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New Remapping Strategy for PDCCH Scheduling for LTE-Advanced Systems

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Abstract —In LTE-A, efficient Physical Downlink Control Channel (PDCCH) scheduling is fundamental to ensuring not only users' Quality of Service (QoS) but also bursty data channels. However, the limited resource available for PDCCH has proven to be a major issue that hampers users' scheduling. By principle, every user equipment (UE) admitted into the network is expected to be scheduled by the control channel prior to gaining access to data channel's resources (i.e. Physical Resource Blocks-PRBs). However, the limited PDCCH resources in traditional systems usually result to some UEs being deprived from accessing PRBs because they have not been scheduled for resource access by PDCCH. This situation is a major connectivity challenge in LTE-A systems. As such, we have proposed a new remapping strategy for PDCCH resource scheduling based on linear transformation matrix. Our scheme remaps the users' search spaces using a transformation function derived from their previous search spaces and the available resources in order to efficiently address PDCCH resource utilization issue. Extensive simulation results show that our new scheme is able to reduce UEs' average blocking probability and as well improve PDCCH resource utilization. Notwithstanding this enhancement, our scheme still maintains the decoding procedure and search space concept in LTE-A systems.

Index Terms—Physical downlink control channel (PDDCH), aggregation level, search space, control channel element, user equipment (UE).

I. INTRODUCTION

The physical downlink channels are designed for different purposes. The numbers of physical channels in the downlink are limited to only six. Four are supporting channels that provides; multicast/broadcast information, ACKS & NACKS, information about the size of the control channel. That leaves us with two key channels namely the Downlink Shared Channel (PDSCH) and Downlink Control Channel (PDCCH) [1], [2]. The PDCCH lies within the control region of every sub-frame along with Reference Signals (RS), Physical Control Format Indicator Channel (PCFICH) and Physical Hybrid ARQ Indicator Channel (PHICH) among others. whereas, in the data region, there are Physical Broad Channel, (PBCH), Primary Synchronization Signals (P-SS), Secondary Synchronization Signals (S-SS), Physical Multicast Channel (PMCH) and Physical Downlink Shared Channel (PDSCH).

PDSCH performance evaluation cannot be discussed without making reference to characteristics and constrain of PDCCH because of the fact that downlink capacity and control channel scheduling are functionally interdependent in LTE systems. The PDSCH is the channel that carries all UEs' data and some signaling information. Conversely, PDCCH carries Downlink Control Information (DCI), the DCI information could be meant for a UE or a group of UEs and several DCI messages can be transmitted in a sub-frame.

The flexibility of resource allocation in LTE-A systems makes it robust because allocation procedure can be realized using; time domain multiplexing, frequency-domain multiplexing, modulation and coding scheme or combination of two or more of these methods. Looking at the permutation of these possible ways, it becomes imperative to figure out clearly how each UE should determine where in the subframe its data are located and which modulation scheme is used by the base station (eNB) to transmit such data. This is the purpose of DCI in LTE. This type of special information is also common in earlier wireless communications technologies, for example; TFCI in WCDMA R99, HS-HSCCH in HSDPA and E-TFCI in HSUPA [3]-[5]. Hence, in LTE-A each UE must first decode its DCI message (s) before it can receive or send data successfully. It means without DCI, sending or receiving data will be out of the question. DCI are fashioned in various formats depending on the type and size of the payload. Details of DCI formats defined for LTE systems could be found in [3].

Schedulers in LTE performs two major objectives, namely: maximizing network resource utilization and optimizing users' Quality of Experience (QoE) subject to; available resource (either in time domain or frequency domain), users' capabilities and channel conditions [4]-[6]. The Scheduler at each eNB in LTE-A systems is responsible for scheduling the downlink and uplink shared channels (PDSCH and PUSCH) as well as the PDCCH. The other control channels (e.g. PCFICH, PHICH) do not require scheduling. In the downlink direction, scheduling is done in two facets that are always complimentary namely packet and PDCCH scheduling. One of the most important from scheduling perspectives

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is the PDCCH [7]. The initial packet scheduling is usually complimented by the PDCCH scheduling. Hence, the robustness of any mechanism defined for packet scheduling for UEs to achieve any diversity (spatial, antenna, frequency) is dependent on the effectiveness and capacity of the PDCCH. Although, resource scheduling priority for the PDCCH is directly derived from the packet scheduling, one thus concludes that the interdependence of the packet scheduling and PDCCH is a must to discuss issue to achieve seamless/significant improvement in LTE-A systems resource utilization.

The basic resource for PDSCH is Primary Resource Block (PRB) while in the PDCCH perspective Control Channel Element (CCE) is defined as the basic resource unit. Research is replete of discussions about bandwidth, which is the aggregate of the PRBs; however, the issue of CCEs is seldom discussed despite their enormous importance.

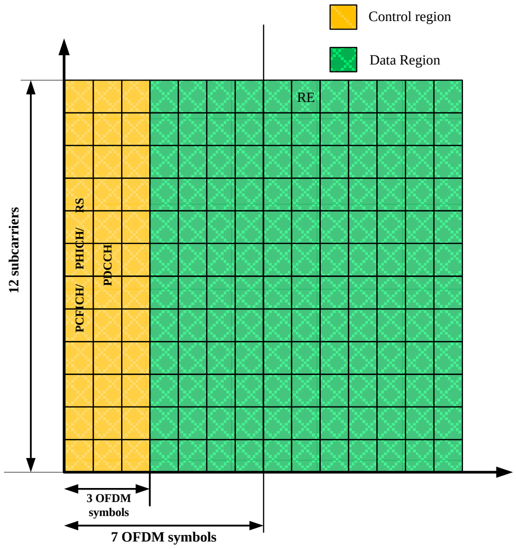

Fig. 1. Illustration of control and data region in LTE Sub-frame

As depicted in Fig. 1 PDCCH and other control channels occupy up to three OFDM symbols in a sub-frame with normal cyclic prefix, the maximum number of DCI messages that can be transmitted per sub-frame depends on the format adopted; there are 9 DCI formats for DL scheduling assignment two for UL grant and two for transmit power control [8]. However, not all formats can be adopted for various DCI messages. Similarly, the possible number of bits that could be transmitted in data channel is higher compared to that of PDCCH because higher code rates (4 QAM, 16 QAM and 64QAM) can be applied unlike PDCCH that adopts only lowest code rate of QPSK for PDCCH processing [3]. These PDCCH impediments would impact the performance of the data channels because higher bit rate in data channels need to be supported by wider control channel. This case becomes more demanding in carrier aggregation in LTE-A systems with cross carrier scheduling wherein the limited CCEs of a PDCCH in one component carrier is designed to be responsive for itself and other component carriers. Sequel to aforementioned challenges and others discussed in [7], [9], the need for proper design for PDCCH scheduling became indispensable. Discussion and proposal about PDCCH is however, receiving wider attention by 3GPP as from Release 8 through 11 and even beyond, this is because control channel design form part of the key technologies for effective operation of LTE-A system [9].

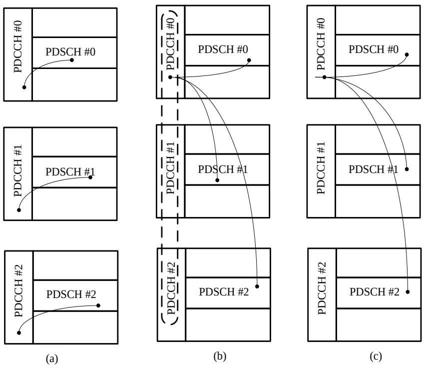

Fig. 2. PDCCH Design options for LTE-A systems

A. *PDCCH Functionality in LTE-Advanced Systems*

As measures are being taken to restrict the adverse impact of control channels on performance of data channels in multi carrier systems, the following alternatives were considered for designing control channels. Fig. 2 shows the design pattern [9].

a) Control channel on the same component carrier as the data channel.
b) Control channel always spans the entire bandwidth.
c) Control channel transmission in one component carrier.

In case of (a), the control channel is separately coded and associated with the PDSCH corresponding to its carrier bandwidth which maintains fully backward compatibility design. As an example, if a user is not scheduled in a particular component carrier, its control information is not transmitted in that carrier. With this design, the Rel-8 control structure can be reused with minor modifications. However, this design incurs a higher overhead, large number of blind decoding and lower frequency diversity. This design concept would also increase the complexity of UEs because a UE with *n* carrier aggregation will be required to span *n* control channels for its possible control information.

In Option (b), the PDCCH is jointly coded and sent over the entire bandwidth spanned by the component carriers. This alternative also has several advantages and disadvantages. The advantages are lower overhead, lower number of blind decoding and increased frequency diversity, on the other hand, the disadvantages are; increased UEs' battery consumption rate, backward compatibility issues with Rel-8 UE's and new DCI formats, etc.

In the 3rd option (c), the PDCCH from multiple carriers are jointly coded and transmitted in one primary component carrier. The advantages of this approach are lower overhead, less number of blind decoding and same CCE structure as Rel-8 while the disadvantages are lower frequency diversity and need to define new DCI formats. This option seems to be attractive and has so far been accepted for Release 9, 10, 11 and even beyond.

B. *PDCCH Structure*

The generic radio frame structure in LTE can be described in two dimension/domains (i.e. time and frequency domains). One radio frame has time duration of 10ms, comprising of 20 slots of 0.5ms each. Two consecutive slots form a sub-frame. The 1 ms covered by a sub-frame is known transmit-time interval (TTI). Furthermore, each slot consists of seven OFDM symbols with normal cyclic prefix (CP) or six OFDM symbol in case of extended CP. In the frequency domain; every OFDM band is made of small space channels known as sub-carriers. These spacing between two adjacent channels (sub-carriers) is always uniform (i.e. 15 kHz) regardless of total bandwidth.

Now looking at the resources from two dimension perspectives, the minimum unit would be a resource element (RE) which is made of a unit sub-carrier in frequency axis and one symbol in the time axis. A combination of 12 consecutive sub-carriers in frequency domain and a unit time slot is known as Physical Resource Block (PRB), this is the far-famed unit in LTE-A for both radio frequency measurements and protocols. Fig. 1 show how the resources are culled in LTE frame structure.

Notably, out of 84 REs that made up one PRB, only 36 REs are reserved for control channel. PRBs are widely considered while talking about bandwidth allocation or RF resources. In control region, four resource elements form a group known as Resource Element Group (REG) and nine resource element groups (REGs) constitute a control channel element (CCE). Certainly, the number of CCEs available to transmit the control information will be variable depending on the; (a) PCFICH value (b) Total system Bandwidth (c) Number of antenna ports present (d) reference signals and (e) PHICH resource mapping, hence the three symbols used for building the control channel region resources are not meant for only PDCCH.

It is obvious that the limited CCEs being used for PDCCH are expected to serve UEs alongside abundant PRBs in PDSCH. For example, in 20MHz bandwidth, a UE can have all the 100 PRBs available to its advantage if situation permits against a limited number of 1 or 2 or 4 or 8 CCEs maximum. As noted earlier, the number of symbols commonly used for Downlink Control Channel (DCCH) is 3, out of which only four-fifths $^4\!/_5$ (approximately) is dedicated to PDCCH the remainders are occupied by PCFICH, PHICH and reference signals. The total available REs for DCCH is given as $N_{RE}^{DCCH} \approx N_{RE}^{CCH} \bullet {}^{BW}\!/_{\Delta}$ where N_{RE}^{DCCH} is the number of REs available for control channel, N_{RE}^{CCH}, BW and Δ are number of resource elements for entire control channel , the system bandwidth and subcarrier spacing respectively [7].

In discussing PDCCH two points must be tracked. Firstly, the number of resources to be assigned to the PDCCH. Secondly, how UEs should effectively receive their DCI messages from PDCCH. The first point is primarily handled by PCFICH design, which is not discussed in this work the latter is the center point of our discussion in this paper. The PDCCH configuration requires that each UE does blind decoding of a set of candidate locations to ascertain which, if any, contains its DCI message(s). [10], [11] mentioned that; “the amount of resources allocated to the PDCCH can be varied. However, if the allocated amount is too small, then the uplink and downlink data schedulers will not be able to schedule all UEs. On the other hand, if the allocated amount is too large, then resources that could have been used for transmitting data would be wasted”.

The key parameters mostly highlighted in the design of PDCCH includes; UE specific search space, common search space, search space size, blind decoding, candidate location to be monitored by UE in search of its possible control information, a starting point for the search space and aggregation level by UE. The resource elements allocated to PDCCH could be arranged in a set as; $R_{CCE}^{Total} = \left\{ r_{0,} r_{1,} r_{2,} ....r_{NCCE-1} \right\}$ where $NCCE$ is the total number of control channel elements available for PDCCH. Each PDCCH carries one DCI and is identified by RNTI. The RNTI is implicitly encoded in the CRC attached to DCI. The authors in [12] gives an outline of DCI decoding procedure.

II. PDCCH SCHEDULING

In a PDCCH scheduling process, the UE is expected to blindly decode its DCI message(s), which is usually located within the mainstream of the CCEs but unknown to the UEs priori. Making every UE to conduct a search for its possible DCI by scrutinizing every CCE would lead to time and power wastages. To avert such wastages, limited subsets of CCEs are specified in LTE for UEs to look-up for their possible DCI messages. This subset is known as the *search space*. LTE also defined two types of search spaces; common search space and UE specific search space. The common search space carries the DCIs for system information using the (SI-RNTI), paging (P-RNTI), PRACH responses (RA-RNTI), or UL TPC commands (TPC-PUCCH/PUSCH-RNTI). It is also meant to handle scheduling of multiple UEs and such DCI must be accessible by targeted UEs. UE’s specific search space is bounded for transmitting DCIs for a particular

UE and it carries DCI(s) for a UE using its C-RNTI, semi-persistent scheduling (SPS C-RNTI), or initial allocation (temporary C-RNTI). A UE is required to monitor both common and UE-specific search spaces during blind decoding. There might be overlap of common and UE-specific search spaces for a particular UE. The UE monitors the common search space using aggregation level 4 and 8 only. The UE could monitor the UE-specific search space at all aggregation (1, 2, 4, or 8) levels.

In Release 8, UE specific search space is given as [13];

$$SP^{AL}_{k,LTE} = AL\left\{\left(Y_k + m\right)\bmod\left(N^{K}_{CCE}\Big/AL\right)\right\} + i \qquad (1)$$
$$Y_K = \left(AY_{K-1}\right)\bmod D$$

$i = 0,\cdots,AL-1$ and $m = 0,\cdots,M^{(L)}-1$. $M^{(L)}$ is the number of PDCCH candidates to monitor in a given search space, where $Y_{-1} = n_{\mathrm{RNTI}} \neq 0$, $A = 39827$, $D = 65537$ and $k = \lfloor n_s/2 \rfloor$, n_s is the slot number within a radio frame. In a multi-carrier system, if the UE-specific and common search spaces relating to different component carriers happen to overlap for some aggregation levels when cross-carrier scheduling is configured, the UE only needs to monitor the common search space [12]. Before we talk of PDCCH scheduling, some key terms need to be clearly defined.

A. *Aggregation Level*

One PDCCH may occupy a number of CCEs depending on channel quality, bandwidth, and the number of OFDM symbols used for the PDDCH. The number of CCEs occupied by a PDCCH carrying DCI for a UE or groups of UEs could be 1, 2, 4 or 8, which are signified as aggregation levels for the UEs denoted as AL in equation (1).

B. *Candidate Location*

This is the number of locations (subset of CCE) to be checked by UE(s) for its possible DCI message(s) at any given aggregation level, denoted as $M^{(L)}$ in equation (1). The number of candidate location is already standardized by 3GPP. Table I shows the summary.

TABLE I: PDCCH CANDIDATES MONITORED BY UE.

Type	Aggregation level AL	Search space Size [in CCEs] $SP^{AL}_{k,LTE}$	Number of PDCCH candidates $M^{(L)}$
UE-specific	1	6	6
	2	12	6
	4	8	2
	8	16	2
Common	4	16	4
	8	16	2

C. *Blind Decoding*

The UEs are expected to search across all their PDCCH candidate locations without any prior knowledge about the exact location of CCE(s) used. This process is known as blind decoding.

III. PDCCH SCHEDULING ALGORITHMS

PDCCH Scheduling answers two basic questions, 1. How many CCEs are required by UE during each transmission time interval (TTI)? 2. How should the CCEs be distributed among the UEs? Aside the base line algorithm for CCE resource allocation described in [13] there are a number of solutions in literature proposing different algorithm to distribute CCEs. Table II summarizes the strength and weakness of some of the scheduling techniques we reviewed. In some scenarios, authors tried to combine any of these techniques to achieve a better result [13]-[17]. UEs' aggregation levels, search space, co-channel interference and power consumption are mostly the basic parameters used for developing any algorithm to optimize the PDCCH scheduling [15]. Other metrics includes RNTI, hashing function and offset as in [14]. Individual UEs could have the same aggregation level, use the same hashing function, and experience similar co-channel interference and power consumption but the RNTI or C-RNTI is peculiar to each UE.

TABLE II: SUMMARY PDDCH SCHEDULING ALGORITHMS REVIEWED

	Algorithm/Technique for PDCCH scheduling	CCE Utilization	Blocking probability	Process Complexity
1	Base Line scheduling	low	high	simple
2	Min-AL	low	average	Simple
3	Min-Start Point	low	average	Simple
4	CCE allocation Reshuffling	average	average	complex
5	Power adjustment	High	low	moderate
6	Co-Channel Interference Avoidance	high	high	complex
7	Offset adjustment	high	low	Complex

A. *Baseline Algorithm*

In the baseline scheduling algorithm, the UEs' priority order received from packet scheduler is retained. The baseline scheduler then tries to find vacant PDDCH resource for each UE in a sequence, if the number of vacant CCEs found is equal to the aggregation level of the UE being scheduled, the UE is scheduled successfully and the CCEs found on PDCCH are marked 'utilized. If otherwise, no vacant CCEs are found or the number of resources found is less than the UE's aggregation level, then the UE is blocked and the baseline scheduler moves to the next UE in the sequence. Because of the limitations of PDCCH, not all the CCEs are always assigned as long as there are wide spaces between the search spaces of UEs, see Fig. 3 for a demonstration for UE-A and UE-B search spaces at different aggregation levels, assuming the UE-A and UE-B have similar aggregation levels for all sub frames. As shown in the Fig. 3, the overlap of the search spaces becomes more prevalent at higher aggregation levels, hence the baseline scheduler performance exhibit unacceptable performance particularly for cell edge UEs in terms of UE blocking probability and PDCCH resource utilization. Fig. 4 summarizes the procedure for baseline algorithm for PDCCH scheduling.

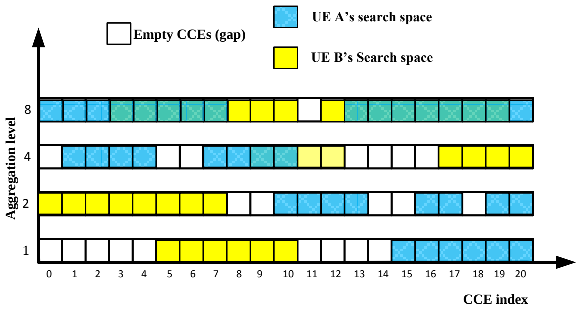

Fig. 3. An illustration of for search space distribution for two UE during PDCCH scheduling

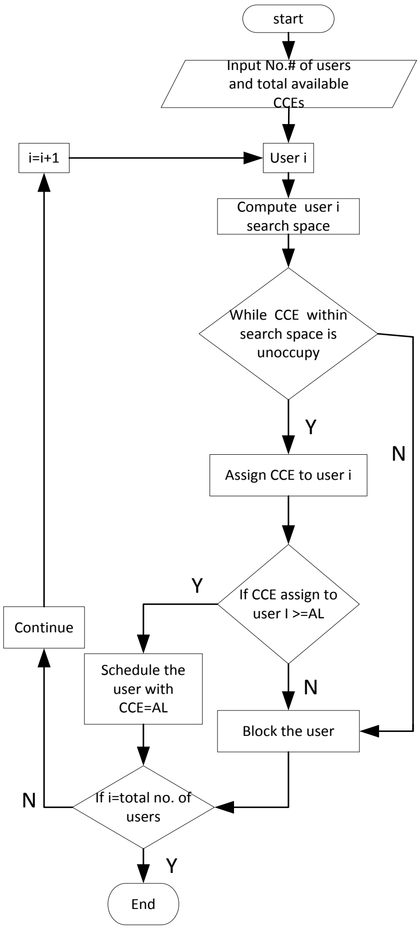

Fig. 4. Base line algorithm flow chart

B. *Minimum Aggregation Level (Min. AL) Algorithm*

If the UEs with higher aggregation levels (4 or 8) were allowed to be the priority users to access PDCCH resources, there could be greater blocking probability. This is because the probability for resource conflict tends to be higher with an increasing demand for the CCEs. In Min-AL scheduler, UEs are sorted in ascending order in accordance with their aggregation levels such that the UEs with lower aggregation levels are given higher priority. This arrangement will place all the UEs with lower aggregation at advantage. For example; if we have 21 CCEs and seven UEs with aggregation levels 1, 1, 2, 24, 8 and 8 respectively to be scheduled prior to rearrangement, each UE has equal probability of been scheduled. The probability for each UE will be;

$$p_i = \frac{1}{\sum_{j=1}^{k} UE} \tag{2}$$

where k the total is number of UEs to be scheduled and i is the index for the UEs. After rearrangement, probability would then be given as;

$$p_i^* = \frac{AL_i}{\sum_{j=1}^{k} AL_i}, \quad AL_i < AL_{i+1} \tag{3}$$

where AL_i is the aggregation level for the $i-th$ UE. The idea of Min-AL scheduler is to allow more UEs to have better chances to find empty CCEs. As demonstrated in numerical examples in Table III, if the scheduling is processed according to direct demand (using equation (2)), the UEs with higher CCE demand are likely to be the top priority UEs. With such procedure, only 4 UEs can be scheduled to exhaust the 21 CCEs. After rearrangement, it is obvious that more number of UEs (up to six UEs) can be successfully scheduled with only 18 CCEs and UEs with higher aggregation level are likely to be blocked. Therefore, this scheduler will have lower CCE utilization because not all the CCEs are utilized. This scheduler is also biased in favour of cell-center UEs because most cell-edge UEs always have higher aggregation level compare to cell-center UEs.

TABLE III: MINIMUM AGGREGATION LEVEL PROBABILITIES

Index (i)	AL_i	Probability prior to rearrangement (p_i)	probability According to CCE demand	Probability after rearrangement (p_i^*)
1	1	0.14	0.05	0.95
2	1	0.14	0.05	0.95
3	2	0.14	0.10	0.90
4	2	0.14	0.10	0.90
5	4	0.14	0.19	0.81
6	8	0.14	0.38	0.62
7	8	0.14	0.38	0.62

C. *Minimum Start Point Algorithm*

The technique for minimum start point algorithm is the same for minimum aggregation level except that the start points are used in place of aggregation levels. The UEs start points are rearranged in ascending order prior to resource allocation such that the CCE resource allocated to UE_{i+1} will be preceded by UE_i ' s resources. The start point for each UE is determined according to equation (5). This algorithm seems to perform remarkably only if there more UEs with lower aggregation levels with marginal gaps between their start points. If otherwise, the search space overlaps can become even worst thereby increasing the chances of UEs' blockage.

D. CCE Allocation Reshuffling

This algorithm is triggered only when there are conflicts during resource allocation. For example; if in the course of identifying the resources to be allocated to UE_{i+5} there is a conflict, then the algorithm will attempt to reallocate the resources of all the preceding $UE_{i+0,}UE_{i+1,}UE_{i+2,}UE_{i+3,}UE_{i+4,}$ so as to accommodate UE_{i+5}. The computational overhead is the key problem for implementing this algorithm.

E. Power Adjustment Algorithm

Given that the maximum power available for the PDDCH is P_{PDCCH} then CCE power will be given as;

$$P_{CCE} = \frac{P_{PDCCH}}{N_{CCE}} \tag{4}$$

The minimum CCE power $P^C_{\min}$ required by eNB to serve the cell-center UEs is expected be $P^C_{\min} \leq P_{CCE}$. If the $P^C_{\min} \ll P_{CCE}$ then P_{CCE} is reduced to $P^C_{\min}$ in order to save power for cell-edge UEs. This technique maximizes power as well as CCE utilization for the PDCCH scheduling.

F. Co-Channel Interference Avoidance Algorithm

This algorithm adopts the techniques of fractional frequency reused (FFR) analogous to what is being used for inter-cell interference coordination (ICIC) in LTE. In its case, the underlying mechanism is to apply a frequency reuse factor of 1 for center-UEs' CCEs and frequency reuse factor of N for cell-edge UEs' CCEs. See Fig. 5 for illustration for $N = 3$. The transmit power for center-UEs' CCEs is kept at $P^C_{\min}$, while the frequencies of the cell-edge CCEs are made orthogonal to reduce the co-channel interference.

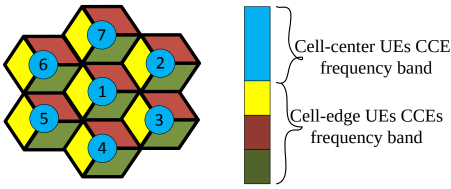

Fig. 5. Fractional frequency reuse pattern for PDCCH CCEs to avoid co-channel interference

IV. KEY PERFORMANCE INDICES IN PDCCH SCHEDULING

The performance metrics mostly evaluated in PDCCH scheduling are blocking probability, CCE utilization and delay. Though, the former is seldom evaluated. Blocking probability per sub-frame is expressed as;

$$\text{Blocking probability} = \frac{\text{number of blocked UEs}}{\text{sum of scheduled UEs}}$$

similarly, CCE utilization is given as;

$$\text{CCE Utilization} = \frac{\text{sum of CCEs utilized}}{\text{Total number of CCEs}}$$

while delay is; $\text{Delay} = \sum_{i=0}^{k} TTI_i$ i.e. sum of average delays experience from every TTI. Blocking probability can also be visualized from baseline algorithm flow chart illustrated in Fig. 4. The PDCCH scheduler interacts with packet scheduler, in most cases the PDCCH scheduler does maintain the priority list created by the packet scheduler.

However, for system optimization purposes, the priority is sometimes altered to achieve better results, e.g. to enforce fairness or manage UEs' power. Fig. 6 shows the basic interaction of PDCCH scheduler with packet scheduler.

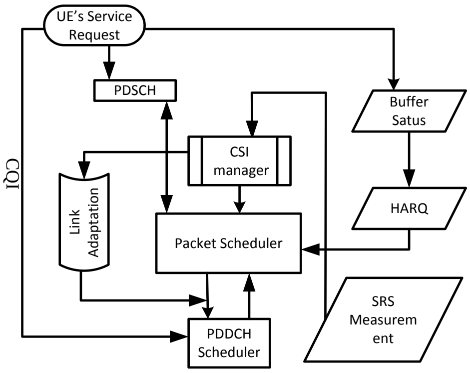

Fig. 6. PDCCH interactions with packet scheduler

V. PROBLEM STATEMENT

Search space sizes and candidate locations to be monitored are the key factors in PDCCH scheduling. Though, the duo is already standardized by 3GPP. Confining UEs' search space to limited locations as prescribed would actually save UEs' power but increases the blocking probability, especially for the UEs with aggregation levels 4 and 8 and encourages underutilization of CCE resources if adequate measures are not taken to ensure that every scheduled UE is served so long there are empty CCEs available for PDCCH.

The first measure to curb these challenges is to avoid request conflicts (i.e. search space overlap). Randomizing starting points for UEs could lessen this problem, especially in multicarrier systems. The starting point is the CCE's index that can be obtained by UEs using a formula based on; the RNTI (-the RNTI is used for computing initial hashing function in sub-frame), the slot number within a radio frame, the total number of CCEs within the control region of a sub-frame, and the aggregation level. Equation (5) defines the start point index for LTE [18].

$$ST^{AL}_{k,LTE} = AL * \left\{ Y_k \bmod \left(N^K_{CCE} \middle/ AL \right) \right\} \tag{5}$$

One may still need to ask if randomizing starting point resolves all problems assuming every UE has its unique starting point. The answer is no, because the tendency of overlapping of a UEs' search spaces with one another cannot be ruled out completely, especially when their starting points are close and aggregation levels are similar. Therefore, further measures are required to improve PDCCH scheduling in multicarrier systems like LTE-A.

VI. PROPOSED METHOD

The need for PDCCH scheduling is concerned with optimal CCEs allocation to UEs. Without deviation from general concept, we propose new remapping strategy as follows;

A. Initial Assumptions

- eNB is aware of UEs' channel quality
- UEs' channel quality information (CQI) report is effective
- UEs within $\frac{2}{3}$ radius of serving eNB are tagged as center UEs
- eNB is capable of randomizing UEs search spaces through permutation of their hash functions

B. Algorithm Procedure

Step1: Co-channel interference can have a very crucial effect on the scheduling of UEs if not avoided, and will likely impair the UEs' QoS. To curb this effect, we adopt the method of fractional frequency reused (FFR) explained in Section IV (6) to lessen the co-channel interference. Furthermore, to ensure optimal power utilization, the eNB will restrict both the center and cell-edge CCEs powers to $P_{\min}^{C}$ and $P_{\min}^{edge}$ respectively such that the power pattern can be as depicted in Fig. 7.

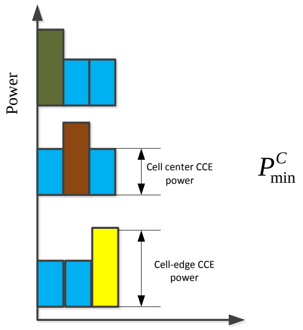

Fig. 7. CCEs transmit power bound

Step 2: eNB allocates CCEs according to priority list received from packet scheduler

Step 3: if UE successfully decode all its DCI messages (this implies eNB has successfully assigned resources to UE equal to its aggregation level). If otherwise proceed to step **5**

Step 4: eNB marks the CCEs assigned to UE in previous step and then proceed to step **7**

Step 5: keep the UE on hold and remap its DCI messages to another sets of CCEs.

Step 5.1: because eNB is unable to allocate the required number of CCEs to UE (i.e. $0 \le nCCEs_{assigned} < nCCEs_{required}$), eNB will retain $nCCEs_{assigned}$

Step 5.2: The eNB will then make use of the initial candidate locations monitored by the UE to form foundation matrix P_m formulated as in equation 6;

$$P_m = \begin{pmatrix} p_{1,1} & p_{1,2} & \bullet & & \bullet & p_{m,l} \\ p_{2,1} & p_2 & \bullet & \bullet & & \bullet \\ \bullet & \bullet & & & & \bullet \\ \bullet & \bullet & & \bullet & & \bullet \\ \bullet & \bullet & & & \bullet & \bullet \\ p_{l,1} & p_{l,2} & \bullet & \bullet & \bullet & p_{l,m} \end{pmatrix} \tag{6}$$

Note: matrix P_m is made of m columns and l rows where l is the aggregation level for the UE whereas is the number of locations monitoredis m; further, our D matrix is derived from P_m using the relation;

$$D = \frac{P_m * (\Delta_{CCE})}{m} \tag{7}$$

where $\Delta_{CCE} = NCCE_{total} - \max(P_m)$, $\max(P_m)$ is the value for maximum element in matrix P_m and finally, we express our remapping matrix as;

$$\begin{gathered} Q = Round[D \setminus P_m] \\ \text{where} \\ D \setminus P_m = \{x \in D \mid x \notin P_m\} \end{gathered} \tag{8}$$

Step 5.3: eNB remap the UE's DCI messages to new set of CCEs using the elements of matrix Q as the index for new remapping.

Step 6: release UE to complete decoding, if successful return to step 4, otherwise block the UE

Step 7: returns the UE for the next scheduling

VII. RESULTS

To evaluate the performance of the proposed scheduling technique, we conducted Monte Carlo simulation with 19 UEs and 5MHz bandwidth. Aggregation level for each UE is chosen randomly with replacement and weighting probabilities of 45%, 30%, 15% and 10% for aggregation levels 1, 2, 4 and 8 respectively.

As a bench mark, we simulated the behavior of the PDCCH scheduler and record the optimal performance using the base line algorithm described in Section III A. Subsequently, we focus on emulating some of the techniques described in Section III. In each case, we recorded the average performance of the scheduler. Finally, we simulated our proposed remapping method to see the effect on the performance. Fig. 8 shows the comparative performance for blocking probability for various methods simulated and Fig. 6 for CCE utilization.

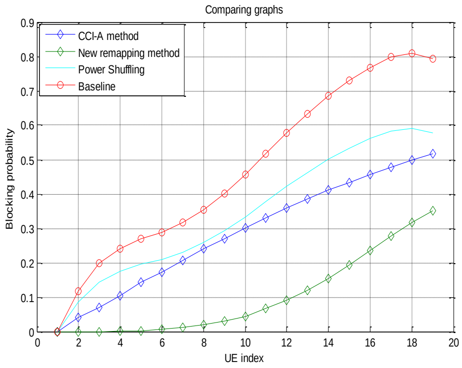

Fig. 8. Comparing the blocking probability of various algorithms

In Fig. 8, the baseline algorithm tends to have higher blocking probability because UEs’ are schedule without any predefined priority pattern. The situation becomes worst when the cell-edge UEs happen to occupy top priority. Co-channel interference avoidance algorithm display better results compare to power shuffling and look more stable because the it combined the method of power shaping and interference avoidance during resource scheduling.

Our proposed algorithm outperformed the former methods irrespective of the number UEs in the system.

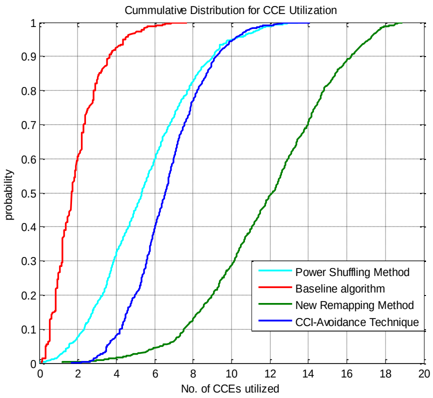

Fig. 9. CCE utilization of various algorithms

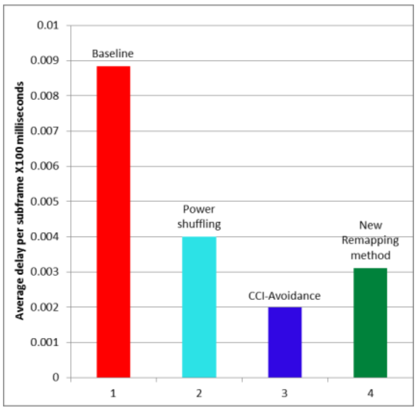

Fig. 10. Delay

In Fig. 9, looking at the probability at 50% resource utilization, the corresponding CCE occupied are 1.8, 5.2 6.3 and 12 for baseline (BL), power shuffling (PS), Co-channel interference avoidance (CCA-I) and new remapping method respectively. The PS and CCI-A exhibit nearly similar performance at 90% and beyond. The increase in delays set-in (see Fig. 10) by second level decoding in our proposed scheme is the price for total blockage of the UEs which is considered a better tradeoff.

VIII. CONCLUSION

The ever increasing traffic for data channels for LTE-A systems requires complementary and efficient PDCCH scheduling. Issues of PDCCH scheduling are increasingly receiving more attention every day. In this paper, we develop a linear transformation function that remaps UEs’ DCI message(s) to avoid total denial/access to network resources.

Our new PDCCH scheduling stems from a Co-channel interference avoidance with remapping technique added for enhancement. Through simulation, the result of our new remapping strategy yielded lower blocking probability along with higher CCE utilization. The complexity in remapping is minimal and is only triggered when the need arises. That is, when a UE is being blocked and there are still available CCEs. Relative to other schemes, we achieved better results with less intricacy. This makes the scheme a suitable alternative for PDCCH scheduling, especially for multi carrier systems like LTE-A systems.

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