A Solution to Relieve ICI Effects on System Control Information in OFDM-based Mobile Networks: Conflict Coordination on PDCCH via PCI Planning

Hemin Yang[1], Ruipeng Gao[2], Anpeng Huang[1, 2] and Linzhen Xie[1]
[1]*State Key Lab of Advanced Optical Communication Systems and Networks, Peking University, Beijing, China*
[2]*PKU-UCLA Joint Research Institute, Peking University, Beijing, China*
{yhm11, hapku}@pku.edu.cn

Abstract—**In OFDM-based mobile networks, the full-cell coverage of SCI (System-level Control Information) must be guaranteed for a user that can communicate with its eNB (evolved Node Base station) system. The requirement of SCI coverage causes severe ICI (Inter-Cell Interference) effect. Furthermore, the negative effect is intensified owing to single-frequency networking and physical control region configuration in OFDM-based networks. To enhance the reliability of SCI under the coverage constraint, we investigated how SCI is carried in the Physical Downlink Control Channel (PDCCH) in the common search space, and proposed a solution of Conflict Coordination on PDCCH via PCI (Physical Cell Identifier) Planning (CCP^3). In our proposal, PCI planning is used to relieve the ICI effect of the SCI. Thus, a heuristic algorithm is developed for the PCI planning since it is an NP-Complete optimization problem. The link-level simulation experiments and numerical analysis results demonstrate that the proposed CCP^3 can improve effective SINR (Signal to Interference plus Noise Ratio) of PDCCH significantly, and reduce RE (Resource Element)-occupation conflict probability of PDCCH around 50%. To the best of our knowledge, this study is the first effort to strengthen the SCI reliability from the view of networking optimization.**

Keywords—CCP^3 (Conflict Coordination on PDCCH via PCI Planning); ICI (Inter-Cell Interference); PDCCH (Physical Downlink Control Channel); PCI (Physical Cell Identifier); SCI (System-level Control Information)

I. INTRODUCTION

With the rapid socio-economic development, OFDM-based mobile networks are playing an important role in emerging mission-driven applications. For example, healthcare information is delivered in mobile networks for real-time health-risk monitoring [1 - 2]. To facilitate these key applications, it is necessary to guarantee the reliability of System-level Control Information (SCI), including paging messages, radio resource control messages, random access channel messages, etc., irrespectively of a UE (User Equipment) at a cell center or edge. In OFDM-based mobile networks, the SCI is carried in the Physical Downlink Control Channel (PDCCH) that is located within the common search space[1] [3]. However, the SCI in the PDCCH in the common search space ("PDCCH" for short in the rest of the paper) suffers from various interferences. In all kinds of interference, ICI (Inter-Cell Interference) has directly impact on the SCI reliability in the PDCCH. This is because there is an internal conflict between the SCI full-cell coverage and SCI reliability (dominated by ICI effect). To make one better, the other one gets performance degradation. The full-cell coverage of SCI is necessary to guarantee control signaling available for any user within a cell. Otherwise, the user may be not admitted to its eNB (evolved Node Base station) system if losing the control signaling. Additionally, the ICI effect on the PDCCH is magnified due to single frequency networking and physical control region configuration in the OFDM-based system[2]. In fact, the ICI challenge attracts extensive attention [4-7]. So far, problem-solving strategies can be classified as follows, i.e., signal processing in the physical layer and interference management in the upper layer.

In the physical layer, signal processing can reduce the ICI effect by using interference randomization and beamforming approaches. The randomization approach is to whiten the ICI effects over the whole system bandwidth using scrambling and interleaving [4], which is applied before radio transmission, but it cannot lower down interference power. The beamforming approach directs the focused power over the transmission path for a particular user with very limited signal leakage, which is used to mitigate aftereffects [5].

In the upper layer, interference management methods include power control and resource scheduling. In the literature [6], the Binary Power Control (BPC) scheme was proposed to maximize system throughput by adjusting conflict channel power. About scheduling approaches, a utility matrix was investigated to minimize unexpected interference between neighboring cells using X2-interface information [7], but this caused extra signaling overhead. Unfortunately, a scheduling strategy cannot be applied to a control channel because its resource occupation is predetermined by some particular system-related parameters, e.g., PCI. Consequently, it is possible to enhance SCI reliability in power control (which is another important topic that is studied in the future. In this paper, we focus on how to enhance SCI reliability by avoiding

[1]In a cell, a UE is blind of the PDCCH location. Thus, a search space is defined as a group of REs (Resource Elements) where the UE may find its PDCCHs. There are two kinds of search spaces, common search space and user-specific search space. The common search space carries the system-level control information that is monitored by all UEs in a cell. The user-specific search space carries dedicated control information for a particular UE in a cell.

[2]In the OFDM-based mobile system, only limited radio resources are assigned to PDCCH, in order to save the major part of radio resources to support high-rate services.

and reducing ICI effect), and there is no possible to deal with the ICI issue in a control channel by a scheduling strategy.

These solutions above may achieve relative performance gain, but they are unable to handle the ICI issue of the PDCCH since the PDCCH has its own specific features. These features should be taken into account when conceiving a feasible solution to relieve the ICI effects on the SCI. Please refer to 3GPP (3rd Generation Partnership Project) technical specifications [3, 8 - 9], a PDCCH occupies a number of REs (Resource Elements) in the control region per subframe, which carrying SCI by using a suitable modulation and coding scheme. In nature, the ICI issue is born from RE-occupation conflict events between neighboring-cell PDCCHs. In fact, the RE–occupation of PDCCH in a cell is determined by a HASH function whose input variable is the PCI (Physical Cell Identifier) of the cell. Thus, PCI planning plays a unique role to avoid or reduce these conflicts for relieving ICI effects. Motivated by this new perspective, we propose Conflict Coordination on PDCCH via PCI Planning (CCP[3]), which is to coordinate RE-occupation on PDCCHs between neighboring cells through PCI planning.

II. The Relationship between PDCCH and PCI

In OFDM-based mobile networks, the basic unit of radio resource is called "Resource Element (RE)" which consists of one subcarrier and one OFDM symbol. Generally, an RE can be labeled by an index pair (k, l), where k and l are the subcarrier index and the OFDM symbol index, respectively. To obtain a large granularity of radio resources, every consecutive 4 or 6 REs form a Resource Element Group (REG), and 9 REGs constitute a Control Channel Element (CCE), as shown in Fig. 1. A subframe is divided into control region and data region in the physical layer. The control region is configured in the first n ($n \leqslant 3$) OFDM symbols, which contains Cell Reference Signal (CRS), Physical Control Format Indicator Channel (PCFICH), Physical Hybrid ARQ Indicator Channel (PHICH) and PDCCH. In other words, each control channel occupies specific REs in the control region [8].

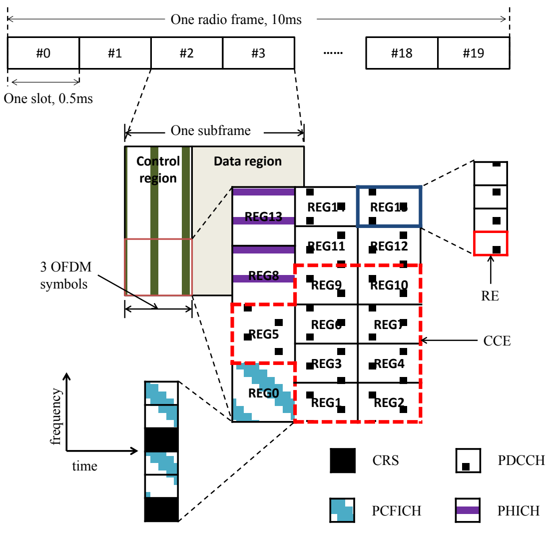

Fig.1. The resource occupation in control region

A. PDCCH Resource Occupation and PCI

According to 3GPP regulations [7], which REs are assigned to CRS, PCFICH and PHICH are determined by dedicated HASH functions, respectively. These HASH functions have a common input variable, PCI. Let us take PCFICH as an example. In the physical layer, the information carried by PCFICH is a quadruplet sequence $z(i)$ (i = 0, 1, 2, 3), which is mapped to the k^{th} REG in the first OFDM symbol per subframe. And the index k is determined by the HASH function $k = 6(N_{ID}^{cell} \ mod \ 2N_{RB}) + 6\lfloor i \cdot N_{RB}/2 \rfloor$, where N_{RB} is the number of Resource Blocks (RBs) which consists of 84 REs, and N_{ID}^{cell} is the PCI. From this HASH function, it is evident that REs occupied by the PCFICH is closely related with the PCI. In practice, REs are first assigned to CRS, PCFICH and PHICH via HASH functions, and then the rest of REs are mapped into the PDCCH, as illustrated in Fig. 1. Thus, PDCCH is also determined by an implicit HASH function with the input variable of PCI.

B. Definition of PDCCH RE-occupation Conflict Probability

In terms of the RE-conflict influence on the ICI, the control channels are classified into two kinds below.

1) PDCCH in the common search space, CRS, and PCFICH: The signals (carrying system-level information) in the three control channels are monitored by all users within a cell. To guarantee full-cell coverage for them, their signal power in a cell must be strong enough to tolerate interference from its neighboring cells. No doubt, these signals have significant influence on the ICI effect.

2) *PDCCH in the user-specific search space and PHICH*: Since the two channels are dedicated to particular users, their transmit power can be dynamically adjusted. For example, the ICI effect on the PDCCH in the user-specific search space can be limited because its signal strength can be finely tuned to only reach its own user through partial path-loss compensation.

Since the first kind of physical control radio signals are more critical in terms of ICI effect, we will mainly investigate them in the rest of this paper. Let us return to the last subsection. The conflict of RE-occupations in PDCCHs between neighboring cells is the source of ICI, which lowers down the reliability of SCI in the PDCCH. For considering there is a direct relationship between PDCCH and PCI, we define the conflict probability $P(id_1, id_2)$ of REs in PDCCHs in a cell, where id_1 and id_2 are the PCI of a cell and the PCI of its neighboring cell, respectively. To calculate the conflict probability $P(id_1, id_2)$, an algorithm is shown in Algorithm 1. Accordingly, we can get a conflict probability matrix P.

Algorithm 1: Conflict probability of REs in PDCCHs

for every two neighboring cells whose PCIs are (id_1, id_2) ***do***
  for every $SRE(id_1, i, j)$ ***do***
    If $SRE(id_1, i, j) = S_{pdcch}$ and $SRE(id_2, i, j) = S_{crs}$ or S_{pcfich} or S_{pdcch} ***then***
      $P(id_1, id_2) = P(id_1, id_2) + 1$;
  $P(id_1, id_2) = P(id_1, id_2)/N_{com}$.

Notations: N_{com} stands forthenumberof REs in PDCCHs, $SRE(id,i,j)$ represents the occupation state of $RE(i,j)$ when PCI is id, and its value can be $S_{crs}, S_{pcfich}, or S_{pdcch}$, which indicates the RE is occupied by CRS, PCFICH, or PDCCH.

III. AN OPTIMIZATION SOLUTION: CCP^3

All proofs above show that the conflict events in the PDCCH may be avoided or reduced if each cell PCIs can be planned optimally. To achieve this objective, we propose a solution to the ICI issue of PDCCH: Conflict Coordination on PDCCH via PCI Planning (CCP^3). We formulate the NPC (NP-complete) optimization problem of CCP^3 first. To carry out CCP^3, a heuristic algorithm is developed.

A. Formulation of CCP^3 optimization problem

Based on 3GPP specification [9], a number of cells are grouped into a cluster, which can use 504 PCIs at most. Within a cluster, each cell consists of three sectors with indices 0, 1 and 2, clockwise, and each sector is assigned with a unique PCI. To formulate CCP^3 optimization problem, we set a network scenario in which a sector is labeled by a three dimensional vectors, as shown in Fig. 2. Based on the scenario, we formulate CCP^3 problem below.

Notations:

- $(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$**:** Three-dimension vectors to label a sector where x = a cell's X-axis index, y = a cell's Y-axis index, $0 \le x < N_{cell}^x, 0 \le y < N_{cell}^y$ ($N_{cell}^x \cdot N_{cell}^y \leqslant$ 168), and z = a sector index in the cell, $0 \le z < 3$.
- $\boldsymbol{N_{x,y,z}}$**:** For the sector (x, y, z), $\boldsymbol{N_{x,y,z}}$ isthe set of its neighboring sectors. For example, the sector (3,2,0) has a set of six neighboring sectors, $N_{x,y,0}$={(3,1,1), (23,2), (2,2,1), (2,2,2), (3,2,1), (3,2,2)}.
- $\boldsymbol{id_{x,y,z}}$: The PCI of the sector (x, y, z), and $0 \le id_{x,y,z} \le N_{ID} - 1$, where N_{ID}= the number of PCIs.
- $\boldsymbol{Q}$: The set of all available PCIs, and $Q=\{0,1,2,\ldots, N_{ID} - 1\}$.
- $\boldsymbol{U}$: The set of assigned PCIs.
- $\boldsymbol{\overline{U}}$: The set of free PCIs, and $Q = U + \overline{U}$.
- $\boldsymbol{P}(id_{x,y,z}, id_{x',y',z'})$: The RE-occupation conflict probability of PDCCH in the sector (x, y, z) caused by its neighboring sector (x', y', z').
- $\boldsymbol{P_{x,y,z}}$: The total conflict probability of the sector (x, y, z) caused by all its neighboring sectors, namely, $P_{x,y,z} = \sum_{(x',y',z')\in N_{x,y,z}}(P(id_{x,y,z}, id_{x',y',z'}) + P(id_{x',y',z'}, id_{x,y,z}))$.

Given:

- The conflict probability matrix $\boldsymbol{P}$, whose element is $P(id_{x,y,z}, id_{x',y',z'})$.
- A network scenario (N_{cell}^x, N_{cell}^y, *N), where* $N_{cell}^x$is the up bound of x, N_{cell}^y is the up bound of y, $\boldsymbol{N}$ is the set of all $\boldsymbol{N_{x,y,z}}$, namely, $\boldsymbol{N} = \{\boldsymbol{N_{x,y,z}} | 0 \le x < N_{cell}^x, 0 \le y < N_{cell}^y, 0 \le z < 3\}$.

Variables:

- $id_{x,y,z}, 0 \le x < N_{cell}^x, 0 \le y < N_{cell}^y, 0 \le z < 3$.

Constraints:

- Two neighboring sectors could not have a same coresidual of PCI mod 3 [9]:
$$id_{x,y,z} \bmod 3 = z \tag{1}$$
- Sector (x', y', z') neighbors to sector (x, y, z):
$$(x', y', z') \in N_{x,y,z} \text{ and } N_{x,y,z} \in N \tag{2}$$
- $P(id_{x,y,z}, id_{x',y',z'})$ is one element of P:
$$P(id_{x,y,z}, id_{x',y',z'}) \in P \tag{3}$$

Objective: minimizing the overall conflict probability

$$min \sum_{x=0}^{N_{cell}^x} \sum_{y=0}^{N_{cell}^y} \sum_{z=0}^{2} \sum_{(x',y',z')\in N_{x,y,z}} P(id_{x,y,z}, id_{x',y',z'}) \tag{4}$$

The CCP^3 optimization is an NP problem, since the optimization results can be verified in polynomial time if a given objective of conflict probability can be obtained by a given PCI arrangement. Furthermore, the problem is also NP-HARD because it can be deduced to the Hamilton-cycle problem in polynomial time [10]. In fact, the Hamilton-cycle problem is just a special case of the CCP^3 problem (the detailed proof is skipped due to the limited space here). Thus, the CCP^3 is an NPC problem. For an NPC problem, a heuristic problem-solving strategy is the only choice so far. Below, we develop such a heuristic algorithm to the CCP^3 optimization.

B. A heuristic algorithm to CCP^{3}optimization

The proposed heuristic algorithm consists of three components, PCI initialization, PCI perturbation, and conflict objective justification. In the first step, each sector is assigned a PCI randomly. To reach a given conflict objective, perturbation method is used in the second step, in which a number of sectors are selected to exchange PCIs with each other, or updated with new available PCIs. After the perturbation, we get a new value of conflict objective function. The new value will be accepted if this perturbation shows profit when it is compared with the existing result (the concept of the profit is defined in Table I). And then this perturbation is in force for the adjustment of PCI assignment. In the last step, we iterate this perturbation until the given conflict objective is obtained. At this time, the algorithm outputs an optimal result (in our implementation, the perturbation process is ended if there is no gain available any more). The heuristic strategy for CCP^3 is shown in Algorithm 2.

Algorithm 2: A heuristic algorithm to CCP^3

1) Initialization of PCI assignment for sectors.
   1.1) Choose a cell, which consists of three sectors, $(x, y, 0)$, $(x, y, 1)$ and $(x, y, 2)$.
   1.2) $id_{x,y,0} = 3k_1$, $id_{x,y,1} = 3k_2 + 1$ and $id_{x,y,2} = 3k_3 + 2$, where k_1 , k_2 and k_3 meeting the following conditions concurrently:
   - $0 \le k_1, k_2, k_3 < N_{ID}/3$
   - $3k_1, 3k_2 + 1, 3k_3 + 2 \notin U$;

   1.3) Choose an unassigned cell and go back to Step 1.1, until all sectors of all cells are assigned PCIs.
2) Perturbation of PCI assignment.
   2.1). Choose a sector (x, y, z), which is assigned a PCI id_{ori} in Step 1.
   2.2). If $P_{x,y,z}(id_{x,y,z} = id_{ori})$ is minimal, go to Step 2.6;

if else, go to Step 2.3.

2.3). Find the best PCI id_{best} from the whole PCI set Q which makes $P_{x,y,z}(id_{x,y,z} = id_{best})$ minimal.

2.4). If id_{best} is free, replace id_{ori} with id_{best} as the PCI of the sector (x, y, z), go to Step 2.6; if else go to Step 2.5.

2.5). If id_{best} is already assigned to a sector (x', y', z'), choose one of the following four schemes which can achieve maximum profit to update $id_{x,y,z}$ (the profits of these four schemes are defined in Table I).

- **Scheme 1**: no change, namely, $id_{x,y,z} = id_{ori}$, $id_{x',y',z'} = id_{best}$;
- **Scheme 2**: switch the PCIs of (x, y, z) and (x', y', z'), namely, $id_{x,y,z} = id_{best}$, $id_{x',y',z'} = id_{ori}$;
- **Scheme3**: find the second best PCI $id_{best',\bar{U}}$ for the sector (x', y', z') from the free PCI set $\bar{U}$, which makes $P_{x',y',z'}(id_{x',y',z'} = id_{best',\bar{U}})$ minimal. And then allows $id_{x,y,z} = id_{best}$, $id_{x',y',z'} = id_{best',\bar{U}}$;
- **Scheme 4**: find the second best PCI $id_{best,\bar{U}}$ for sector (x, y, z) from the free PCI set $\bar{U}$, which makes $P_{x,y,z}(id_{x,y,z} = id_{best,\bar{U}})$ minimal.And then allows $id_{x,y,z} = id_{best,\bar{U}}$.

2.6). Go back to Step 2.1 for the next sector, until all sectors of all cells perform substeps2.1~2.5.

3) Gain justification of the perturbation above. Repeat Step 2 if the objective gain can be achieved. Otherwise, output the results.

IV. Performance Evaluation

To evaluate our proposal effectiveness, we compare CCP^3 with an alternate algorithm, in which each sector in an eNB is randomly assigned a PCI. Below, we first analyzed the conflict probabilities in numerical results, and then conducted link-level simulation experiments for performance evaluation in an LTE-A (Long-Term Evolution-Advanced, one of OFDM-based networks) system.

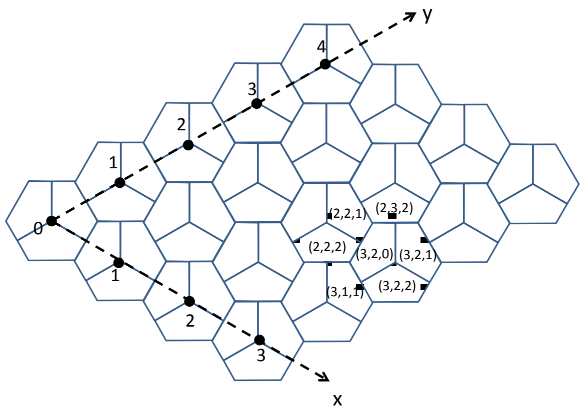

Fig. 2. A network scenario model.

TABLE I. Profits of PCI update schemes.

Scheme	Profit
1	0
2	$P_{x,y,z}(id_{x,y,z} = id_{ori}) + P_{x'y'z'}(id_{x'y'z'} = id_{best}) - P_{x,y,z}(id_{x,y,z} = id_{best}) - P_{x'y'z'}(id_{x'y'z'} = id_{ori})$.
3	$P_{x,y,z}(id_{x,y,z} = id_{ori}) + P_{x'y'z'}(id_{x'y'z'} = id_{best}) - P_{x,y,z}(id_{x,y,z} = id_{best}) - P_{x'y'z'}(id_{x'y'z'} = id_{best',\bar{U}})$.
4	$P_{x,y,z}(id_{x,y,z} = id_{ori}) - P_{x,y,z}(id_{x,y,z} = id_{best,\bar{U}})$.

A. Numerical Analysis

CCP^3 aims to minimize PDCCH RE-occupation conflict probability in average. As analyzed in Section II, the conflict probability is determined by N_{RB} and the number of REs occupied by PDCCHs. To evaluate their impacts on CCP^3, we introduce the parameter of load factor $L = N_{com}/N_{ava}$, where N_{com} is the number of REs occupied by PDCCHs, and N_{ava} is the number of candidate REs for PDCCHs. According to 3GPP specifications [7], the N_{ava} can be expressed as

$$N_{ava} = 4(8N_{RB} - 4 - 3\lceil N_{RB}/16 \rceil). \qquad (5)$$

For different load factor cases, numerical results are shown in Figs.3 and 4. In Fig. 3, we can see that CCP^3 performance is degraded when the load factor increases. From results in the figure, CCP^3 can achieve nearly 50% performance gain when the load factor is lower than 20%. However, when the load factor is greater than 66%, CCP^3 gets little performance gain compared with the alternate. In Fig. 4, we take the 5% worst sectors where the PDCCHs are suffering from the highest conflict probabilities. This worst case study is to learn about effectiveness of our proposal. In general, a strategy may promote system performance, but cause more penalties to some particular users. In other words, the users in the worst cases may suffer more unfair services if the whole system performance is aggressively pursued. But results in Fig. 4 show that CCP^3 can avoid this phenomenon.

In LTE-A networks, for 15 MHz and 20 MHz system bandwidths (N_{RB}= 75, or 100, respectively), the maximum number of REs occupied by the PDCCHs is 512 (namely, the maximal number of CCEs in the common search space is 16) [3]. From results in Figs. 3 and 4, we can observe that CCP^3 can always achieve around 50% performance gain when the load factor is lower than 20%. Please note, the gain is most significant because the two typical system bandwidth configurations in LTE-A networks, i.e., 15 MHz, and 20 MHz, have typical lower than 20% load factors (the claim can be verified in Function (5)).

B. Link-Level Simulation Experiments

To evaluate physical layer performance of CCP^3, we conduct link-level simulation experiments, where urban macro-cell scenario is applied [11], and the effective SINR of PDCCH received by UEs is cited as the performance matrix [12]. The main simulation parameters are given in Table II.

Results in Fig. 5 show the Cumulative Distribution Function (CDF) of the effective SINR (Signal-to-Interference plus Noise Ratio) in PDCCH received by UEs in the LTE-A network. For an expected effective SINR, results show that CCP^3 can accommodate more UEs than that of the alternate. For example, there are nearly 370 UEs in CCP^3 which effective SINR is higher than 10 dB, while the number of UEs in the alternate declines to 150 (there are 960 UEs totally in our simulation experiments). This is because CCP^3 can reduce the average RE conflict probability to relieve the ICI effect of the PDCCH. It is also clear that CCP^3 significantly obtains the best effective SINR up to 20 dB, which gets around 4 dB more compared with the alternate. For the worst 5% UEs, our proposal also can get nearly a 2.5 dB gain, when compared with the alternate.

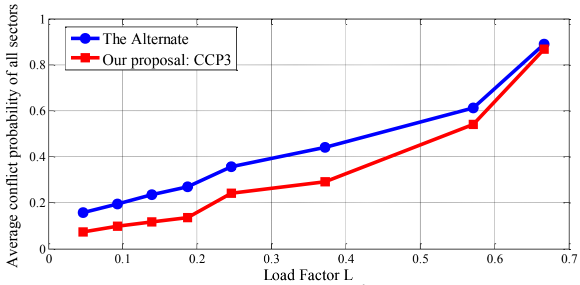

Fig.3. Performance comparison between CCP^{3}and the alternate, when taking all sectors into account.

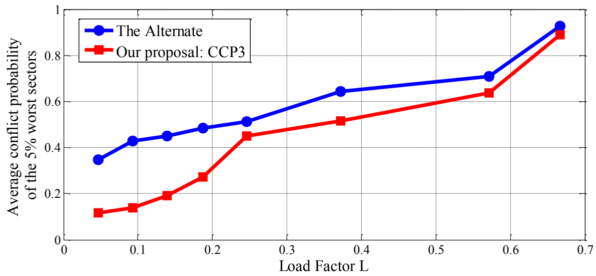

Fig. 4. Performance comparision beween CCP^{3}and the alternate, only considering the 5% worst sectors.

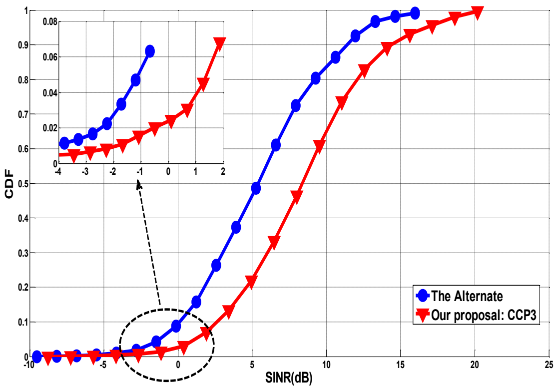

Fig. 5. Results of link-level simulation performance in the PDCCH.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
The number of sectors	48
Transmit model	SISO
The number of UEs in a sector	20
Cell radius	500m
Number of available PCIs	120
The thermal noise power spectral density	-174dBm/Hz
N_{RB}	randomly choose from 50,75 and 100
The number of OFDM symbols in control region	3
Antenna pattern	$A_H(\varphi) = -min\left[12(\frac{\varphi}{\varphi_{3dB}})^2, A_m\right], -180 \le \varphi \le 180,$
	φ_{3dB} = 70 degrees, A_m = 25 dB

V. CONCLUSION

In this study, we proposed a CCP^3 solution by using networking optimization to promote the effective SINR of the PDCCH. Our illuminative results demonstrate that our proposal can obtain performance gain around 50% when the load factor is lower than 20% (which is significantly a popular system configuration in LTE-A networks). Furthermore, our proposal can also get nearly 4 dB effective SINR gain in the best case and 2.5 dB effective SINR in the worst case, when compared with the existing solutions. More importantly, our proposal is developed based on networking optimization. It is worthwhile to study how our proposal can work together with any existing ICI solutions in either physical or upper layers. This topic is left for our future study.

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