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Cluster-Based Hybrid Approach for PCI Configuration and Optimization in 5G EN-DC Heterogeneous Networks

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Abstract
With the development of 5G technologies and the implementation of EN-DC architecture in heterogeneous networks, managing Physical Cell Identity (PCI) has become increasingly complex. EN-DC, facilitating the coexistence of eNBs and gNBs, creates a densely populated environment that heightens the risk of PCI collisions and confusions. This study introduces a novel hybrid approach to PCI configuration in EN-DC networks, integrating centralized and distributed strategies. By organizing the network into clusters and employing newly introduced algorithms, Symmetrical Comparison (SC) and Symmetrical Triangular Cycling (STC), the method efficiently identifies and resolves PCI confusions. Simulations were conducted to evaluate the effectiveness of the proposed model under various scenarios, revealing its proficiency in preventing PCI confusion and $mod\ 30$ collisions. The results underscore the critical role of PCI pool size and offer insights into network planning and optimization. Despite some challenges in handling specific collisions, such as $mod\ 3$ and $mod\ 4$, the study suggests that incorporating reinforcement learning techniques could provide more adaptive solutions, laying the foundation for future research in this area. The research contributes to the evolving landscape of 5G EN-DC networks, emphasizing the importance of intelligent design and meticulous planning in network management.

Keywords: Physical Cell Identity (PCI), EN-DC Architecture, Heterogeneous Networks, PCI Collision and Confusion, 5G Network Optimization

1. Introduction

Wireless communication technology has evolved rapidly, transitioning from 3G to 4G and now moving towards 5G and beyond, with LTE networks playing a significant role [1]. With the increased demand for higher user throughput, the deployment of multi-layer networks, commonly called heterogeneous networks (HetNets), has become essential [2]. These developments in network densification and heterogeneous systems have emphasized the importance of autoconfiguration and optimization of radio parameters, such as Physical Cell Identity (PCI) [3-5]. PCI serves as a critical cell identifier in LTE networks, and improper assignment can lead to challenges such as PCI collisions, confusions, and $mod\ q$ interference [4, 6-8]. The limited number of available PCIs (504 in LTE, 1008 in 5G NR) further complicates the management in ultra-dense network environments, with the deployment of small cells alongside traditional macro cells adding to the complexity [2, 9]. Bandh et al. [3] and Liu et al. [4] have discussed the challenges in configuring network parameters, specifically focusing on PCI allocation and management.

Several approaches to PCI allocation have been proposed, ranging from graph coloring-based methods [3-4, 10] to neural network-based techniques [11]. For instance, Bandh et al. [3] mapped the PCI assignment problem to graph coloring, offering an efficient solution for initial assignment and network growth. Liu et al. [4, 12] explored automatic centralized and distributed PCI assignment mechanisms for LTE, utilizing graph coloring algorithms. Mwanje et al. [2] examined the limits of PCI autoconfiguration in ultra-dense networks, shedding light on the challenges in such complex environments. The integration of machine learning and heuristic optimization has also been explored for PCI configuration, as demonstrated by Shahab et al. [11], Wu et al. [13], and Chen et al. [14].

Shahab et al. [11] proposed a neural network-based graph coloring technique for PCI assignments in self-organized LTE networks, highlighting its efficiency. Wu et al. [13] proposed a heuristic optimization model for PCI allocation in real-life LTE networks, demonstrating its effectiveness in reducing interference. The application of self-organizing networks (SONs) and novel algorithms to address PCI conflicts in LTE-femtocell networks has also been a focus of research [10, 15-16]. Abdullah et al. [15] introduced a novel scheme to resolve PCI conflicts in LTE-femtocell networks, conserving network resources. Mwanje and Ali-Tolppa [16] presented a layer-independent PCI assignment method for Ultra-Dense multi-layer co-channel mobile Networks, optimizing PCI assignment without requiring information exchange across layers.

Despite these advancements, challenges remain in implementing efficient PCI assignment, particularly in large-scale, complex networks [17-19]. Acedo-Hernández et al. [6, 19-20] conducted comprehensive analyses on the impact of PCI planning on downlink and uplink performance in LTE, emphasizing the importance of avoiding interference problems. Acharya et al. [10] proposed a combined MST and graph coloring algorithm for PCI distribution in Self Organizing Networks, aiming to decrease collisions and confusion. Sedlacek et al. [21] and Chandra et al. [22] further explored the optimization of PCI interference, while Zeljković et al. [23] introduced new algorithms taking advantage of weighted ANR. These studies underline the ongoing need for research and innovation in this domain.

The aim of this study is to explore a novel approach to PCI assignment that takes into consideration the complexity of contemporary wireless networks, especially 5G. Leveraging advanced optimization techniques, the research seeks to develop a robust and adaptable PCI allocation algorithm that can handle various constraints and scenarios. The scope encompasses the analysis of existing PCI allocation methods, the design of a new algorithm, and extensive simulations to validate its efficacy in diverse network configurations. By addressing the critical issue of PCI assignment in modern wireless networks, the study contributes to the broader goal of optimizing network performance and user experience. The findings may offer valuable insights and practical solutions for network operators, researchers, and policymakers engaged in the design, deployment, and management of next-generation cellular networks. The remainder of this paper is organized as follows: Chapter 2 delves into PCI assignment-related problems and techniques, including the study of dual connectivity and the interfaces. Chapter 3 introduces the determination of constraints, the consultation mechanism, and the proposed PCI self-configuration and optimization algorithms. In Chapter 4, we present a fictitious EN-DC dense heterogeneous network topology, along with the simulation results and corresponding analyses. The final considerations are presented in Chapter 5. Experimental results are shared on GitHub.

2. Related Work

2.1 Cell Search in UE Initial Access

Before gaining network access, User Equipment (UE) must conduct a Cell Search to achieve time-frequency synchronization, identify cellular entities, and obtain Physical Cell Identity (PCI). This process, as depicted in Figure 1, involves the following steps:

1) Central frequency scanning: This initial stage entails sweeping through the central frequency to measure the frequencies of potential cellular entities within the searching spectrum. Frequencies exhibiting strong signals are subsequently reserved for demodulation analysis.

2) Primary Synchronization Signal (PSS) demodulation: UE performs PSS analysis on the subcarriers within the frequency. Transmitted at a 5 ms interval in the case of LTE, three distinct primary synchronization sequences are generated in frequency domain using Zadoff-Chu sequence. By detecting PSS, UE can identify the cell identity within a cell identity group.

3) Secondary Synchronization Signal (SSS) demodulation: SSS is positioned in the last OFDM symbol of both subframe 0 and subframe 5, with each subframe transmitting distinct SSS at a period of 10 ms in the case of LTE.

UE can compute SSS to identify the cell identity group and establish the 10 ms LTE radio frame time synchronization. At this time, PCI can be obtained.

4) Cell Reference Signal (CRS) demodulation: Determine the position of CRS and the antenna port configuration of the cell through PCI.

5) Broadcast information acquisition: Upon confirming frame synchronization and antenna configuration, UE can proceed decoding and analysis of Master Information Block (MIB) and the System Information Block (SIB).

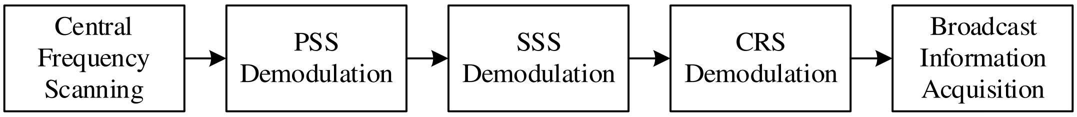

Figure 1 Cell Search Procedures in LTE.

2.2 PCI Assignment Methodology

In 4G LTE, Physical Cell Identifier (PCI) has a total of 504 available distinct values with the range of 0 to 503 under 3GPP specification 36.211 [26], and a PCI can be expressed as equation (1).

$$N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)} \quad (1)$$

Where $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$ represents the physical cell identity group (0 to 167) and the cell identity within the group (0 to 2), correspondingly. Moreover, each cell identity group encapsulates three singular cell identities, and every cell identity is intrinsically tied to the Primary Synchronization Signal (PSS). Therefore, after successfully demodulated PSS, $N_{ID}^{(2)}$ can be obtained since the PSS is linked to the cell identity within the group. Similarly, $N_{ID}^{(1)}$ can also be obtained by demodulating SSS which is linked to the cell identity group. While the value of $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$ are both established, physical cell id N_{ID}^{cell} can be easily determined through equation (1). Collectively, PSS and SSS, embedded within the structure of PCI, significantly enhance the efficiency and robustness of cell identification, selection, and reselection procedures in LTE network.

The assignment and optimization of PCI plays a vital role in optimal operation of LTE network. Due to the limited number of PCIs, it is unavoidable to re-use the same PCI between cells when performing PCI assignment under the condition of a large-scale mobile communication system, so there may be a certain amount of interference between adjacent cells. Thus, the goal of PCI optimization is to avoid PCI Collision, that is, a situation in which two contiguous cells possess identical PCI as shown in Figure 2 (a), and PCI Confusion, where two cells situated on an identical path exhibit the same PCI as shown in Figure 2 (b).

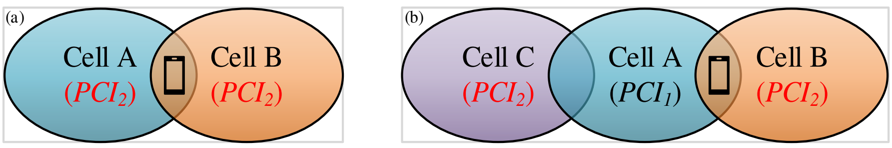

Figure 2. (a) PCI Collision, (b) PCI Confusion.

In situations where the PCIs of neighboring cells are the same, the reference signal sequences will be identical, which will engender CRS interference. Additionally, identical PCI $mod\ 3$, $mod\ 6$, and $mod\ 30$ in adjacent cells can also induce PCI interferences. These interferences are manifested in the following scenarios:

1) When PCI $mod\ 3$ of adjacent cells is identical, it will result in the interference of PSS according to the PCI calculation equation (1). In such instances, UE cannot discern a unique identifier from the three cell identities within the cell identity group when detecting PSS, which leads to the disruption of UE's access to the network.

2) In the case where PCI $mod\ 6$ of neighboring cells is identical, the position of reference signal on the antenna port aligns [20]. Consequently, the reference signal of adjacent cell in the frequency domain will be completely the

same, leading to CRS interference between cells.

3) If PCI $mod\,30$ of neighboring cells are the same, since the Physical Uplink Shared Channel (PUSCH) carries Demodulation Reference Signal (DM-RS) and Sounding Reference Signal (SRS), and they are composed of 30 basic ZC sequences, implying 30 different sequence combination, the mutual interference will occur between DM-RS and SRS, thus, significantly impacts channel estimation and demodulation.

With the standardization of 5G NR, the available values of $N_{ID}^{(1)}$ have been doubled from 168 to 336, leading to the enhancement in quantities of the PCI pool, ranging from 0 to 1007, as stipulated by 3GPP specification 38.211 [27]. This expansion is driven by the anticipatory denser deployment scenarios intrinsic to 5G. Nevertheless, 5G NR retains similarities with 4G, particularly concerning the challenges of PCI collision and confusion. Despite the technological advancements and increased intricacy of 5G network architecture, issues such as $mod\,4$ collision which affects the Demodulation Reference Signal (DM-RS) of Physical Broadcast Channel (PBCH), remain exist. The complex task of managing PCI in a densely populated network environment continues to present substantial obstacles to realizing optimal network performance. The enduring nature of these challenges emphasizes the critical need for meticulous PCI planning and optimization, specifically adapted to the distinctive characteristics and demands of 5G networks.

2.3 PCI Optimization in Self-Organizing Networks

With the rapid advancement of wireless network technology and the increase in the number of various intelligent devices, the scale of wireless networks has also grown considerably. This expansion has led to an increasingly complex task of network parameter configuration. The intricacy and growing scale of these tasks have made manual completion increasingly challenging, and the OPEX have escalated accordingly. To mitigate these issues, mobile operators introduced Self-Organizing Networks (SON) during the standardization stage of LTE, aiming to minimize manual intervention, reduce operational costs, and enhance network efficiency.

Self-Configuration, which plays a key role in SON, means that after a new base station is connected to the network, it can automatically download and configure network parameters such as PCI, Automatic Neighbor Relation (ANR), and Radio Frequency (RF) parameters. Self-configuration operation commences upon the activation of the base station and ceases once the RF transmitter is switched on. It autonomously generates a planning strategy based on network parameters and accomplishes the initialization of various parameters. At the same time, eNB or gNB can be seamlessly integrated into the operation, cataloging, and reporting the information of relevant devices that joining the network, and automatically manage neighbor relations such as automatic addition and deletion of neighbor cells, self-configuration of PCI and other wireless parameters. Additionally, the base station also possesses self-inspection and independent fault analysis functionalities for each network product, aiding system verification and potential fault elimination. Therefore, the self-configuration process effectively mitigates the challenges associated with manual active investigation and operational errors. Moreover, it simplifies network deployment and management, enhancing the efficiency and cost-effectiveness of wireless network operations.

In the current landscape, with the emergence of 5G NR networks and ultra-dense networking, the importance of SON has become ever more prominent. Depending on the distinct characteristics of various networks, the functionalities achieved through SON are also different. In practice, there are mainly three architectural approaches to implementing SON in the consideration of PCI optimization, which will be described in the following subsections.

2.3.1 Centralized PCI Self-Configuration

The first approach is a centralized model, illustrated in Figure 3 (a). In this model, SON-related functions including PCI self-configuration are primarily implemented in the upper-level network elements of eNB and gNB, such as the Operation Administration Maintenance (OAM). OAM assigns valid PCI values to each base station based on their activation status within the specified area. It continually monitors the state of base stations within the area, collecting PCI-related data, and concurrently analyzes the collected PCI configuration information from each base station. Subsequent analysis and processing are conducted to identify any occurrences of PCI collisions and confusions between NR or LTE cells. When PCI collision or confusion happens, PCI self-configuration function allocates new PCI values to the affected cells via OAM. This process is repeated until all PCI collisions and confusions are fully resolved, to ensure efficient operation and network stability. This approach has the advantage of providing extensive control, effectively mitigating PCI collision. However, it has the downside of slower operational speed due to the interface differences between the endpoints, which will be described in section 2.4, and a more complex PCI allocation algorithm.

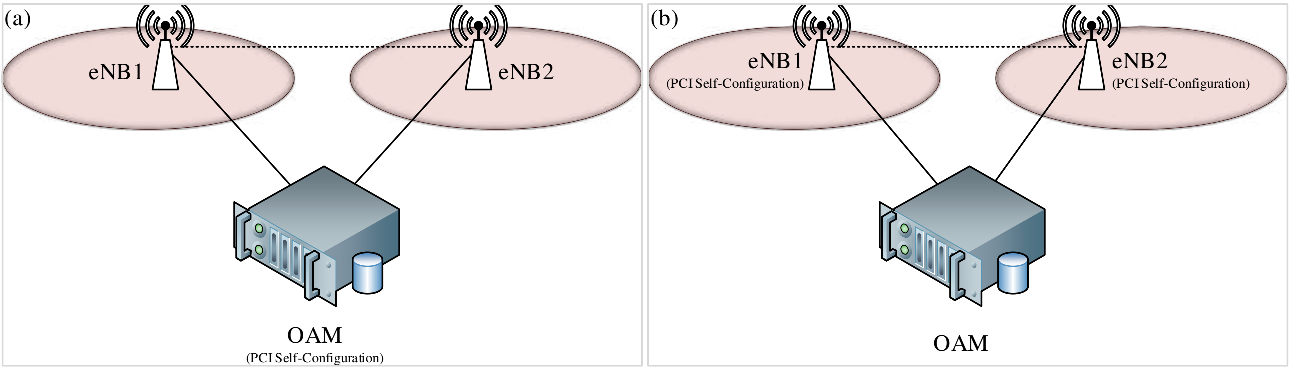

Figure 3. Self-Organizing Networks considering PCI optimization. (a) Centralized approach. (b) Distributed approach.

2.3.2 Distributed PCI Self-Configuration

The second approach employs a distributed model, as depicted in Figure 3 (b). In this method, SON-related functions are implemented individually on each eNB or gNB. Contrasting with the centralized model, the distributed method enables each base station to execute PCI allocation in parallel. PCI self-configuration function is realized on each eNB or gNB. Upon activation of a base station within a given area, OAM provides a list of valid PCI values to the corresponding base station. Leveraging the distributed PCI self-configuration functionality, the base station randomly selects a valid PCI value from this list and communicates the related information back to OAM. Subsequently, all base stations within the area check for potential PCI collisions and confusions based on their neighbor relation lists. If a PCI collision or confusion is detected, the affected cells use ANR function to eliminate the unavailable PCI values. Then randomly select a new valid PCI value from the remaining PCI list. This approach ensures efficient management of PCI values, enhances network performance by preventing and resolving PCI collisions and confusions, heightens the network expandability and PCI assignment efficiency. However, it also introduces a notable disadvantage, that is, an elevated level of complexity in the consultation process between base stations.

2.3.3 Hybrid PCI Self-Configuration

The hybrid model, depicted in Figure 4, adopts a comprehensive approach by implementing SON-related functions both at OAM level and within individual eNBs or gNBs.

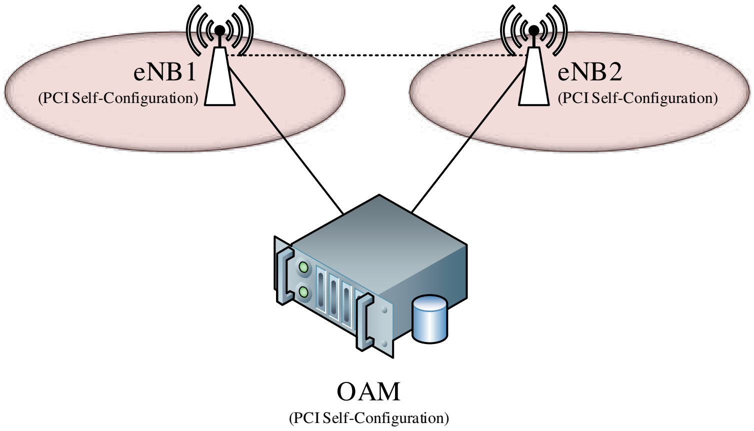

Figure 4. Hybrid PCI Self-Configuration in Self-Organizing Networks

This approach realizes SON functionalities by integrating the merits of both the centralized and distributed structures. Consequently, it necessitates the use of specific algorithms designed with topological considerations that covers both centralized and distributed scenarios. In this study, we have implemented a hybrid PCI algorithm that employs a symmetrical method for PCI optimization. Moreover, we have developed a topological structure comprising both eNBs and gNBs of 5G EN-DC heterogenous network, which is utilized for network visualization and algorithm verification. These developments will be elaborated in Chapter 3 and 4, respectively.

2.4 Dual Connectivity in 5G Heterogeneous Network

Homogeneous Network refers to the use of same Radio Access Technology (RAT) to provide support for diverse functionalities or application devices under the same protocol. In such network, all operative units share similar capabilities. On the other hand, in contrast to the former, Heterogeneous Network integrates two or more RATs. For instance, the topic of this study is conducted under the scenarios incorporating both 4G LTE and 5G NR technologies. Heterogeneous Network is composed of network equipment or systems manufactured by different vendors. It offers various functionalities. These network endpoints support a variety of functions or application devices under different protocols. Therefore, Heterogeneous Networks make full use of various existing wireless communication technologies, it provides wireless access services for diverse users, thereby enhancing communication efficiency and network coverage quality.

Dual Connectivity (DC) is a significant technology proposed under the 3GPP specification [28-29]. It means that UE establishing connections with two base stations, thereby interconnecting the same or two RATs within the network. This technique enhances the utilization rate of mobile communication's wireless resources and effectively reduces the time required for handover, thereby improving overall network performance [35]. The LTE/5G Dual Connectivity structure can be categorized into three major types according to the core network accessed and the characteristics of the primary and secondary endpoints [1]:

1) EN-DC (E-UTRA-NR Dual Connectivity) Architecture: This structure consists of a 4G EPC core network, a 4G base station eNB as the Master Node (MN), and a 5G base station gNB as the Secondary Node (SN), as shown in Figure 5 (a).

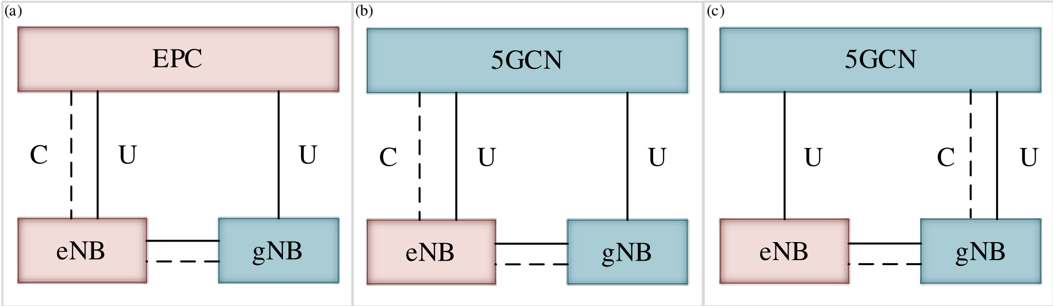

Figure 5. Different combinations of core network and RATs. (a) E-UTRA-NR Dual Connectivity. (b) NG-RAN E-UTRA-NR Dual Connectivity. (c) NR-E-UTRA Dual Connectivity.

2) NGEN-DC (NG-RAN E-UTRA-NR Dual Connectivity): This configuration includes a 5G Core (5GC) network, a 4G base station eNB as the Master Node, and a 5G base station gNB as the Secondary Node, as depicted in Figure 5 (b).

3) NE-DC (NR-E-UTRA Dual Connectivity): This setup involves a 5G Core (5GC) network, a 5G base station gNB as the Master Node, and an upgraded LTE base station, termed as ng-eNB, acting as the Secondary Node, as illustrated in Figure 5 (c).

There are mainly two application scenarios for LTE/5G dual connectivity, namely the deployment and interconnection of LTE and 5G NR under homogeneous networks and heterogeneous networks. In the context of a homogeneous network, both eNBs and gNBs function as macro or small base stations, adopting a uniform deployment strategy to provide identical and overlapping coverage, thereby enhancing network performance, as illustrated in Figure 6.

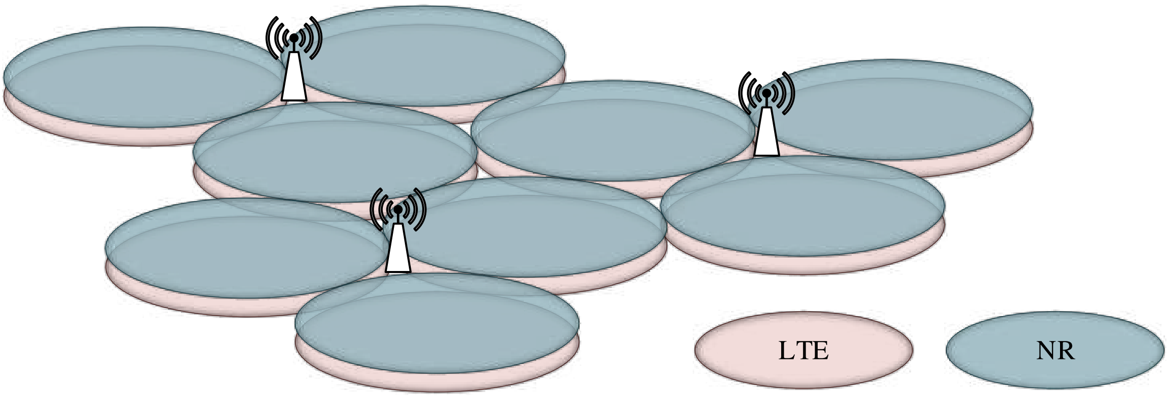

Figure 6. Deployment of LTE and 5G NR under homogeneous network.

In contrast, within a heterogeneous network, eNBs and gNBs serve as macro and small base stations, respectively. This implies a hybrid deployment of macro and small base stations to achieve separation of control and data traffic. Acting as the primary base station, eNB utilizes LTE technology to provide macro coverage, responsible for low-rate, high-mobility transmissions. Simultaneously, gNB functions as a small base station, utilizing 5G NR technology to flexibly deploy small cells within its specific region, thereby enhancing the network capacity within that area, as depicted in Figure 7.

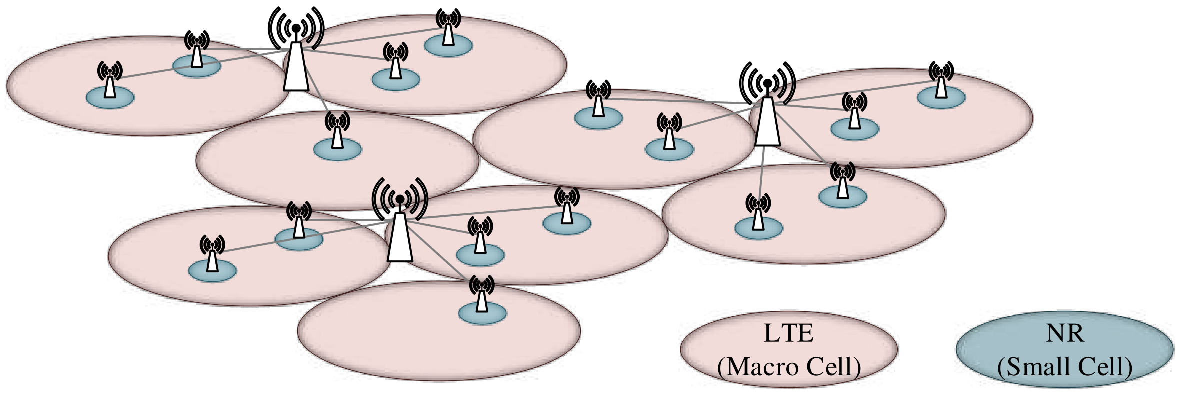

Figure 7. Deployment of LTE and 5G NR under heterogeneous network.

Under the architecture of LTE/5G Dual Connectivity, there are three types of neighbor relations: eNB-eNB neighbor relation, eNB-gNB neighbor relation, and gNB-gNB neighbor relation. Communication between neighboring cells relies on either the S1/NG interface, which involves communication through core network, or the X2/Xn interface, which enables direct communication between the cells. The Round-Trip Time (RTT) of S1 interface in LTE is generally larger than that of the X2 interface [30-32]. S1 interface works as a star network which serves as a feeder between each cell and the advanced gateway, while X2 interface operates as a meshed network that enables mutual information exchange between the cells. In LTE release 8, X2 may be used to accelerate occasional handover and the X2 traffic remains small compare with that of S1 [30]. In 5G NR, the NG and Xn interfaces are respectively based on the S1 and X2 interfaces of 4G LTE, thereby inheriting the characteristics of their predecessors. Furthermore, compared to the one-to-one communication model of X2/Xn interface, the one-to-many communication model of the S1/NG interface is more likely to encounter bottlenecks. However, it is also important to note that actual RTT or latency of the transmission may vary depending on the specific conditions such as distance between two endpoints, type of network traffic, and quality of network connection. The farther the distance between the two endpoints, the longer the RTT or latency will be. As for traffic types, real-time traffic, such as voice and video, requires lower latency than non-real-time traffic, such as file transfers. The quality of network connection can also affect RTT or latency. For example, a wireless connection is typically slower and has higher latency than a wired connection [33-34]. Thus, a primary objective of this study is to minimize the utilization of S1/NG interface by maximizing the use of X2/Xn interface wherever feasible.

2.5 X2 and Xn Interface

During the process of distributed PCI optimization, eNBs or gNBs need to filter out unavailable PCI values from the PCI list sent by OAM according to their neighbor relations listed in the neighbor relation list. Subsequently, they randomly select a PCI value from the PCI list to avoid PCI collision and confusion. Therefore, obtaining the neighbor relation list is of paramount importance, and since the base stations exchange information through X2/Xn interface, so in the following subsections, we will specifically introduce the working principle of the information exchange between different base stations through X2/Xn interface.

2.5.1 Information exchange between eNBs

First, eNB_1 initiates the process by sending X2 SETUP REQUEST message containing its serving cell information to eNB_2. Upon receiving the information, eNB_2 updates its configuration and related data, then sends its updated serving cell information back to eNB1 through X2 SETUP RESPONSE message, as shown in Figure 8 (a).

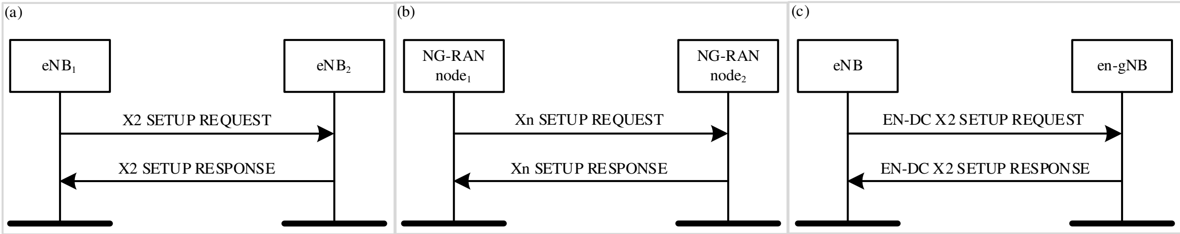

Figure 8. Interface establishment between base stations. (a) X2 interface establishment between eNBs. (b) Xn interface establishment between gNBs. (c) EN-DC X2 interface establishment under EN-DC architecture.

Both X2 SETUP REQUEST message sent by the initialized eNB_1, and X2 SETUP RESPONSE message sent by eNB_2 contain Neighbor Information IE (Information Element) and NR Neighbor Information IE. The Neighbor Information IE includes E-UTRAN cells that are directly adjacent to the eNB. And the NR Neighbor Information IE only includes NR cells that can perform EN-DC operations together with the corresponding serving E-UTRA cell [24].

2.5.2 Information exchange between gNBs

The process is initiated when gNB_1 sends an Xn SETUP REQUEST message containing its serving cell information to gNB2. Upon receiving the information, gNB_2 updates its configuration and related data, and then sends its updated serving cell information back to gNB_1 through Xn SETUP RESPONSE message, as shown in Figure 8 (b). Both Xn SETUP REQUEST and Xn SETUP RESPONSE messages contain Neighbor NG-RAN Node List IE for exchanging neighbor information [25].

2.5.3 Information exchange between base stations under EN-DC architecture

The process is initiated when an eNB sends EN-DC X2 SETUP REQUEST message containing its serving cell information to en-gNB. Upon receiving the information, en-gNB sends its serving cell information according to Cell and Capacity Assistance Information IE of the EN-DC X2 SETUP REQUEST message to the eNB through EN-DC X2 SETUP RESPONSE message. The process is illustrated in Figure 8 (c).

If EN-DC X2 SETUP REQUEST message contains the Protected E-UTRA Resource Indication IE, the receiving en-gNB should consider performing cell-level resource coordination with the eNB. Before receiving a new IE update for the same eNB, the en-gNB shall assume that the received Protected E-UTRA Resource Indication IE remains valid [24].

3. Hybrid PCI Self-Configuration and Optimization in Heterogeneous Network

3.1 Model initialization

The PCI Self-Configuration and Optimization model in this study is based on a dense heterogeneous network with dual connectivity, it utilizes a consultation mechanism through EN-DC X2 interface among base stations to achieve PCI initial configuration in this network. In terms of distributed portion of PCI allocation algorithms, it requires less information but provides more efficiency. Therefore, during the optimization phase, a SON network based distributed PCI Optimization algorithm is employed to solve PCI collision and confusion of the network to achieve a rational PCI allocation. However, as a downside of distributed PCI allocation approach during the phase of network initialization, the lack of centralized control may lead to information inconsistency. That is, when an eNB receives multiple requests for information exchange initiated by other eNBs at the same time, multiple eNBs may simultaneously choose the same PCI value, which will exacerbate PCI collision and confusion within the network, leading to a significant degradation in network quality after the initial configuration of PCI. Therefore, during the functionality design of PCI Self-Configuration, it is necessary to determine constraints on PCI allocation to partially introduce centralized control while utilizing a consultation mechanism. Thus, when multiple base stations engage in information exchange simultaneously, the probability of PCI collision and confusion can be effectively reduced through the consultation mechanism. By employing these two approaches, the optimized hybrid solution which induces the benefits of both centralized and distributed methods to the collision and confusion issues in PCI initial allocation can be obtained, thereby reducing the difficulty of resolving PCI collision and confusion during the self-optimization phase. During model initialization, it is essential to determine the constraints and incorporate the consultation mechanism at first, then perform the PCI initial configuration. Therefore, the three processes will be explained separately in the following sections.

3.1.1 Constraints Determination

In this paper, only the interference between neighbor cells is considered according to the PCI interference and PCI planning principles. Additionally, because there are 4G base stations (macro cells) and 5G base stations (small cells) in the network at the same time, the initial configuration method is designed to reserve the PCI values for macro cells first, followed by the initial configuration of PCIs for small cells. The purpose is to avoid PCI collision and confusion between macro cells and small cells, utilizing a hierarchical approach to achieve a logical separation between macro cells and small cells.

1) Constraint of Interference: Adjacent 4G base stations shall have different values of PCI $mod\ 3$, $mod\ 6$, and $mod\ 30$, to avoid PCI interference. Similarly, adjacent 5G base stations must have different PCI $mod\ 3$, $mod\ 4$, and $mod\ 30$ values to avoid PCI interference.

2) Constraint of Collision: Two neighboring cells cannot use the same PCI value.

3) Constraint of Confusion: Same PCI cannot occur in the neighbor cells of any cell within the network.

4) Hierarchical Constraint: PCI values assigned to macro cells cannot be assigned to small cells.

Above constraints are established to ensure the proper allocation of PCIs and prevent interference, collision, and confusion within the network.

3.1.2 Consultation Mechanism through EN-DC X2 Interface

PCI allocation algorithm with consultation mechanism is implemented in base station, each eNB and its surrounding gNBs forms one cluster, the central eNB works as a cluster head. Firstly, central eNB receives a PCI list from OAM, and then exchanges information through EN-DC X2 interfaces with surrounded gNBs to obtain neighbor cell information. When multiple eNBs or gNBs request for neighbor information, they need to send EN-DC X2 SETUP REQUESTs to the central eNB. Central eNB shall determine the order and timing of receiving EN-DC X2 SETUP REQUESTs then send EN-DC X2 SETUP RESPONSEs or EN-DC X2 SETUP FAILUREs to the corresponded eNBs or gNBs [24]. Central eNB is also responsible for obtaining neighbor information and select an available PCI value from the PCI list. The principles and processes of the consultation mechanism are detailed below and illustrated in Figure 9.

1) Connection establishment between central eNB and OAM: After the eNB is powered on, it sends a SETUP REQUEST message to the OAM, and the OAM responds with a SETUP RESPONSE message, establishing a connection between central eNB and OAM. OAM then sends a valid PCI list to the central eNB.

2) Allocation of PCI values: After receiving the PCI list, central eNB first allocates a PCI value to its own cell and then waits for connection establishment requests from gNBs. The remaining PCI values in the list are to be allocated to gNB cells.

3) Response order determination: Assuming that the response time of central eNB to a gNB is denoted as τ. As shown in Figure 9, when gNB_1 and gNB_2 send EN-DC X2 SETUP REQUEST messages to central eNB within time τ, central eNB needs to sort gNB_1 and gNB_2 in the order of arrival time.

4) Sequential response: Once the response order is determined, central eNB sends an EN-DC X2 SETUP

RESPONSE to gNB_1 first. After gNB_1 finished PCI assignment process, central eNB shall receive EN-DC CONFIGURATION UPDATE message from gNB_1, updates the neighbor relation list, then sends an EN-DC CONFIGURATION UPDATE ACKNOWLEDGE message to gNB_1. Only after this process is complete can central eNB respond with EN-DC X2 SETUP RESPONSE to the messages sent by gNB_2. Before that, gNB_2 will receive EN-DC X2 SETUP FAILURE messages from central eNB for any messages it sends. Therefore, gNB_2 needs to wait for a time of τ before sending the connection establishment information to central eNB, repeating the information exchange process between the central eNB and gNB_1.

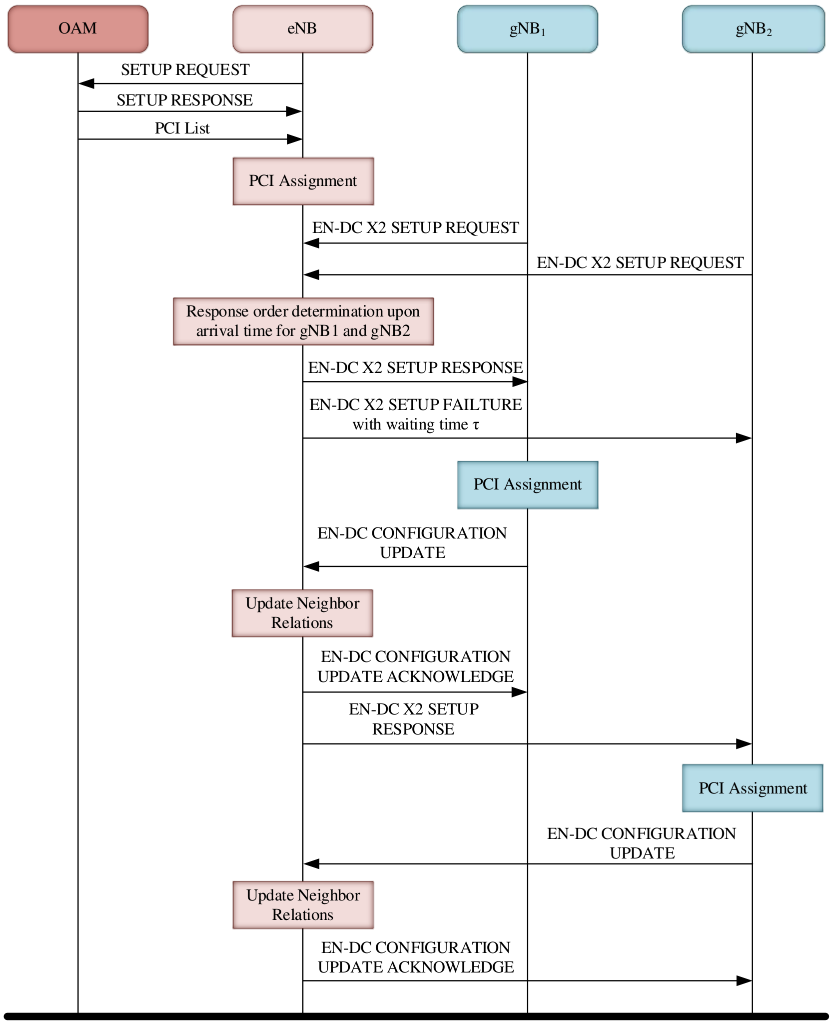

Figure 9. Consulting Mechanism through EN-DC X2 interface.

3.1.3 Initial Configuration

To improve the efficiency of PCI allocation, the concept of partitioning and hierarchical management is introduced in EN-DC heterogeneous network, where eNB serves as macro cell and gNB serves as small cell. The network is divided into multiple clusters, each consisting of a central eNB and neighboring gNBs.

Firstly, after eNBs and gNBs are powered on and accessed to the network to initialize relevant configurations then exchanged information with OAM, OAM shall determine the total number and relative locations of eNBs and gNBs, followed by creating a base station mapping table as $nodeMapList$, and defines PCI_Range which could be assigned, also initializes OAM_PCI_List which stands for the PCI list managed by OAM as well.

By using the concept of partitioned management, the network is divided into multiple clusters, with each cluster being managed by a cluster head eNB in a distributed manner. Here, $eNBList$ is established to keep track of all cluster heads. Then, following the hierarchical management approach, eNBs and gNBs search for neighboring base stations within a fixed search radius, determine the neighbor relationships, and exchange information with neighbor cells through X2 or Xn interface and consultation mechanism. This process enables the central eNB to collect information from all neighboring base stations then individually generate $gNBList$ for each eNB within $eNBList$, as shown in Figure 10.

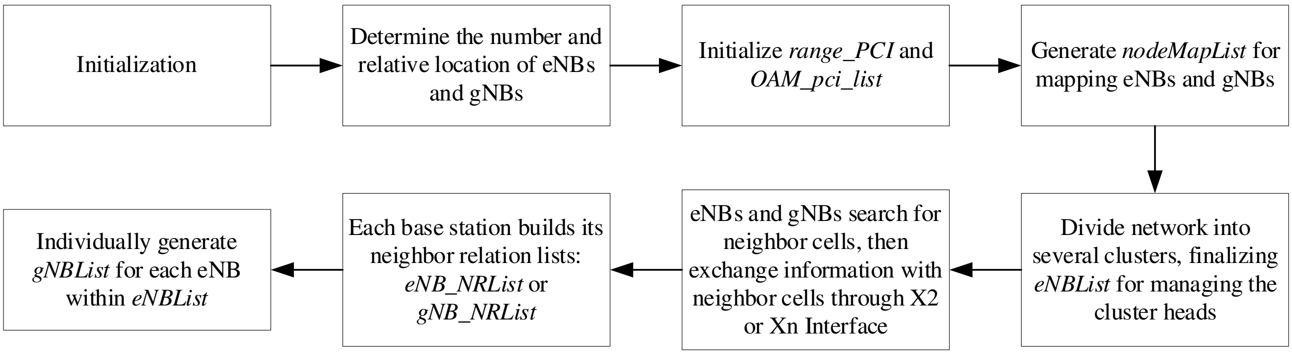

Figure 10. Initial Configuration

3.2 PCI Self-Configuration and Optimization Algorithm

After neighboring base stations of the eNB have completed the power-on and PCI initial self-configuration, Symmetrical Comparison (SC) algorithm and Symmetrical Triangular Cycling (STC) algorithm are introduced to solve the PCI confusion problem.

Symmetrical Comparison algorithm: As shown in Figure 11 (a), during the phase of self-optimization, when center eNB detects PCI confusion among neighboring cells, SC algorithm is triggered to check whether there are identical PCI values between neighboring eNBs that are symmetrically positioned around the central eNB, such as eNB$_1$ and eNB$_4$, eNB$_2$ and eNB$_5$, and eNB$_3$ and eNB$_6$. Details on SC algorithm are given in Algorithm 1.

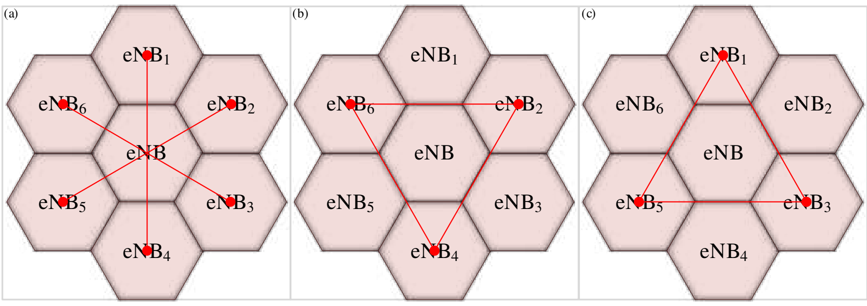

Figure 11. PCI Optimization Algorithms for PCI confusion. (a) Symmetrical Comparison algorithm. (b) and (c) Symmetrical Triangular Cycling algorithm.

Algorithm 1 Symmetrical Comparison (SC) algorithm for eNBs

```
Start;
for each eNB in eNBList do
    for each neighbor eNB in eNB_NRList do
        Get relative position of center eNB.
        Get 2 neighbor eNBs {eNB_m, eNB_n} on the same diagonal.
        Get PCIs {PCI_m, PCI_n} corresponding to {eNB_m, eNB_n}.
        if PCI_m == PCI_n then
            PCI confusion detected.
            Search eNBList to locate eNB_m.
            From OAM_pci_list, randomly choose PCI that is unused or differ from PCI_n then assign to PCI_m.
        end if
    end for
end for
Repeat above process until all PCI confusions among diagonal neighbors are located and resolved.
```

Symmetrical Triangular Cycling algorithm: STC algorithm takes central eNB as the center of a triangle, with the neighboring eNBs forming the vertices of the triangle. This creates two symmetric triangles, as shown in Figure 11 (b) and (c), where maximum six neighboring eNBs are positioned at the vertices of the two triangles. During the optimization phase, when central eNB performs PCI confusion detection among neighboring cells, it conducts pairwise cycling detection for the neighboring cells located in each symmetric triangle. In Figure 11 (b), it checks whether eNB_2, eNB_4, and eNB_6 are using the same PCI value, and in Figure 11 (c), it checks whether eNB_1, eNB_3, and eNB_5 are using the same PCI value. Details on STC algorithm are given in Algorithm 2.

Algorithm 2 Symmetrical Triangular Cycling (STC) algorithm for eNBs

Start;
for each eNB in *eNBList* **do**
  for each neighbor eNB in *eNB_NRList* **do**
    Get relative position of center eNB.
    Get 3 neighbor eNBs $\{eNB_m, eNB_n, eNB_p\}$ that forming 3 vertices of a triangle.
    Get PCIs $\{PCI_m, PCI_n, PCI_p\}$ corresponding to $\{eNB_m, eNB_n, eNB_p\}$.
    if $PCI_m == PCI_n$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_m.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_n then assign to PCI_m.
    else if $PCI_n == PCI_p$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_n.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_p then assign to PCI_n.
    else if $PCI_p == PCI_m$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_p.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_m then assign to PCI_p.
    end if
    Get 3 neighbor eNBs $\{eNB_\alpha, eNB_\beta, eNB_\gamma\}$ that forming 3 vertices of the symmetric triangle.
    Get PCIs $\{PCI_\alpha, PCI_\beta, PCI_\gamma\}$ corresponding to $\{eNB_\alpha, eNB_\beta, eNB_\gamma\}$.
    if $PCI_\alpha == PCI_\beta$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_α.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_β then assign to PCI_α.
    else if $PCI_\beta == PCI_\gamma$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_β.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_γ then assign to PCI_β.
    else if $PCI_\gamma == PCI_\alpha$ **then**
      PCI confusion detected. Search *eNBList* to locate eNB_γ.
      From *OAM_pci_list*, randomly choose PCI that is unused or differ from PCI_α then assign to PCI_γ.
    end if
  end for
end for
Repeat above process until all PCI confusions are found and resolved.

Process of self-configuration and optimization: PCI self-configuration is performed with OAM sending the same PCI list to all connected central eNBs. Central eNB randomly assigns a PCI value to itself according to the PCI list. Afterwards, the central eNB assigns PCIs that is differ from its own to the gNBs within its cluster based on $eNBList$. Once PCI assignment is completed, the central eNB and neighboring eNBs, as well as the gNBs in their respective clusters, exchange information through X2 or Xn interface using the consultation mechanism. Then the management lists including eNB_NRList, gNB_NRList, $eNBList$, and $gNBList$, are updated in a timely manner and stored in the central eNB. After PCI self-configuration is completed, PCI optimization process is performed to check whether there are any PCI collisions and confusions in the network among the central eNBs according to the constrains. Firstly, each central eNB examines its neighbor relations listed in eNB_NRList to identify collision. If the PCI value of a central eNB has the same $mod\ 30$, $mod\ 6$ or $mod\ 3$ as its neighboring eNBs, the central eNB selects another PCI value from the provided PCI list randomly. This process continues until the central eNB applied a different $mod\ 30$, $mod\ 6$ or $mod\ 3$ PCI value from its neighbors. The same operation is repeated for each central eNB. Afterwards, the neighboring eNBs listed in eNB_NRList are examined using both SC algorithm and STC algorithm to identify any PCI confusions. If PCI confusion is detected among the neighboring eNBs, the affected eNBs will be notified in a predetermined order by the central eNB, then the notified eNB shall perform PCI reallocation. This process continues until there is no PCI confusion among the neighbors. The iterations involve multiple checks for $mod\,30$, $mod\,6$ or $mod\,3$ collision, applications of SC and STC algorithm for PCI optimization, and repeats until all collisions and confusions among the eNBs in the network are resolved. Central eNB examines each gNB through the gNB_List within its respective cluster then individually assigns a random PCI value from the PCI list to the gNB which has the same PCI $mod\,30$, $mod\,4$ or $mod\,3$ value as its neighboring gNBs in gNB_NRList. This process continues until the PCI $mod\,30$, $mod\,4$ or $mod\,3$ value of the gNB is different from its neighbors, same operation is performed for each gNB. Afterwards, the neighboring gNBs listed in gNB_NRList are examined using both SC algorithm and STC algorithm to identify whether there are any PCI confusions. If PCI confusion is detected among the neighboring clusters, the center eNB of the respective cluster notifies the corresponding eNBs in a predetermined order, and the notified eNBs perform PCI reallocation for the target gNBs within the cluster. This process continues until there is no PCI confusion among the neighbors. The iterations also involve multiple checks for $mod\,30$, $mod\,4$ or $mod\,3$ collision, applications of SC and STC algorithm for PCI optimization, and continue until all collisions and confusions among the gNBs in the network are resolved. Additionally, PCI confusion check for the neighbors that are directly adjacent to each other is also performed to eliminate the underlying issues at network edge. These procedures complete the resolution of PCI collisions and confusions among all base stations in the network. The overall process is illustrated in Figure 12.

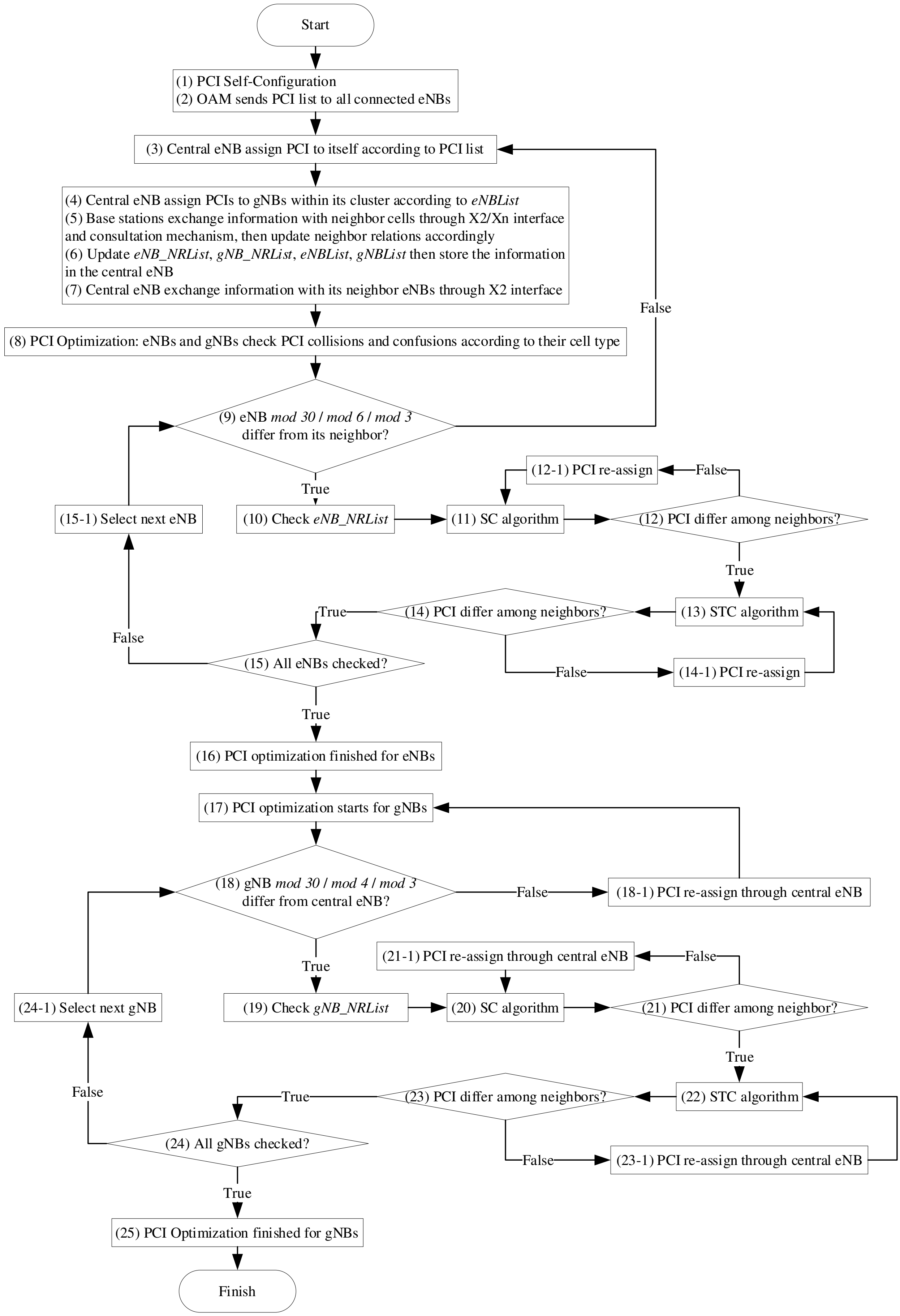

Figure 12. Overall process of PCI Self-Configuration and Optimization

4. Simulation and Performance Evaluation

4.1 Dense Heterogeneous Network Topology under EN-DC Structure

Evaluating the effectiveness of the proposed PCI assignment algorithm necessitates the introduction of an idealized densely populated heterogeneous cellular network topology featuring both eNBs and gNBs. Considering this study is based on heterogeneous network utilizing EN-DC architecture to achieve interconnection between 4G and 5G base stations, the network topology model consists of a dense heterogeneous network where 4G eNBs serve as macro cells, and 5G gNBs serve as small cells. Partial network is illustrated in Figure 13, pink and blue hexagons denote eNBs and gNBs, correspondingly.

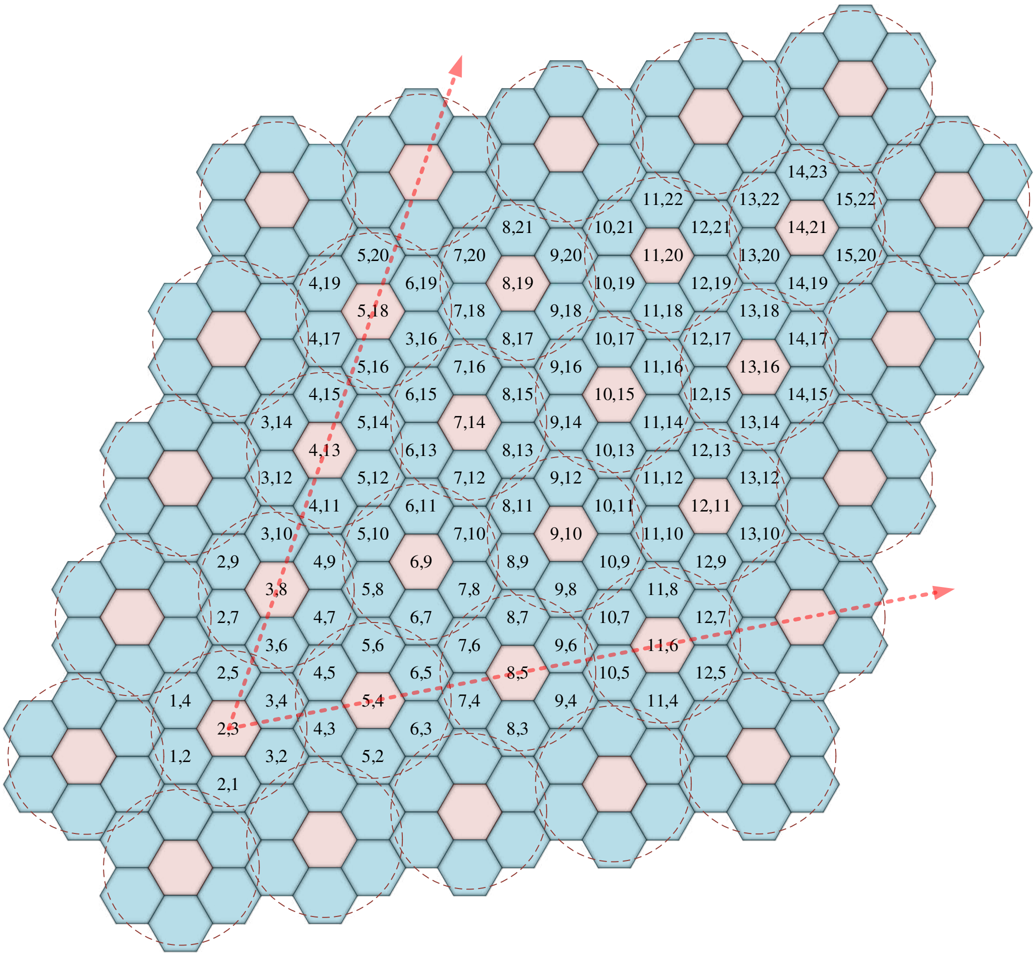

Figure 13 Fictitious dense heterogeneous cellular network with the coexistence of both eNB and gNB (Partial).

1) In the EN-DC stage of 5G rollout, eNBs are primarily operational within Frequency Range 1 (FR1), whereas gNBs predominantly function within Frequency Range 2 (FR2) [1]. Consequently, the network topology should conceptualize eNBs and gNBs as constituting separate layers indicative of their respective operating frequencies, with eNBs exclusively neighboring other eNBs and gNBs solely neighboring other gNBs.

2) Given eNBs' operation in a lower frequency range (e.g., sub-3GHz or FR1) that yields expansive coverage, their reach is depicted through dashed circles in Figure 13. Which also make it necessary to consider that an individual eNB is surrounded by a maximum of 6 neighboring eNBs.

3) eNBs and gNBs are segmented into distinct clusters, with each cluster comprising up to 1 eNB and 6 gNBs. Within this configuration, a single gNB is limited to a maximum of 5 neighboring gNBs.

4) The relative positioning coordinates of base stations are assimilated into the network topology, facilitating the implementation and execution of SC algorithm and STC algorithm for each cell enumerated in the neighbor list.

Furthermore, dashed directional markers signify the potential expansion trajectory of the topology in response to an augmented base station count.

4.2 Simulation and Analysis

To evaluate the efficacy of the proposed PCI optimization approach in preventing PCI collision and confusion, and to conduct a comprehensive performance analysis, we have considered a diverse number of both base stations and available PCIs. This strategy ensures a thorough examination across different scenarios, reflecting various quantity combinations of both base stations and PCIs. The simulation process is conducted as following steps.

1) Set the number of available PCIs (e.g., 20 PCIs) then initialize the OAM_PCI_List, which is formed as $(PCI_n \in [0,19], isUsed \in [False, True])$.

2) Configure the number of eNBs (e.g., 9 eNBs), and gNBs (e.g., 54 gNBs) in the network. Then mapping all eNBs and gNBs into the initially generated base station mapping list $NodeMapList$ as $\left(Index \in [0{\sim}215], nodeType_{(rPosX\in[1,11], rPoxY\in[1,17])}, PCI_{initial} = -1\right)$. The size of $NodeMapList$ is determined by the number of base stations according to Equation (2).

$$L_{NodeMapList} = \left(4 \times \left(Ceil\left(\sqrt{N_{eNB}}\right) - 1\right) + 3\right) \times \left(6 \times \left(Ceil\left(\sqrt{N_{eNB}}\right) - 1\right) + 5\right) \tag{2}$$

3) Divide the network into multiple clusters, each of which is centrally managed by an eNB (Cluster Head), and then a management list for the central eNBs, $eNBList$, is generated, as partially shown in Table 1.

Table 1. Initialized management list $eNBList$ and the $gNBList$ within each cluster.

$Index_{eNB}$	$nodeType_{(rPosX,rPosY)}$	$Index_{gNB}$	$nodeType_{(rPosX,rPosY)}$	$PCI_{initial}$
0~8	$eNB_{(2,3)}$	$0{\sim}m, m \le 5$	$gNB_{(1,2)}$	-1
			$gNB_{(1,4)}$	-1
			$gNB_{(2,1)}$	-1
	$eNB_{(5,4)}$	$0{\sim}n, n \le 5$	$gNB_{(4,3)}$	-1
			$gNB_{(4,5)}$	-1
			$gNB_{(5,2)}$	-1

4) OAM disseminates the initialized OAM_PCI_List to the eNBs cataloged in $eNBList$. Each central eNB subsequently assigns a PCI to itself in a stochastic manner according to the OAM_PCI_List, subsequently generating the neighbor relation list, denoted as eNB_NRList. The composition and details of eNB_NRList are partially illustrated in Table 2. In this particular scenario, while numerous neighbor relations are not depicted in the table, several PCI $mod\ 6$ collisions occur between $eNB_{(2,3)}$ and its adjacent $eNB_{(5,4)}$, $eNB_{(5,4)}$ and $eNB_{(8,5)}$, $eNB_{(8,5)}$ and $eNB_{(6,9)}$, which are going to be resolved during the subsequent PCI optimization phase.

Table 2. Central eNBs with their 1st and 2nd neighbor eNB in eNB_NRList after PCI configuration.

$Index_{eNB}$	$nodeType_{(rPosX,rPosY)}$	PCI	$Index_{neighbor}$	$neighborNode_{(rPosX,rPosY)}$	PCI
0~8	$eNB_{(2,3)}$	0	$0{\sim}m, m \le 5$	$eNB_{(5,4)}$	12
				$eNB_{(3,8)}$	5
	$eNB_{(5,4)}$	12	$0{\sim}n, n \le 5$	$eNB_{(2,3)}$	0
				$eNB_{(8,5)}$	6
	$eNB_{(8,5)}$	6	$0{\sim}p, p \le 5$	$eNB_{(5,4)}$	12
				$eNB_{(6,9)}$	6

5) Each central eNB, in accordance with $eNBList$, assigns PCIs to the gNBs within its cluster, and updates the neighbor relations, thereby generating the post-assignment gNB list and neighbor relation list in the similar manner as Table 2, respectively, thus determines PCI optimization sequence for each central eNB and its managed gNBs.

Subsequently, PCI optimization is performed sequentially on each cluster within the network, resulting in the optimized $eNBList$, $gNBList$ and neighbor relation lists eNB_NRList, $gNBS\_NRList$. Table 2 after optimization is shown as Table 3.

Table 3. Central eNBs with their 1st and 2nd neighbor eNB in eNB_NRList after PCI optimization.

$\boldsymbol{Index_{eNB}}$	$\boldsymbol{nodeType_{(rPosX,rPosY)}}$	$\boldsymbol{PCI}$	$\boldsymbol{Index_{neighbor}}$	$\boldsymbol{neighborNode_{(rPosX,rPosY)}}$	$\boldsymbol{PCI}$
0~8	$eNB_{(2,3)}$	2	$0 \sim m, m \leq 5$	$eNB_{(5,4)}$	7
				$eNB_{(3,8)}$	13
	$eNB_{(5,4)}$	7	$0 \sim n, n \leq 5$	$eNB_{(2,3)}$	2
				$eNB_{(8,5)}$	17
	$eNB_{(8,5)}$	17	$0 \sim p, p \leq 5$	$eNB_{(5,4)}$	7
				$eNB_{(6,9)}$	19

Simulations and statistics were conducted based on different numbers of base stations and PCIs to analyze the instances of confusion and collision. It can be observed that during PCI configuration phase, a range of base station and PCI quantity combinations consistently engenders certain levels of collision and confusion.

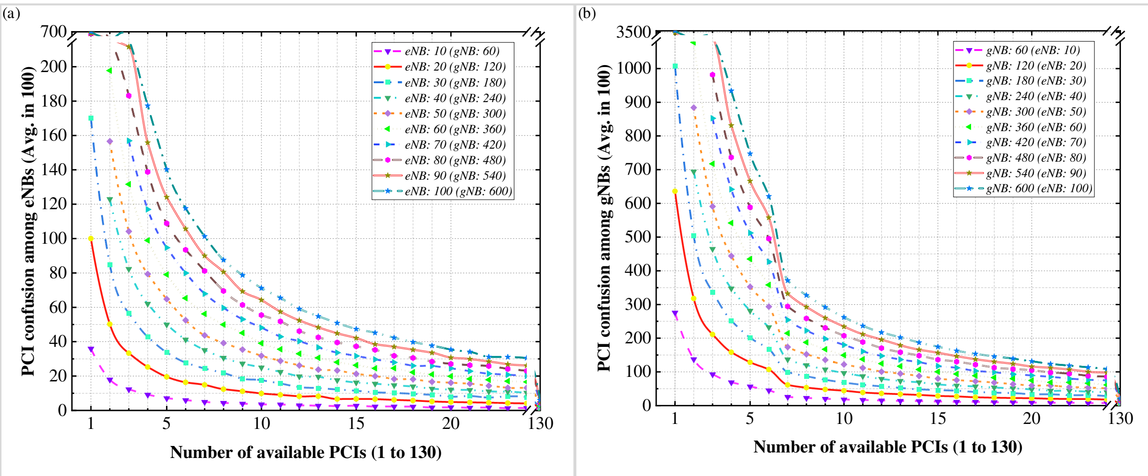

Figure 14. Average PCI confusion occurrence. (a) PCI confusion among eNBs. (b) PCI confusion among gNBs.

Figure 14 (a) and (b) depict PCI confusions within eNBs and gNBs, respectively, in relation to diverse configurations of base station quantities and PCI availabilities. Each data point signifies the mean occurrence of PCI confusion across 100 test episodes for a specific combination of available PCIs and base station counts. Empirical evaluations indicates that, with a fixed number of available PCIs, a rise in the number of base stations directly heightens the probability of PCI confusion within base stations of the same frequency layer. Conversely, when the number of base stations is fixed, as the number of available PCIs increases, the instances of PCI confusion within the network decrease correspondingly. A subset of the numerical results detailing PCI confusion among eNBs is presented in Table 4. The complete simulation dataset is accessible to the public on GitHub.

Table 4. Partial numerical results of PCI confusion among eNBs.

Avail. PCIs	eNB: 10 (gNB: 60)	eNB: 20 (gNB: 120)	eNB: 30 (gNB: 180)	eNB: 40 (gNB: 240)	eNB: 50 (gNB: 300)	eNB: 60 (gNB: 360)	eNB: 70 (gNB: 420)	eNB: 80 (gNB: 480)	eNB: 90 (gNB: 540)	eNB: 100 (gNB: 600)
5	7.11	19.5	33.73	49.93	64.76	79.06	94.7	108.86	124.04	140.22
10	3.47	9.87	17.57	24.94	31.77	39.1	48.16	55.5	64.19	71.12
15	2.75	6.69	11.41	16.19	21.27	26.31	31.67	37.26	42.07	47.32
20	1.81	4.86	7.95	12.09	16.06	19.9	24.47	27.08	30.65	35.38

Figure 15 (a), (b) and (c) delineate the average PCI $mod\ 30$, $mod\ 6$ and $mod\ 3$ collisions among eNBs, respectively. Conversely, Figure 15 (d), (e) and (f) portray the average PCI $mod\ 30$, $mod\ 4$ and $mod\ 3$ collisions among gNBs. Analysis from Figure 15 (a) and (d) resonate with the insights of Figure 14, that is, a static number of available PCIs coupled with an increasing base station count leads to elevated PCI collision rates. In contrast, when the base station count is constant, the incidence of PCI collision recedes with an increase in available PCIs. It is noteworthy that Figure 15 (b), (c), (e) and (f) initially exhibit analogous trends to their preceding counterparts, specifically, as the count of available PCIs rises from 1 to either 5 or 7, there's a marked reduction in PCI collisions. However, for any subsequent growth in available PCIs, unlike their predecessors, the collision rates in these figures stabilize. This phenomenon can be attributed to the fact that, compare to PCI confusion and $mod\ 30$ collision, $mod\ 6$, $mod\ 4$, and $mod\ 3$ collisions are inherently more probable, with $mod\ 3$ being especially prevalent.

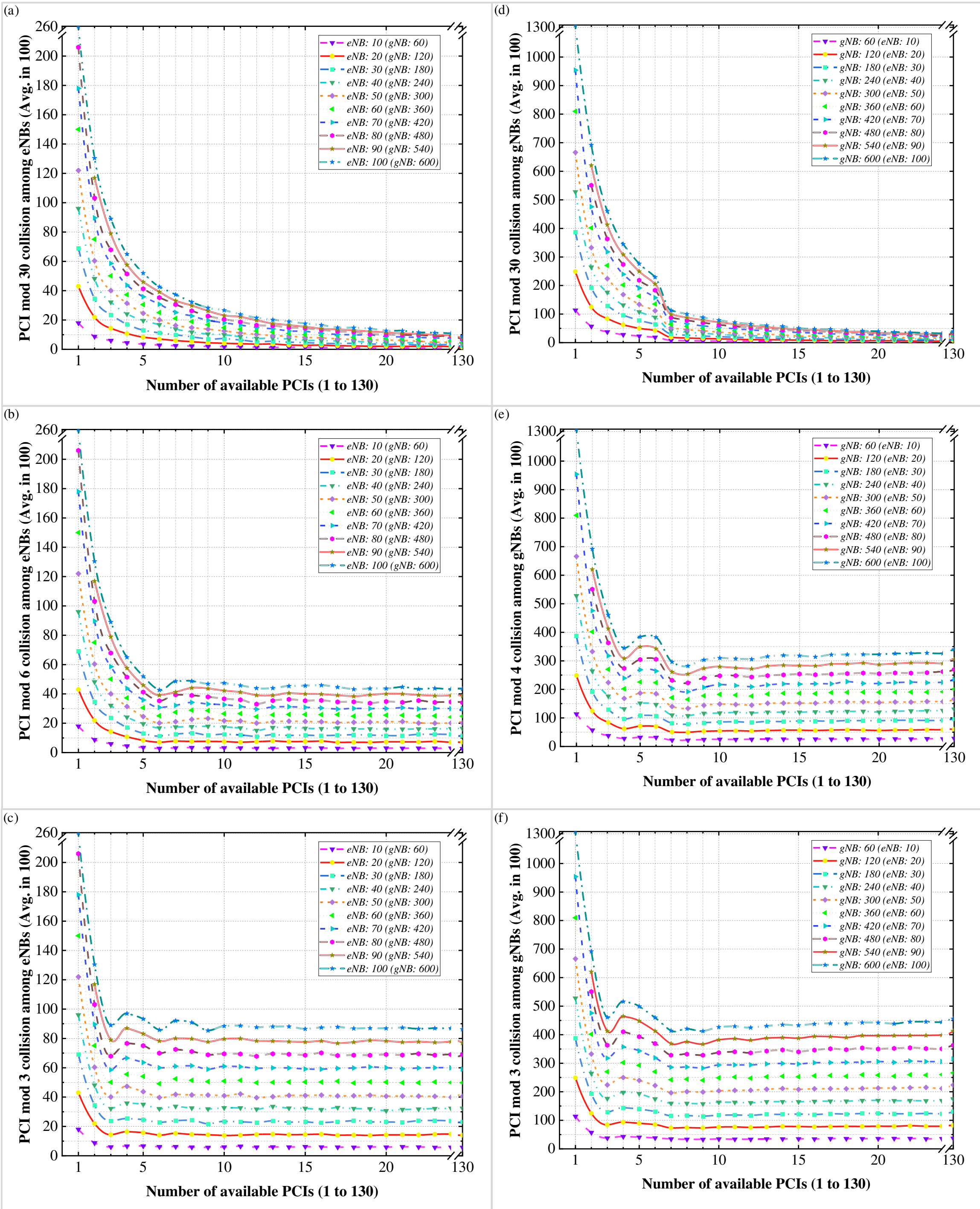

Figure 15. Average PCI collision occurrence. (a) PCI $mod\ 30$ collision among eNBs. (b) PCI $mod\ 6$ collision among

eNBs. (c) PCI $mod\ 3$ among eNBs. (d) PCI $mod\ 30$ collision among gNBs. (e) PCI $mod\ 4$ collision among gNBs. (f) PCI $mod\ 3$ collision among gNBs.

Building on above observations, the subsequent section delves into simulation results and analyses centered on the optimization of PCI collisions and confusions for network performance enhancement. Given the distinct attributes of different PCI collision categories, we employ a series of Heatmap figures for a nuanced analysis of simulation results, complemented by a Boxchart figure for a better overall comparison of the optimization performances.

In Figure 16 (a) and (b), the average PCI optimization episodes required for resolving PCI confusion among eNBs and gNBs are delineated. Each datum encapsulates the mean optimization episodes, derived from 100 iterations, contingent upon a specific configuration of base station quantities and available PCIs. For instance, a scenario with 120 gNBs (20 eNBs) and 20 PCIs necessitates an average of 20.01 optimization episodes to resolve the PCI confusion among gNBs. A pronounced gradient in the visual representation corresponds to variations in episode counts, with darker hues representing elevated episode counts and lighter tones signifying reduced counts. A restricted PCI availability, particularly in the range of 1 to 10, manifests heightened optimization challenges, a trend consistently observed across eNB scenarios, underscoring the inherent complexities of dense network topologies. While gNBs exhibit analogous diminishing trends with augmented PCI ranges, their intrinsic denser deployment—each eNB being encircled by up to 6 gNBs—complicates the optimization landscape, necessitating more episodes. Recognizing the prospective overlaps in PCI assignments between adjacent eNBs and gNBs, judicious consideration during PCI allocations is paramount to ensure neighboring entities are not allocated identical PCIs, thus mitigating operational ambiguities.

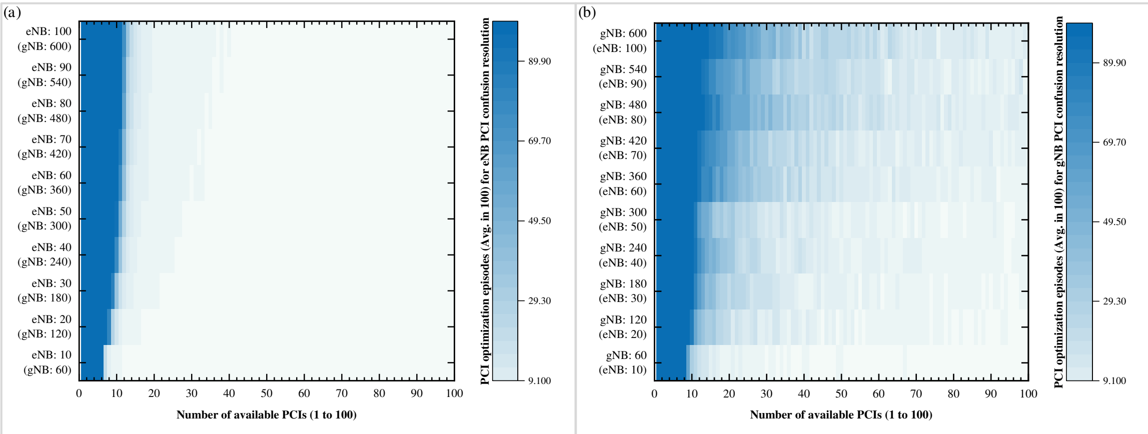

Figure 16. Average PCI optimization episodes for confusion resolution. (a) For PCI confusion among eNBs. (b) For PCI confusion among gNBs.

Figure 17 (a), (b), and (c) depict the average PCI optimization episodes needed for the resolution of PCI $mod\ 30$, $mod\ 6$, and $mod\ 3$ collisions among eNBs. Figure 17 (d), (e), and (f) illustrate the average PCI optimization episodes needed for the resolution of PCI $mod\ 30$, $mod\ 4$, and $mod\ 3$ collisions among gNBs. Each data point represents the average optimization episodes out of 100 episodes for a specific configuration of the number of base stations and the number of PCIs. Darker shades indicate more optimization episodes, while lighter shades signify fewer episodes. The $mod\ 30$ collision heatmap for eNBs shows a pronounced decrease in average optimization episodes as the available PCIs increase, especially during the initial stages. For scenarios with fewer eNBs, the increased optimization episodes can be attributed to the limited PCI pool available. In the case of $mod\ 6$ and $mod\ 3$ collisions, the trend remains consistent across eNB scenarios, with a marked reduction in optimization episodes as the available PCIs grow. The gNB collision heatmaps, whether for $mod\ 30$, $mod\ 4$, or $mod\ 3$, present a similar pattern.

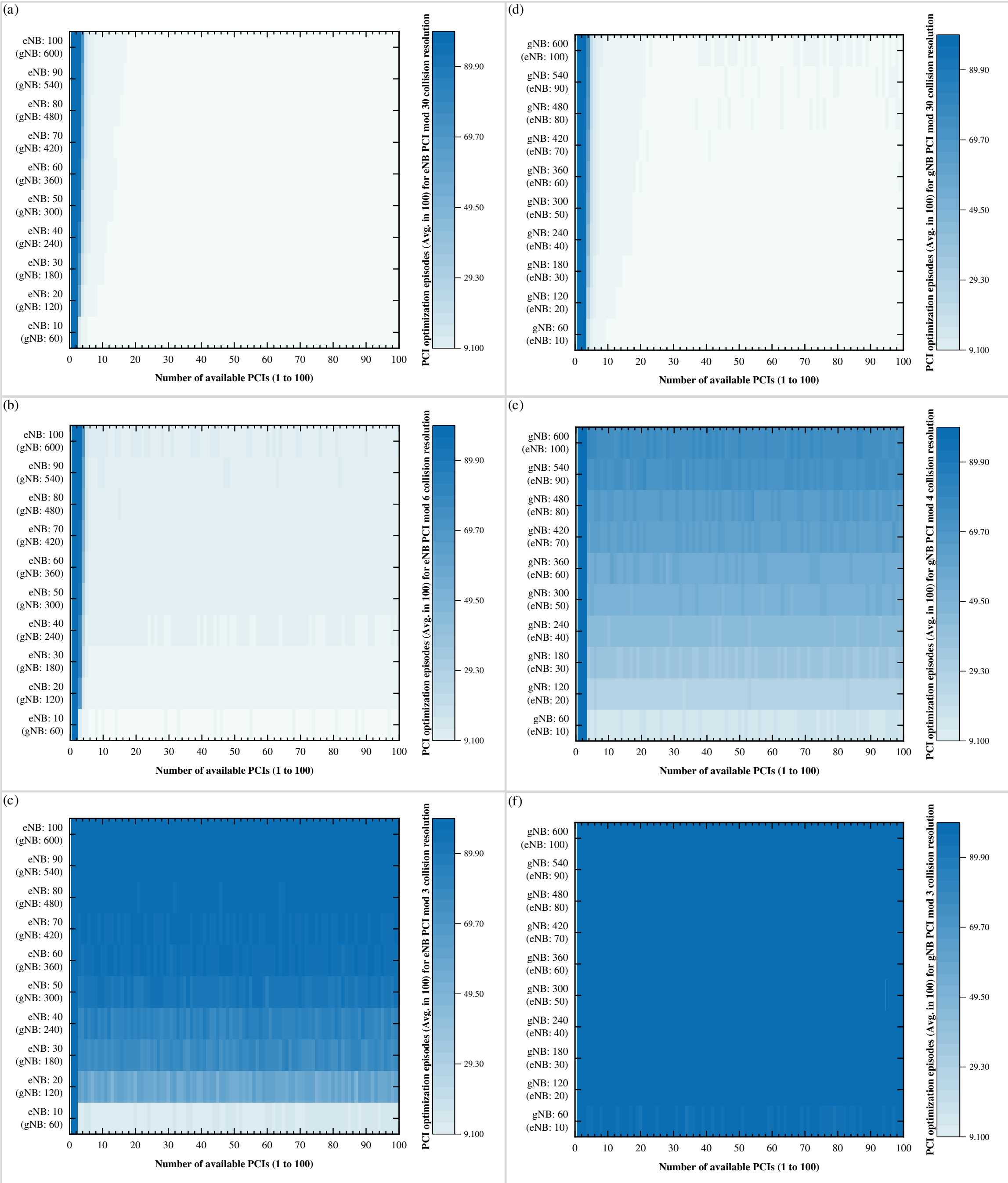

Figure 17. Average PCI optimization episodes for PCI collision resolution. (a) For PCI mod 30 collision among eNBs. (b) For PCI mod 6 collision among eNBs. (c) For PCI mod 3 collision among eNBs. (d) For PCI mod 30 collision among gNBs. (e) For PCI mod 4 collision among gNBs. (f) For PCI mod 3 collision among gNBs.

Both eNB and gNB $mod\ 30$ collision resolution exhibit analogous trends, indicating a decline in optimization episodes with the expansion of the PCI pool, predominantly during the initial stages. For $mod\ 6$ (eNB) and $mod\ 4$ (gNB) collisions, the resolution patterns highlight a decreasing trend as the PCI pool expands. It is noteworthy that gNBs, particularly within a medium PCI pool range, exhibit a more pronounced reduction in optimization episodes compared to eNBs in $mod\ 6$ collision resolution. For $mod\ 3$ collisions, while eNBs display a distinct downward trend as the PCI pool grows, gNBs show a more subtle decline. This variation can be attributed to the dense deployment pattern where each eNB is surrounded by up to 6 gNBs, potentially intensifying the PCI $mod\ 3$ collisions among eNBs.

Across all scenarios and collision types, there is a consistent trend of reducing optimization episodes with an increasing PCI pool size, particularly evident in the early stages of PCI availability. Comparing eNB and gNB optimizations, gNBs tend to benefit more from the medium PCI pool, especially for $mod\ 4$ collision resolution, than eNBs in $mod\ 6$ collision resolution. The trends highlight the importance of considering both the network configuration and the available PCI pool when optimizing network deployments.

Following the heatmap insights, we turned to box charts to provide a comprehensive comparison of the average PCI optimization episodes across all datasets and scenarios. This approach allowed us to holistically assess the optimization performance for each type of confusion or collision, encompassing all eight datasets.

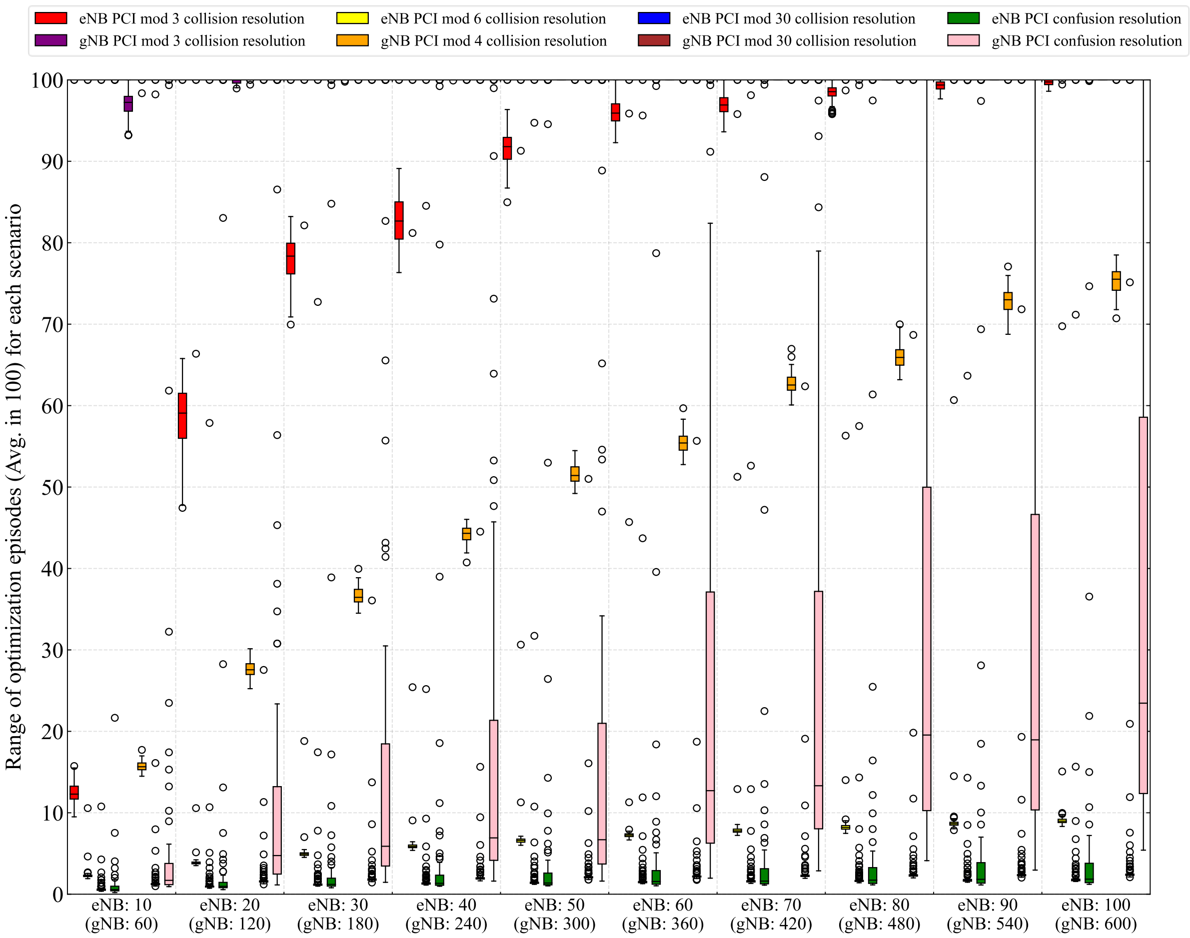

Figure 18. Comparison in ranges of average optimization episodes for individual scenarios.

In Figure 18, the box chart offers a comprehensive portrayal of the optimization episodes across diverse scenarios and PCI issues. For both eNB and gNB configurations, $mod\ 3$ collisions consistently necessitate more optimization episodes, underscoring their inherent intricacy. eNBs stand out with a broader spread of optimization episodes, particularly for $mod\ 3$ collisions, highlighting the sensitivity to PCI availability and network density. In contrast, gNBs, when observed under similar scenarios, manifest tighter distributions, suggesting a more consistent optimization behavior. When examining the patterns between eNBs and gNBs within comparable scenarios, gNBs unveil an expansive spread for confusions but a more compact range for collisions. Such patterns elucidate the distinct challenges each network configuration faces in densely deployed networks. In sum, the chart emphasizes the cardinal role of meticulous PCI planning in optimizing network performance.

Emerging from real-world challenges faced in mobile communication networks, the inception of this study was driven by the intricacies associated with PCI collisions and confusions. These complexities become especially pronounced in dense deployments using small cells, accentuating the need for effective solutions. To address this, our research introduces a hybrid approach to PCI configuration, melding the strengths of both centralized and distributed strategies. This method organizes the network into clusters, each comprising an eNB and its associated gNBs. The eNB serves as the cluster head, orchestrating coordinated PCI configurations.

In the realm of PCI optimization, this study introduces two pivotal algorithms: the Symmetrical Comparison (SC) and the Symmetrical Triangular Cycling (STC). The SC algorithm adeptly detects PCI confusions among neighboring cells, leveraging the symmetrical positions of eNBs and gNBs. On the other hand, the STC algorithm adopts a geometric approach, visualizing eNBs and gNBs as vertices of triangles, thereby facilitating the identification of PCI confusions. These algorithms play a crucial role in ensuring that PCI configurations remain robust and devoid from confusions.

However, while the hybrid approach proffers solutions to PCI confusions and $mod\,30$ collisions, it simultaneously underscores areas in need of further refinement, especially concerning the challenges posed by $mod\,3$ and $mod\,4$ collisions. As we anticipate the evolving landscape of 5G heterogeneous networks, characterized by their diverse and variable nature, the demand for more adaptive, flexible, and robust configuration and optimization strategies become evident. As a potential avenue for future research, integrating Reinforcement Learning might provide a holistic solution to these intricate challenges.

5. Conclusion

The advancement of 5G and the expansion of heterogeneous networks have increased the complexity of Physical Cell Identity (PCI) management. In densely populated network environments, the risk of PCI collisions and confusions has spurred the need for intelligent solutions. This study introduces a hybrid approach to PCI configuration, combining centralized and distributed strategies, and organizing the network into clusters, each comprising an eNB and its associated gNBs. The Symmetrical Comparison (SC) and Symmetrical Triangular Cycling (STC) algorithms were introduced to adeptly identify and resolve PCI confusions, ensuring robust configurations. However, challenges were observed in handling mod 3 and mod 4 collisions, indicating areas for further refinement.

Simulations provided insights into the behavior of the model under various scenarios, revealing its effectiveness in preventing PCI confusion and mod 30 collisions. The results emphasized the critical role of the PCI pool size, with both eNBs and gNBs benefiting from increasing PCI availability. The practical implications of the proposed model include the potential to improve network performance, reduce interference, and enhance user experience. These insights can be applied to guide network planning and optimization, particularly in densely populated urban environments.

However, some limitations include challenges in handling specific collisions and the need for real-world validation still need further refinement. Potential avenues for future research could involve integrating reinforcement learning techniques and conducting experimentation in more practical network scenarios. Such approaches may yield more adaptive solutions and further substantiate the proposed method.

In conclusion, this study contributes to network management by offering a novel approach to PCI configuration and optimization. By addressing challenges faced in mobile communication networks, it emphasizes the importance of careful planning and intelligent design in the evolving landscape of 5G networks and beyond.

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Declarations

Ethical Approval

Not applicable.

Competing interests

I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Authors' contributions

Pengzhao Li and Heng Yang authored the primary manuscript text. Iksang Kim and Zhenyu Liu provided valuable academic support regarding mobile communication and network optimization. Shanshan Li assisted in preparing the simulation datasets and figures. All authors reviewed and approved the manuscript.

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Availability of data and materials

Datasets of the simulation results are accessible through GitHub. URL: https://github.com/didgmd/Network-Optimization/tree/master/01_Hybrid_PCI

References

[1] Dahlman, Erik, Stefan Parkvall, and Johan Skold. 5G NR: The next generation wireless access technology. Academic Press, 2020.
[2] Mwanje, Stephen S., Janne Ali-Tolppa, and Henning Sanneck. "On the limits of pci auto configuration and reuse in 4g/5g ultra dense networks." 2015 11th International Conference on Network and Service Management (CNSM). IEEE, 2015.
[3] Bandh, Tobias, Georg Carle, and Henning Sanneck. "Graph coloring based physical-cell-ID assignment for LTE networks." Proceedings of the 2009 international conference on wireless communications and mobile computing: Connecting the world wirelessly. 2009.
[4] Liu, Yanguang, et al. "Graph based automatic centralized PCI assignment in LTE." The IEEE symposium on Computers and Communications. IEEE, 2010.
[5] Jungnickel, Volker, et al. "Estimating the mobile backhaul traffic in distributed coordinated multi-point systems." 2012 IEEE Wireless Communications and Networking Conference (WCNC). IEEE, 2012.
[6] Acedo-Hernández, Rocío, et al. "A PCI planning algorithm for jointly reducing reference signal collisions in LTE uplink and downlink." Computer Networks 119 (2017): 112-123.
[7] Gui, Jihong, Zhipeng Jiang, and Suixiang Gao. "PCI planning based on binary quadratic programming in LTE/LTE-a networks." IEEE Access 7 (2018): 203-214.
[8] Krishnaswamy, Dilip. "Quasi-Quantum PCI optimization in 5G Networks." 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring). IEEE, 2021.
[9] Pratap, Ajay, Rajiv Misra, and Utkarsh Gupta. "Randomized graph coloring algorithm for physical cell ID assignment in LTE-a femtocellular networks." Wireless Personal Communications 91 (2016): 1213-1235.
[10] Acharya, Sayantan, et al. "Combined MST-graph coloring algorithm for PCI distribution of LTE-advanced self-organizing network." Ambient Communications and Computer Systems: RACCCS 2017. Springer Singapore, 2018.
[11] Shahab, Muhammad Basit, and Abdul Aziz Bhatti. "Neural networks based physical cell identity assignment for self organized 3gpp long term evolution." 2012 35th International Conference on Telecommunications and Signal Processing (TSP). IEEE, 2012.
[12] Liu, Yanguang, et al. "Distributed PCI assignment in LTE based on consultation mechanism." 2010 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM). IEEE, 2010.
[13] Wu, Songrui, Wen Ye, and Qiannan Shi. "Heuristic optimizing of PCI assignment in real-life LTE networks." (2015): 6-6.
[14] Chen, Liuling, et al. "Combining Multi-objective Evolutionary Approach and Machine Learning to Optimize PCI Configuration in Large-scale LTE Networks." 2022 5th International Conference on Communication Engineering and Technology (ICCET). IEEE, 2022.
[15] Abdullah, Labeeb Mohsin, Mohd Dani Baba, and Sinan Ghassan Abid Ali. "A novel scheme to resolve PCI conflicts and assignment problems in LTE-femtocell networks." 2013 IEEE 3rd International Conference on System Engineering and Technology. IEEE, 2013.
[16] Mwanje, Stephen S., and Janne Ali-Tolppa. "Layer-independent PCI assignment method for Ultra-Dense multi-layer co-channel mobile Networks." 2017 IFIP/IEEE Symposium on Integrated Network and Service Management (IM). IEEE, 2017.
[17] Ahmed, Furqan, and Olav Tirkkonen. "Self organized physical cell ID assignment in multi-operator heterogeneous networks." 2015 IEEE 81st Vehicular Technology Conference (VTC Spring). IEEE, 2015.
[18] Wielgoszewska, Anna, et al. "A centralized method for PCI assignment with common reference signal frequency shift control." 2016 IEEE International Conference on Communications (ICC). IEEE, 2016.
[19] Acedo-Hernández, Rocío, et al. "Analysis of the influence of PCI planning on the physical uplink control channel in LTE." Wireless Personal Communications 98 (2018): 629-649.
[20] Acedo-Hernández, Rocío, et al. "Analysis of the impact of PCI planning on downlink throughput performance in LTE." Computer Networks 76 (2015): 42-54.

[21] Sedlacek, Marek, and Robert Bestak. "Evaluation of Random Physical Cell Id Assignment to Femtocells Under Dense Cell Deployment." Wireless Personal Communications 104 (2019): 753-769.
[22] Chandra, Dikky, et al. "The Optimization of PCI Interference in the 4G LTE Network in Padang." JOIV: International Journal on Informatics Visualization 5.3 (2021): 256-263.
[23] Zeljković, Ensar, et al. "ALPACA: A PCI Assignment Algorithm Taking Advantage of Weighted ANR." Journal of Network and Systems Management 30.2 (2022): 33.
[24] 3GPP, TS 36.423 V17.4.0; Technical Specification Group Radio Access Network; E-UTRAN; X2 application protocol (X2AP) (Release 17), Technical Specification, 2023.
[25] 3GPP, TS 38.423 V17.4.0; Technical Specification Group Radio Access Network; NG-RAN; Xn application protocol (XnAP) (Release 17), Technical Specification, 2023.
[26] 3GPP, TS 36.211 V9.0.0; Technical Specification Group Radio Access Network; E-UTRA; Physical Channel and Modulation (Release 9), Technical Specification, 2009.
[27] 3GPP, TS 38.211 V15.0.0; Technical Specification Group Radio Access Network; NR; Physical Channel and Modulation (Release 15), Technical Specification, 2017.
[28] 3GPP, TS 36.300 V16.9.0; Technical Specification Group Radio Access Network; E-UTRA and E-UTRAN; Overall Description; (Release 16), Technical Specification, 2023.
[29] 3GPP, TS 38.300 V16.13.0; Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; (Release 16), Technical Specification, 2023.
[30] Jungnickel, Volker, et al. "Estimating the mobile backhaul traffic in distributed coordinated multi-point systems." 2012 IEEE Wireless Communications and Networking Conference (WCNC). IEEE, 2012.
[31] Panagoulias, Panagiotis I., et al. "A Multirate Loss Model of Quasi-Random Input for the X2 Link of LTE Networks." (2018).
[32] Bharucha, Zubin, et al. "Dynamic resource partitioning for downlink femto-to-macro-cell interference avoidance." EURASIP Journal on Wireless Communications and Networking 2010 (2010): 1-12.
[33] "4G/LTE - Latency." ShareTechnote, https://www.sharetechnote.com/html/Handbook_LTE_Latency.html.
[34] "5G NR Interfaces X2/Xn, S1/NG, F1 and E1 Functions", Techplayon, 2019, https://www.techplayon.com/5g-nr-interfaces-x2-xn-s1-ng-f1-and-e1-functions/.
[35] Khan, Sajjad Ahmad, et al. "Handover management over dual connectivity in 5G technology with future ultra-dense mobile heterogeneous networks: A review." Engineering Science and Technology, an International Journal 35 (2022): 101172.