs). For this study, we use an internal demonstrator that was developed for UDN network level studies to model the coverage and neighbor relationships.

A. Coverage Models

The demonstrator models two types of co-channel cells (macro and pico cells) deployed over a geographical area -

the coverage region. In this case, a 2 x 2 km square coverage region is considered, although any size can be configured.

1) Macro Cell coverage: In practice the actual macro cell coverage varies depending on the instantaneous combination of the cell's transmit power, antenna gains and tilts, and the prevailing propagation conditions. In general however, it is possible to guarantee a desired cell coverage through the combination of transmit power, antenna gain (antenna type) and antenna tilts. In this case we do not model these low level radio properties but assume that each macro cell can cover a maximum distance of 400 m. This implies that some combination of the low level radio properties can be found to guarantee a maximum coverage distance of 400 m. Meanwhile, to achieve a dense macro scenario, we assume 6 sectors (cells) per macro eNB, which translates into a beamwidth of at least 60^o. To allow for overlap regions among the co-BS cells, we assume a larger beamwidth of 75^o. These regions are needed for NRs and subsequently handover among the co-BS cells. Effectively, as shown in Fig. 3, each macro cell can be visualized as an ellipse with a major axis of 400 m and a minor axis of 300 m (beamwidth of 75^o). The macro cells are deployed in a regular hexagonal grid structure, ensuring that they provide full coverage over the considered area. To allow for handover regions among non co-BS cells, we consider an inter-site distance (ISD) of 500 m as shown in Fig. 3.

2) Pico Cell coverage: Similar to the macro cell, an abstract pico cell is modeled but with omni directional coverage of up to 100 m. Pico cells can thus be visualized as circles of 100 m radius as shown in Fig. 3. Since the macro layer offers full coverage, the pico layer does not have to cover the entire area. We are as such able to vary the pico layer ISD so as to evaluate the effect of density on the PCI assignment, but without loss of coverage.

B. Cell Neighborhoods

The most important network information elements for PCI assignments are the cell neighbor relationships. We therefore need to accurately model the rules for determination of cell NRs. Consider that we wish to determine if two cells B and K are neighbors. We assume the following:

- R_B and R_K are respectively the radii of cells B and K.
- R_M and R_P are respectively the maximum coverage distances of a macro cell and a pico cell. As stated earlier, these are set to 400 m and 100 m respectively;
- ν_{BK} is the vector from B to K, so that $\nu_{BK} = -\nu_{KB}$;
- $d = |\nu_{BK}|$ is the distance between B and K
- a Beam-factor τ which is a radiation characteristic parameter that defines the reduction in signal power, relative to the maximum, at a point that is at an angle β from the cell's direction of maximum gain (also called the bore-sight). In effect, τ, indirectly defines the radiation pattern as $cos(\beta)^\tau$. $cos(\beta)^\tau$ which is maximum at the bore sight and reduces towards the half-power beamwidth, defines the rate of roll-off of the ellipse that represents radio pattern. For the 6-sector macro BS, $\tau = 0.75$ is assumed

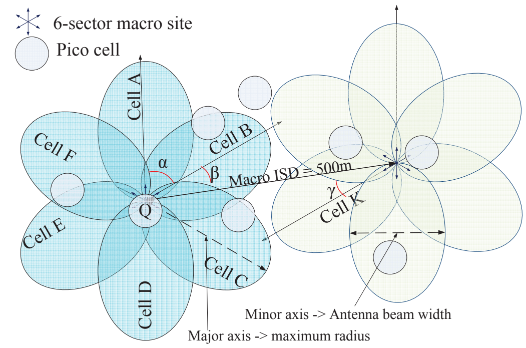

Fig. 3. Cell and network Model

while $\tau = 0.5$ and $\tau = 0.0$ would be appropriate for 3-sector macro and the omni directional BSs respectively.
- Two cells are collocated if their antennas are a very short distance (say 2 m) from each other.

Given these parameters, the simplest relationship is the one between 2 pico cells. Since both have omni directional coverage, the two are considered neighbors if the distance d is less than the sum of the radii of the two cells i.e.

$$d < 2 \cdot R_P \tag{4}$$

Meanwhile, for the macro cell B, a cell K is considered a neighbor if at least one of the following conditions is fulfilled:

1) K is a macro cell that is collocated with B and their directions of radiation differ by no more than 90^o. For example, in Fig. 3, cells A and C are considered neighbors to B while cells D, E and F are not. This condition is also true if K is a pico cell that is collocated with B owing to the omni directional radiation pattern.

2) K, a macro or pico cell, is not collocated with B but is located within B's coverage area. Assuming that the angle between vector ν_{BK} and the direction of radiation of B is β (Fig. 3), K is a neighbor to B if (5) is fulfilled.

$$d < R_M \cdot cos(\beta)^\tau \tag{5}$$

3) K is not collocated with B or located within B's coverage but is close to and (in general) radiating towards B. This means that the distance d fulfills the condition in (6).

$$d < R_B \cdot cos(\beta)^\tau + R_K \cdot cos(\gamma)^\tau \tag{6}$$

In (6), γ is the angle between K's direction and the vector ν_{KB} while β is, as earlier defined, the angle between B's direction and vector ν_{BK}. If K is a macro cell, $R_K = R_B = R_M$. Otherwise if K is a pico cell, $R_K = R_P$ and, owing to the omni directional radiation of the pico cell, $\gamma = 0$.

4) K is a pico cell and B is located within K's coverage. This happens if the distance d fulfills condition in (7).

$$R_P - d < \epsilon * R_P; \epsilon > 0; \tag{7}$$

ϵ, which defines the minimum difference between the pico cell's radius and the B-K distance, should be more than 0 to allow for a handover region between the two cells. In this study, we have assumed $\epsilon = 0.2$, which implies that B and K are neighbors if B is located at most 80 m from K. An example case where this condition fulfilled is the relation between cells Q and B in Fig. 3.

C. PCI Assignment

For both strategies, PCIs are assigned using graph coloring. The solution takes a list of NRs among cells and generates a graph whose nodes are the cells and whose edges are the NRs. For each node, edges are drawn up for all NRs up to the SM. Thus, if a PCI P is assigned to a cell C1, the scheme ensures:

1) to avoid PCI confusions based on the configured SM, i.e. P is marked as forbidden for all cells that are SM or less neighbors away from C1.
2) to avoid mod 30 among direct neighbor cells by marking as forbidden in those cells all PCI values p_i for which $p_i \ mod \ 30 == P \ mod \ 30$.
3) to avoid m_0 and m_1 conflicts among direct neighbor cells by marking as forbidden all PCIs p_i whose m_0 or m_1 are equal to m_0/m_1 values of P as defined in [3].

It follows from this discussion that the real difference between the two PCI assignment strategies is that, besides separating the PCI range into two, range separation restricts cells to having only same layer neighbors, i.e. cells do not have any neighbors in the other layer. In these studies, with the expectation of an average of 6 to 12 pico cells per macro in the eventual UDN, we divide the PCI range in the ratio of 1:5, i.e., so that the macro layer takes the first 80 PCIs and the rest allocated to the small cell layer.

V. Results and Discussion

This section describes the results of applying the two PCI assignment strategies to various UDN scenarios. The scenarios differ in the density of pico cells, represented by pico ISDs. In particular, with the macro ISD at 500 m, we consider the four pico ISD values of 150 m, 100 m, 75 m and 50 m for the pico layer, which translates into densities of 54, 120, 210 and 470 pico cells per km^2 respectively. An example deployment with a pico cell ISD of 100 m is the network in Fig. 4.

We consider three SM values [SM = 2, 3 and 4], the lowest selected because SM = 2 is the minimum required for confusion free assignment, at least in any one layer. Meanwhile, for a comparative evaluation of the effects of density and cell coverage, we also consider a case with extremely high density (pico ISD = 50 m) but where the coverage distance of the pico cell is reduced to only 50 m instead of the original 100 m. This effectively reduces the number of neighbors that are seen by each pico or macro cell.

We evaluate performance in terms of the six metrics given in table II that directly relate with the objectives in Section II. One should note that the four metrics 'conf', 'mod30', 'm_0' and 'm_1', are subject to double counting since each cell that observes the event adds it to the total count. The conclusions drawn from the result are however consistent since the same behavior is applicable in all scenarios.

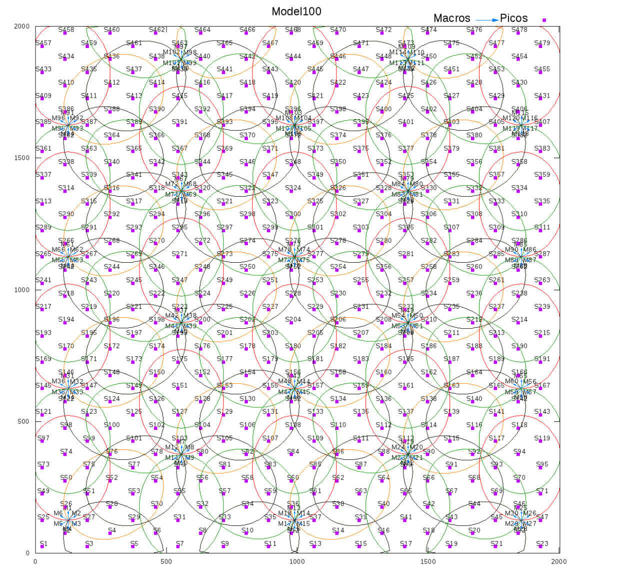

Fig. 4. Example UDN model: 6-sector macro BSs with 500 m ISD and omni directional pico cells with 100 m ISD

TABLE I
SIMULATION PARAMETERS

Item/Parameter	value(s)
simulation area	2 Km x 2 Km
macro cells ISD (m)	500
pico cells ISD (m)	150 100 75 50
macro eNBs	6 cells/macro, $beamwidth = 75^o$
macro cell structure	elliptical, major diagonal 400 m
pico eNBs	Omni, radius 100 m
safety margin	2 3 4

TABLE II
UDN PCI ASSIGNMENT EVALUATION METRICS

Acronym	Description
NoPCIs	Number of cells which have not been assigned PCIs. This happens when the PCIs are exhausted
PCIs	The number of PCIs used for the assignment
conf	The count of PCI confusions after the assignment
mod30	The count mod 30 conflicts after the assignment.
m_0	The count of m_0 conflicts
m_1	The count of m_1 conflicts

The observed results are shown in Figs. 5 and 6. Fig. 5 shows a plot for each of the four UDN models considered while Fig. 6 shows the special case of an extremely dense pico layer but with reduced maximum coverage. Each plot indicates the performance, in terms of the 6 metrics, for each of the different combinations of the strategies and safety margins.

The following observations can be made from the results:

1) As would be expected, the number of assigned PCIs increases with cell density and safety margin.
2) Range separation performs poorly in all scenarios. At its best, it avoids confusions when the SM is high. It, however, still generates too many mod30, m_0 and m_1 conflicts. In principle this strategy is simply unusable even in low density scenarios.
3) The single range strategy performs well in all scenarios except the extremely high density scenario. We observe

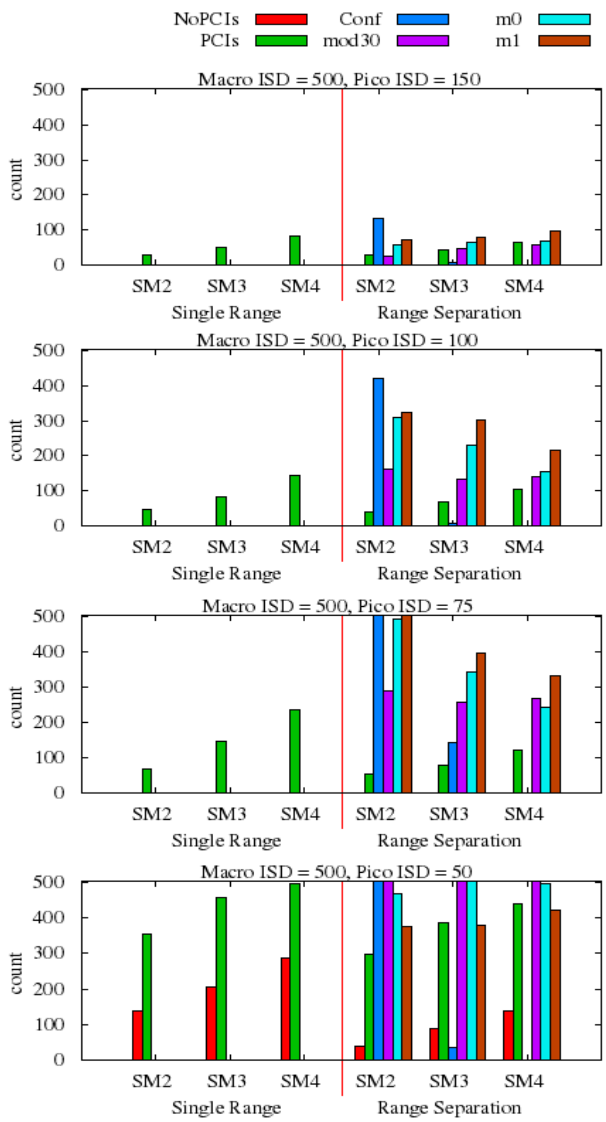

Fig. 5. PCI reuse and conflicts in four scenarios of varying pico cell densities.

in Fig. 5 that with approximately 250 pico cells per Km^2 (Pico ISD = 50 m), many cells cannot be assigned a PCI. Interestingly, some PCIs also remain unused, which is a direct consequence of the multiple constraints placed on any assignment. The unused PCIs would contravene at least one of the constraints if used at any of the unassigned cells.

4) Performance highly depends on the amount of interference in the network. Fig. 6, shows that the 50 m pico ISD density that was initially unachievable with the single range (according to Fig. 5) is now possible, yet with even fewer PCIs. On the contrary, although the number of PCIs used by range separation reduces, the conflicts increase excessively, even with a larger safety margin.

The overarching conclusion is that range separation is totally inapplicable in very dense hetnet environments. Meanwhile the single range approach performs well unless the density is very high and in a network with high interference levels.

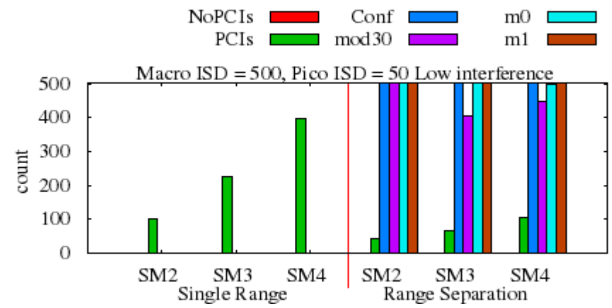

Fig. 6. PCI reuse and conflicts at a high density but with low interference

Such a limit case could include the scenario where pico cells are deployed with high transmit power, high antenna gains and/or small antenna tilts. Meanwhile, the challenge that the single range approach requires information from all layers also remains to be addressed. the reader should also note that changing the number of PCIs per layer would only change the relative number of events in each chart but not the conclusions drawn from the results. If more PCIs are allocated to the macro layer for example, it could allow for a higher SM resulting in less events but may not eliminate m_0 and m_1 conflicts.

VI. Conclusions

Multi-layer networks commonly called Hetnets that are currently in operation are expected to evolve into UDNs in future 4G and 5G networks. Current network auto-configuration solutions may thus cease to be functionally valid in such UDN scenarios. One such function is the auto-configuration of PCIs, where the increased density increases the probability of occurrence of PCI conflicts in these UDN scenarios. We evaluated the extent to which this is likely to happen for the two generic PCI assignment strategies.

Our results show that the two strategies have different performances and limit points. The range separation strategy, which was expected to perform better in terms of PCI efficiency, breaks down completely. It results in high counts of all the PCI conflicts even at low density. This is because without knowledge of the macro cells that are neighbors to each pico cell, two pico cells that are neighbors to one macro end up assigned with the same PCI resulting in a PCI confusion. Similarly, a pico cells could be assigned with a PCI that is related to that of the macro resulting in a mod30, m_0 or m_1 conflict. On the other hand, the single range strategy performs well in most scenarios and only breaks down when the pico cell density is very high and with large overlaps among the pico cells e.g. in a high interference environment. It however remains constricted by its major drawback of requiring knowledge of all layers in each layer under consideration.

The critical conclusion therefore is that solutions need to be devised for a compromise that allows the PCIs to be assigned independently in each layers, but that also reduces the risks of occurrence of PCI conflicts, especially PCI confusions. This is the expected area of our future work.

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