Physical Cell ID Allocation in Multi-layer, Multi-vendor LTE Networks

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Abstract. The evolution of radio access technologies and the user demand for increased capacity drives network deployments towards multiple cell layouts, often referred to as Heterogeneous Networks. With the ongoing rollout of commercial Long Term Evolution (LTE) networks, not only different radio access technologies are offered but LTE networks can also be multi-layered by themselves, consisting of differently sized cells providing coverage in overlapping areas. This comes with increased complexity of network management, which is even more relevant in common multi-vendor deployments, where coordinated configuration and operation of network elements provided by different vendors is essential. In this paper, we investigate and evaluate possible allocation schemes of an LTE radio parameter, the Physical Cell Identity. Results indicate that a particular allocation strategy, the range separation provides an elegant and efficient solution, which makes PCI management in multi-layer, multi-vendor networks easier. The standardization relevance of the range separation scheme is also discussed.

Key words: LTE, multi-layer networks, PCI, physical cell identity, range separation, self-configuration, self-organizing networks

1 Introduction

The increasing user demand for low latency, high speed mobile networks drives the evolution of radio access technology. Network operators deploy new radio access technologies (RAT) such as Long Term Evolution (LTE) to provide the required high data rates to mostly Internet based applications such as interactive web browsing or streaming video. LTE deployments may consist of differently sized cells (i.e., *resource layers*), usually referred to as macro, micro, pico, etc. cells, which may cover geographically overlapping areas in order to provide not only basic coverage but increased capacity where it is needed. Deployments making heavy use of overlapping differently sized cells are commonly referred to as Heterogeneous Networks (HetNet). Within one RAT, resource layers may use different or the same frequency band, the latter option being referred to as co-channel deployment. Additionally, HetNets may contain co-existing RATs including legacy Global System for Mobile Communications (GSM), High Speed Packet Access (HSPA) or Evolved HSPA technologies next to LTE. The scope of this paper focuses on the allocation of an LTE specific radio parameter; therefore, we focus on LTE deployments with multiple resource layers, which will be referred to as multi-layer LTE networks. However, the principles and concepts presented in this paper are applicable to different parameters in other RATs with multiple resource layers as well.

In LTE networks, Physical Cell Identity (PCI) is a low-level cell identifier broadcasted in the System Information Block Type 1 (SIB1), which is accessible after decoding the Master Information Block (MIB) of a cell [5]. There are 504 possible PCI values in the range of 0–503, divided into 168 PCI groups containing 3 IDs each [2]. The PCI is used in various radio related and mobility procedures such as handover, the configuration of physical layer measurements or Self-Organizing Network (SON) [8] use case Automatic Neighbor Relation (ANR) [3].

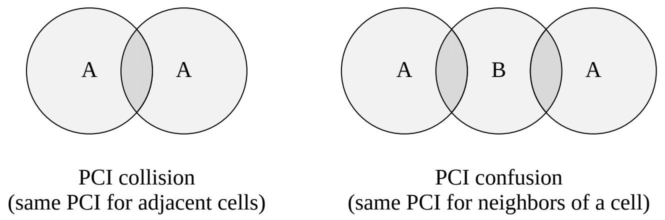


Fig. 1. Illustration of PCI collision and confusion, both of which should be avoided.

The PCI serves as the primary identifier for handover procedures, which are prepared and initiated based on the PCIs reported by the user equipment (UE). In order to allow successful handovers, the PCI allocation in a network has to fulfill two requirements: it has to be both *collision-* and *confusion-free*, i.e., scenarios illustrated in Fig. 1 must be avoided. Collision-free means that adjacent cells must not have the same PCI and confusion-free means that a cell must not have two neighbors configured with the same PCI. If there is PCI confusion, e.g., the serving cell of the UE has two neighbors with the same PCI, there is no unambiguous way to provide the UE with the identity of either of those cells as handover targets and such handovers may fail. Conflicting PCIs also make handovers impossible in case the source and target cells share the same PCI as it would be interpreted by the UE as a command to handover to the same cell to which it is currently connected. Therefore, proper PCI allocation is essential but due to the limited number of PCIs, it is a non-trivial task; proposals exist that aim at the extension of the available PCI range by considering time synchronization information along with the PCI together as the cell identity, effectively increasing the available number of different identities by 1024 times PCIs [9]. However, such solutions are not transparent to the network management and require UE support as well.

Proper PCI assignment in a network is challenging not only due to the limited number of PCIs compared to the large number of cells in different resource layers but also if different network elements are provided by multiple vendors (in particular, the case where each of the resource layers is provided by a different vendor); such multi-vendor setups are very common but often complicate configuration tasks if the required interfaces are not standardized or incompatible algorithms are implemented by vendors to find or assign optimal values to configuration parameters such as the PCI. For proper network operation, the PCI configuration of adjacent cells hosted by base stations from different vendors have to be closely aligned, which is a non-trivial task. A common network planning strategy is to deploy base stations from different vendors to separate geographical areas, which limits the number of adjacent cells on vendor boundaries in case a single resource layer is considered. On the other hand, if different resource layers (i.e., macro, pico, etc. cells) are deployed over the same geographical area to provide overlapping service and the resource layers are provided by different vendors, inter-vendor cell boundaries become very common, making PCI allocation especially complex.

In this paper, we investigate the feasibility of a PCI allocation scheme that can effectively deal with the multi-vendor problems in multi-layer LTE networks. The solution is fully network-based, making cell identity management transparent to UEs. The solution splits the entire PCI range into disjoint ranges and assigns each range to one of the resource layers, which may only use PCIs from their respective PCI range. The number of PCIs required by this range separation method is compared to the number of PCIs in a continuous allocation, i.e., if cells from the different resource layers are allocated PCI from the entire PCI range in a coordinated way so that collision and confusion-free requirement is fulfilled. The comparison is based on simulations of eight multi-layer LTE network scenarios, each having a macro and a pico layer.

The rest of this paper is organized as follows. In Section 2, different PCI allocation scheme for multi-layer networks are discussed and the motivations for using range separation are detailed. Section 3 describes the multi-layer LTE network scenarios taken for comparing the performance of range separation with the continuous allocation. Section 4 describes the simulation setup and Section 5 gives the result and the evaluation of the simulations. Finally, Section 6 concludes the paper.

2 Multi-layer PCI Allocation Schemes

Basically, three different PCI allocation techniques may be considered in multi-layer networks, as illustrated in Fig 2 and detailed below. All strategies assume the existence of an *algorithm* that is able to provide a proper PCI allocation within a single layer.

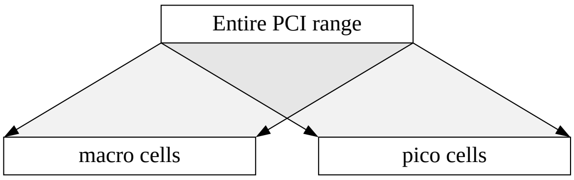
Layer independent: this is a straightforward but somewhat inaccurate scheme where the entire PCI range (0–503) is used independently to allocate PCIs in each layer. Although the PCI allocation within a given layer satisfies the collision- and confusion-free criteria, the same PCI may be allocated to cells in different layers with inter-layer adjacency (e.g, overlapping with each other); therefore, reactive conflict detection and resolution is required to provide also proper inter-layer allocation, which must be executed in the live network, possibly causing service disruption due to the PCI reconfiguration.

Continuous with cross-layer coordination: cells in the different resource layers can be given PCIs from the entire available range but in a way that the PCI allocation is coordinated between layers at run-time, ensuring that inter-layer adjacencies also satisfy the proper PCI allocation requirements.

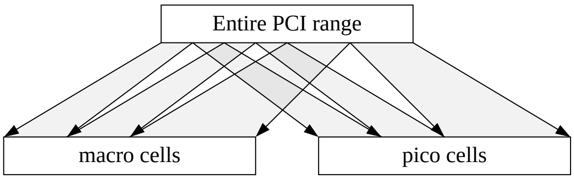
Range separation: the entire PCI range is split a priori into disjoint ranges, each of them dedicated to one resource layer and cells from each layer may only be assigned PCIs from the corresponding PCI range at run-time. This facilitates fully independent PCI allocation in the different layers, at the same time ensuring that no PCI collision or confusion may occur provided that the PCI allocation is proper within each layer. On the other hand, the range separation cannot be adapted at run-time, i.e., it can happen that while one layer runs out of PCIs, the other layer underutilizes its allocated PCI range.

The layer independent allocation scheme is not effective as it trades the complexity of providing proper intra- and inter-layer PCI allocation for the complexity of reactive collision and confusion resolution in the operational network. Despite causing potential service interruption, the conflict resolution has the same multi-vendor issues as if the allocation would have to be coordinated among various layers in case they are provided by different vendors. The continuous allocation with cross-layer coordination has the same complexity (where complexity lies in the coordination), with an advantage of being free from operational-time PCI conflict resolution. However, from multi-vendor point of view, the same constraints apply.

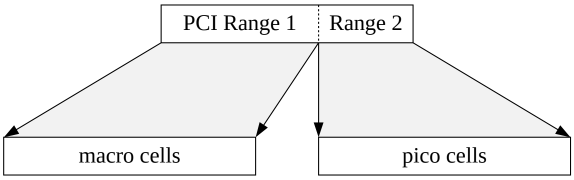
Range separation has two advantages over the other allocation methods: it has lower complexity and it facilitates multi-vendor allocation in case the resource layers are provided by different vendors; however, single vendor deployments are also supported. A requirement for using range separation is the ability to split the entire range into suitable ranges and to convey the configuration to the network entities performing the PCI allocation, which is required to support both centralized and distributed approaches [4]. Defining the PCI ranges is possible only if the sum of the PCIs required to provide the proper allocation in each of the layers is less than 504, i.e., the total number of PCIs. In this study, it is investigated whether a feasible separation can be created in case of different multi-layer LTE scenarios; for comparison, the continuous cross-layer



(a) layer independent



(b) continuous with cross−layer coordination



(c) range separation

Fig. 2. PCI allocation techniques.

coordinated technique is also evaluated. The number of PCIs required by the layer independent allocation is theoretically the same as that of the coordinated allocation as both methods use the entire PCI range and consider all resource layers at the same time; therefore, it is enough to use the coordinated allocation as the reference.

3 Scenario Description

In this paper, eight LTE HetNet scenarios have been studied, each of which having two different cell layers: a macro layer and a pico layer. These scenarios are based on research of the characteristics of the anticipated macro network evolution together with selective deployment of pico cells taking place in Nokia Siemens Networks. The scenario description consists of the location of the macro and pico sites along with a few radio parameters. Each macro site had three or six cells with 46 dBm maximum transmission power and specific antenna bearing and tilting. The pico cells were assumed to be omnidirectional with 30 dBm transmission power. In these scenarios, pico cells are deployed for capacity enhancements as an addition to good macro coverage.

In order to obtain the adjacency information, a simulation has been conducted based on the Okumura-Hata path loss model complemented by horizontal and vertical antenna characteristics for macro cells according to [1]. The deployment area has been traversed with a 1 × 1 m resolution to find the best cell s at each position P having the highest Reference Signal Received Power (RSRP), denoted by $\mathrm{RSRP}_s^{(P)}$. Besides the best cell, each cell $i^{(P)}$ was identified and added to a set $N^{(P)}$ at each position for which

$$\mathrm{RSRP}_i^{(P)} > \mathrm{RSRP}_s^{(P)} - \mathrm{HO}_{\mathrm{offset}} - \mathrm{HO}_{\mathrm{hyst}} \tag{1}$$

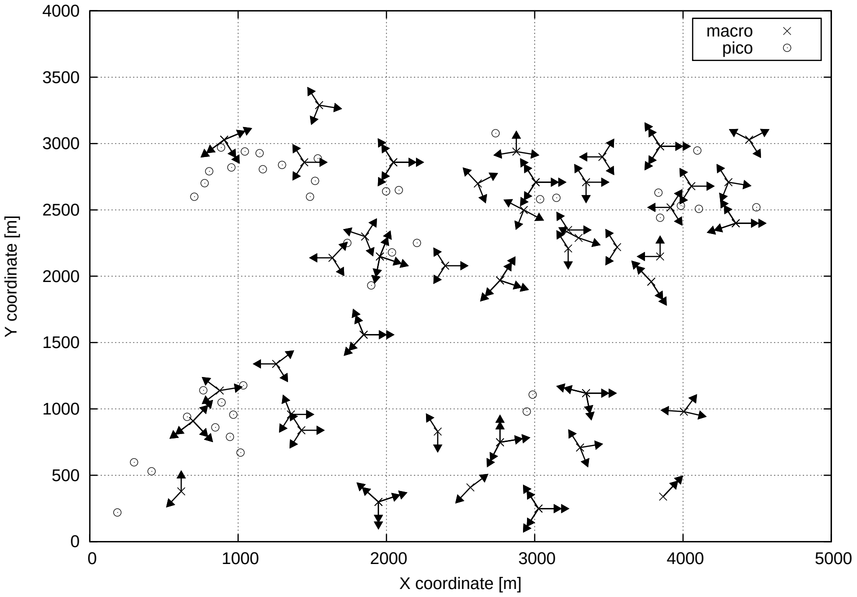
where $\mathrm{RSRP}_i^{(P)}$ is the RSRP of cell i at position P and $\mathrm{HO}_{\mathrm{offset}} = 3$ dB and $\mathrm{HO}_{\mathrm{hyst}} = 0.5$ dB were the handover offset and hysteresis values. Finally, pairwise adjacencies were added between cells in set $N^{(P)}$.

The properties of the adjacency graph built for each scenarios are shown in Table 1. Besides the total number of cells and edges, the number of macro and pico cells as well as the intra- and inter-layer edges are also given separately.

Table 1. Properties of the adjacency graph in the studied scenarios

	cells (graph nodes)			estimated adjacencies (graph edges)			
scenario	macro	pico	all	macro–macro	pico–pico	macro–pico	all
A1	160	40	200	1042	6	139	1187
A2	236	40	276	2346	6	192	2544
A3	236	100	336	2338	54	454	2846
B1	99	20	119	418	7	53	478
B2	135	20	155	528	6	72	606
B3	129	20	149	496	6	72	574
B4	99	70	169	413	43	209	665
B5	99	55	154	413	27	146	586

It is important to note that all cells are assumed to be co-channeled, i.e., deployed in the same or overlapping bandwidth, which means that in case two cells are neighbors from radio propagation point of view, they are potentially conflicting from PCI allocation point of view. In real deployments, separate frequency spectrum may be allocated to overlapping cells, which decreases the adjacencies needed to take into account for proper PCI allocation. Therefore, this study gives an upper bound for the number for PCIs and in case a proper PCI allocation was feasible in the considered scenarios it would be likewise feasible in real deployments. Fig. 3 and Fig. 4 show the layout of two networks, both of them illustrating different evolutionary stages, having fewer or more pico cells and in Fig. 3 even showing the expansion of macro cells as well.



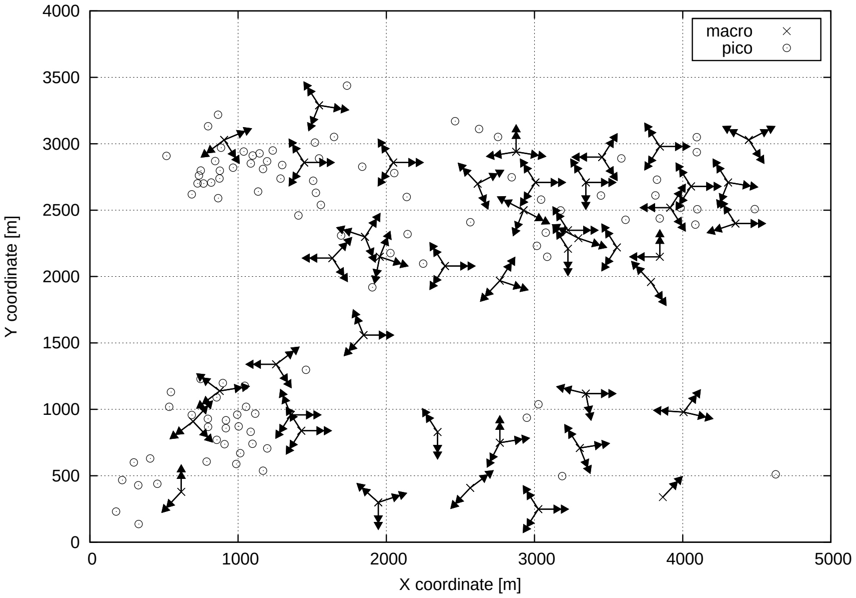
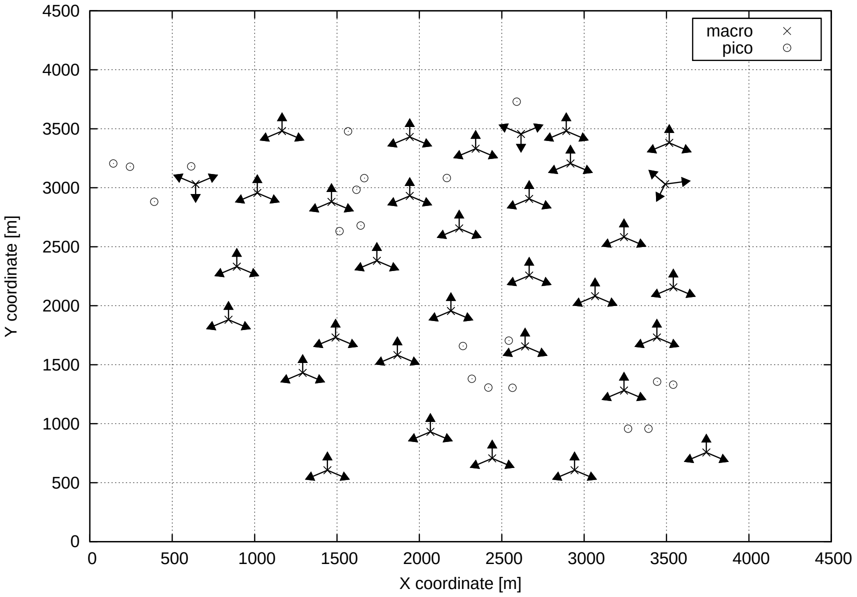


Fig. 3. Two evolutionary stages of the same multi-layer network, scenario A1 (top) and scenario A3 (bottom). Note that the extended layout was also subject to macro cell evolution, switching to 6-sectored cells at all macro sites.



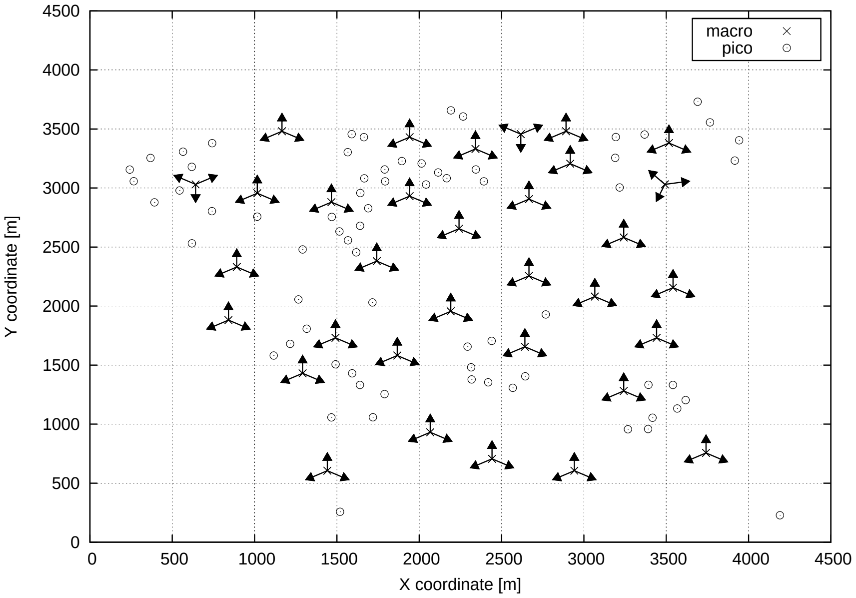


Fig. 4. Overlaying the same macro layer with pico cells having different level of expansion in scenario B1 (top) and scenario B4 (bottom).

4 Simulation Setup

The output of the air interface simulation was the adjacency graph of each scenario. This graph can be taken by a PCI allocation algorithm to find the number of PCIs required to properly allocate the IDs, i.e., in a collision and confusion free way. The algorithm used in this study was the graph coloring based PCI assignment technique explained in [7]. This algorithm takes a graph with cells as nodes and adjacencies as edges and outputs the number of PCIs required for allocation.

In order to compare the number of required PCIs with the continuous allocation and the range separation methods, the PCI allocation algorithm was executed on three different graphs as follows.

1. For the continuous allocation, the graph containing all cells (macro and pico) and all (both intra- and inter-layer) edges was used. The required number of PCIs for the continuous allocation is given directly by the algorithm.
2. For the range separation, the algorithm was run on two subgraphs: the first one containing only the macro cells (and the intra-macro adjacencies as edges) and the second subgraph consisting of the pico cells and the intra-pico adjacencies. The number of PCIs required for the range separation allocation is given by the sum of the PCIs used in the macro and pico layers separately.

Besides the cells and the adjacency information, the graph coloring based PCI allocation algorithm has an extra parameter called the *safety margin* (SM). It gives specifies a range around each cell (in terms of number of hops in the adjacency graph) in which the same PCI cannot be assigned more than once. Specifically, SM = 1 means only collision- but not confusion-free PCI allocation as it mandates that a PCI allocated to a cell must not be reused in any of the direct neighbors of the cell but permits its repeated usage otherwise. The SM = 2 means collision- and confusion free PCI allocation (i.e., this is the minimum SM fulfilling the requirements for proper PCI allocation) as it prohibits the usage of the same PCI not only among the direct neighbors of a cell among but its second level neighborhood as well. Choosing a SM higher than the required minimum 2 as although it results in more number of required PCIs, this also provides additional safety “buffer” in the PCI allocation by means of assuring that even in case new adjacencies are formed later in the operational network (due to neighbor relation discovery via ANR [3], additional cell deployment, etc.), still no or significantly less PCI reconfigurations are needed than with the minimum SM = 2.

5 Evaluation and Results

The performance of the continuous PCI allocation and the range separation approach was compared in scenarios A1–A3 and B1–B5 with different safety margin values. The required number of PCIs for proper allocation for the minimum SM = 2 are shown in Fig. 5.

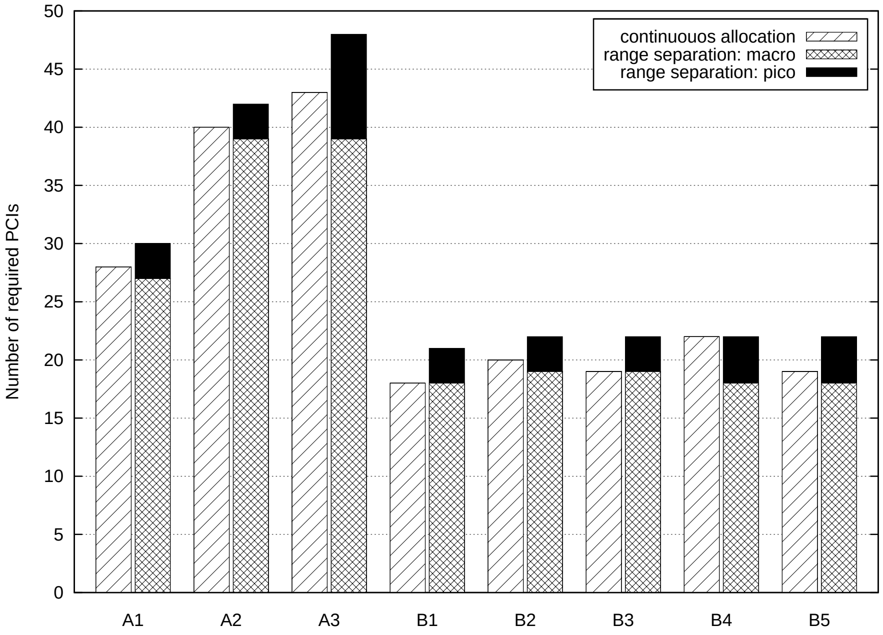


Fig. 5. Number of required PCIs with SM = 2 (collision and confusion free).

The results for higher safety margins (i.e., with additional safety buffer) is given in Fig. 6 for SM = 3 and in Fig. 7 for SM = 5. The latter is a relatively large safety margin to see whether a proper allocation is still possible even in that case. For the given scenario, in practice SM = 3 or 4 would be chosen to on the one hand leave some "headroom" for adding new cells in the same area (SM > 2) and on the other hand to avoid exhausting the full range of the available PCIs.

As the SM increases, range separation results in significantly lower number of PCIs (up to 30% less) in case there is a high number of inter-layer adjacencies (e.g., scenario A3 with 100 pico cells). The inter-layer adjacencies do not increase the connectivity of the per-layer subgraphs used by the range separation scheme, thus an increasing number of inter-layer adjacencies has no effect on the number of PCIs required by using range separation. However, inter-layer adjacencies may heavily increase the connectivity of the whole adjacency graph that has to be taken into account by the continuous cross-layer allocation.

With high SM, the adjacency graph extended with additional level of neighbors can even reach full mesh stage, i.e., each cell is connected with all other cells (e.g., scenario A3 with SM = 5). For the continuous allocation case, this may result in the same number of PCIs as the number of cells (including all layers) due to the inter-layer connections that make the graph fully connected. However, in case of range separation, only intra-layer meshes can be formed as the inter-layer adjacencies are not taken into account. Accordingly, in the macro

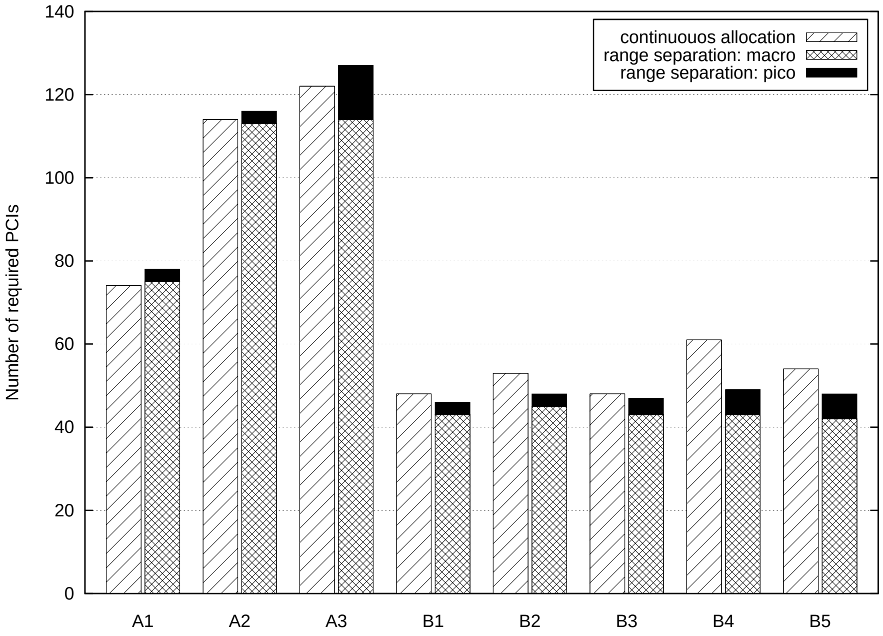


Fig. 6. Number of required PCIs with SM = 3 (collision and confusion free with extra buffer of 1).

layer, there can also be a full mesh due to its dense connectivity; however, in the pico layer, due to the sparser deployment, no full mesh is formed as the pico layer is not a connected graph in the beginning. As a result, with higher SM, the PCI range separation results in less number of PCIs due to the savings realized in the pico layer.

Based on the number of PCIs required for the proper allocation of the macro and pico layers using the range separation method, the splitting of the entire PCI range into macro and pico ranges is straightforward even considering high SM. An example range definition could be to allocate the range [0–399] for the macro cells and range [400–503] for the pico cells.

The PCI range separation scheme requires not only the definition of the PCI ranges but also their signaling to the appropriate network entity running the PCI algorithm. In case of a standardized solution, this information has to be sent via the Northbound management interface (Itf-N) standardized by the 3$^{\text{rd}}$ Generation Partnership Project (3GPP). The communication of the ranges requires a PCI list Information Element (IE); such an IE is currently defined in [6] as the `pciList` as an attribute of the `EUtranGenericCell` abstract information object class. However, the shortcomings of the current definition of `pciList` is that it requires the enumeration of all PCI values allowed to be used by the PCI allocation algorithm. A potential improvement would be to allow the definition of consecutive PCI ranges by specifying only the first and last PCI in

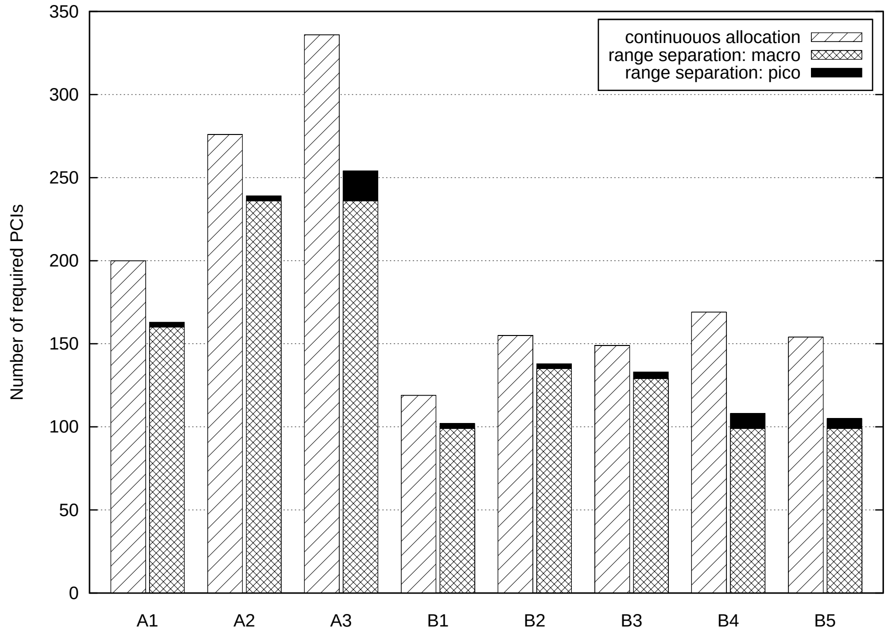


Fig. 7. Number of required PCIs with SM = 5 (collision and confusion free with extra buffer of 3).

the range, making their configuration more effective. The definition of multiple ranges should also be permitted.

The evaluation covered the comparison of the continuous PCI allocation and the range separation techniques. Considering the layer independent allocation with reactive conflict resolution, it can be anticipated that since each inter-layer edge is a potential conflict, the number of reconfigurations required in the live network in that case is proportional to the number of inter-layer edges. Given the number of inter-layer edges in Table 1, it can turn out to be significantly high. An improvement to the layer independent allocation method and partial solution to this problem could be the introduction of an OAM-based cross-layer "auditing" of the initial PCI configuration to spot and resolve obvious inter-layer conflicts offline before the cells are gone operational and thus minimize the required live reconfigurations.

6 Conclusion

In this paper, the PCI allocation was evaluated in eight multi-layer LTE network deployments considering the continuous cross-layer coordinated and the range separation allocation schemes.

The PCI range separation performs similarly to the continuous allocation already at the minimum SM = 2, i.e., satisfying the collision- and confusion free criteria without additional safety buffer. With higher SM, the range separation requires even less number of PCIs than the continuous allocation. This is due to the higher SM creating increased number of inter-layer dependencies, which on the one hand turn into additional constraints for the continuous allocation but on the other hand can be completely ignored by the range separation scheme, making it a more scalable solution. In summary, range separation is a feasible allocation scheme, providing the additional benefits of allowing independent PCI allocation schemes on each layer, which is an enabler for multi-vendor PCI allocation. For the considered scenarios, which are believed to be realistic in the time frame until 2020, even for higher SM, the choice of the ranges provided to be fairly simple. The limit of the ranges was not exceeded in any cases.

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