Adaptive Enhanced Physical Downlink Control Channel (EPDDCH) for LTE-Advanced Systems [??]

Bala Alhaji Salihu [1,*],   Yang Dacheng [1]   Umar Mustapha Mala B. [2]
Suleiman Zubair [3]

[1] *Wireless theory and Technology LAB, Beijing University of Posts and Telecommunications, Beijing 100876, China*

[2] *Electrical Electronics Engineering Dept. University of Maiduguri, Nigeria*

[3] *2UTM-MIMOS Centre of Excellence (CoE) in Telecommunication Technology, Universiti Teknologi Malaysia*

Abstract

Recently, 3rd generation partnership project (3GPP) proposes a new control channel framework known as enhanced physical downlink control channel (EPDCCH) as adjunct to existing physical downlink control (PDCCH). The challenge of scarce resources in PDCCH is almost out of question for EPDCCH. However, the methods of achieving efficient resource utilization are still relevant and important. We have outline new scheme for mapping out the EDPCCH from physical downlink shared channel (PDSCH) with less signaling overhead and also outline new algorithm for distributing its resources among UEs search spaces. Our proposed scheme is design for different scenarios and thus classified as adaptive. Through simulation we have proved that the UEs' blocking probability can be lessen and EPDCCH resource utilization can be improved.

Keywords: EPDCCH, resource utilization, channel quality indicator, aggregation level, search space

1   Introduction

Long Term Evolution (LTE) technology has passed the test of its time because it has responded accordingly to the enormous data demand in wireless/mobile communications industry, thanks to 3rd generation partnership project (3GPP). However, more works are still on underway to improve the capacity of the technology. Outwardly, the data channel is the most topical aspect that has received more suggestions and improvement, but the data channel's capacity can be hampered if the control channel capacity is limited. Since the advent of LTE in 2005, 3GPP has being incorporating outstanding features that would meet the expectations of both the operators and the subscriber such as wider bandwidth, support for heterogeneous and multi-carrier networks,

---

*Corresponding author.

Email addresses: bala.salihu.a@ieee.org (Bala Alhaji Salihu), yangdc@bupt.edu.cn (Yang Dacheng), bkumar52@hotmail.com (Umar Mustapha Mala B.), zsuleiman2@live.utm.my (Suleiman Zubair).

multi-service function and so forth. These entire features primarily rely on the effective control signaling between the base stations and users hereinafter refer to as evolved Node B (eNB) and user equipment (UE) respectively.

In LTE technology, radio resource allocation is network controlled; Physical resource block (RB) comprising of 180 kHz in the frequency domain and 1ms in time domain is the basic resource allocation unit. The eNB periodically inform the UEs about resource allocation on a subframe basis. Every downlink radio frame is distinctively divided into control region and data region, the control region consist of the physical control format indicator channel (PCFICH), physical hybrid ARQ Indicator Channel (PHICH), reference signals (RS), the synchronization signals (primary and secondary), and the physical downlink control channel (PDCCH). PDCCH is one of the most crucial of all because it requires scheduling.

In LTE release 8/9/10, a PDCCH carries a message called downlink control information (DCI), which informs the UE(s) about their respective downlink resource assignment, uplink resource grants , modulation and coding scheme and other control messages[1]. PCFICH is the downlink control channel that carries the control format indicator (CFI) which indicates the number of OFDM symbols (1, 2, 3 or 4) used for downlink control channel information in each subframe[2]. PDCCH and other control channels are located within the first 3 OFDM symbol of a sub-frame for a normal cyclic prefix for bandwidth above 1.4MHz.

In the earlier design adopted for downlink control channel, PDDCH is pseudo-randomly distributed across the whole channel bandwidth at the beginning of each sub-frame in order to exploit channel fading and inter-cell interference diversities[3]. However, introduction of new features (e.g. carrier aggregation, MIMO, HetNet etc.) into LTE that led to advent of LTE-Advanced systems imposed more challenges on the legacy PDDCH and hinder its performance. Some of these challenges include:

- **Lack support for ICIC** ; Lack of support for Inter-cell interference coordination (ICIC) within the control region - this factor encourages radio resource wastage and increase control signaling overhead.

- **Resource bounded** ; Limited resources available for DCI messaging -thereby limiting network capacity and spectral efficiency.

- **Frequency selective scheduling limited** ; This limitation impacts the network coverage.

Due to aforementioned constraints, it becomes desirable to expand the legacy PDDCH to commensurate and support wider resource allocation on the data channel and to also improve the system capacity and coverage. The enhanced PDCCH (EPDCCH) was motivated and introduced in release 11 to salvage these scenarios. Besides increasing the control channel capacity, the EPDCCH was also envisaged to provide the following benefits[1].

- aid frequency-domain inter-cell interference coordination
- support for beamforming and precoding
- support for multi-antenna systems (e.g., MIMO) through spatial multiplexing
- exploit frequency-selective gain

- support operation in multicast-broadcast single-frequency network (MBSFN) sub-frames and co-existence on the same carrier with legacy PDCCH

2   EPDDCH design framework

In order not to overstretch the burdens on the legacy PDDCH, EPDCCH does not derive its resources from the control region of a normal LTE sub-frame, rather, the EPDCCH is Frequency Division Multiplexed (FDM) with the physical downlink share channel (PDSCH) within the data region. Though there are other alternatives considered for EPDDCH and PDSCH multiplexing (as shown in figure 2) but the simplest approach that has minimal impact on the PDSCH is pure FDM as shown in figure 1. In a clearer say, EPDDCH are mapped to PDSCH's RB pairs. The signaling from radio resource control (RRC) to indicate within the system bandwidth which RB pairs are used for the EPDDCH set (N_{RB}^{EPDCCH}) depends on the total number of downlink RBs (N_{DL}^{RB}) available.
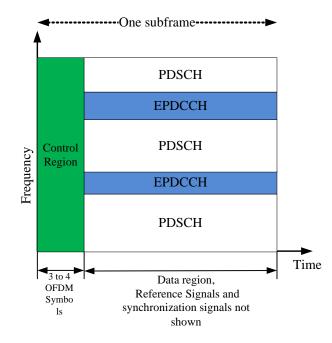

Fig. 1: RB-pair-level based FDM multiplexing of EPDCCH and PDSCH

The number of enhanced control channel elements -ECCEs (which are the basic unit of EPDD-CH) for transmitting UEs' DCI message (s) is influenced by channel conditions and is known as aggregation level. Usually, UEs with better channel would require fewer ECCEs (lower aggregation level e.g. 2 or 4) compare to cell-edge UEs (that may require aggregation level 4, 8 or 16).
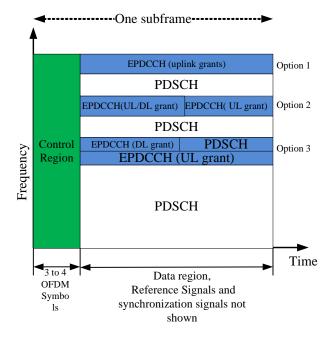
Fig. 2: Options for Multiplexing of EPDCCH and PDSCH

3   Indicating EPDCCH-RBs

3.1   EPDDCH mapping overhead

Earlier suggestions sum-up the number of binary bits required to indicate the EPDDCH-RBs set as given in table 1, these suggestions could be found in [1, 4] and the references therein. Knowing the number of bits to be used for identifying the potential EPDDCH-RB sets is not enough, because there would be several possible combinations especially at higher bandwidth. For example, in a bandwidth of 5MHz there would be 495 possible options for choosing only 4 RBs pairs provided the order of arrangement is ignored. How to effectively maps the EPDCCH-RB sets is worthwhile, we give account of our proposed mapping method in subsection 3.2.

Table 1: Bandwidth and number of bits required for indication EPDCCH-RB sets

N_{DL}^{RB}	Number of bits (N)		
(Bandwidth)	2	4	8
6 (1.4MHZ)	4	4	–
15 (3MHZ)	7	11	13
25(5MHZ)	9	14	21
50(10MHZ)	11	18	30
75(15MHZ)	12	21	34
100(20MHZ)	13	22	38

3.2   EPDDCH mapping structure

The fundamental issues with EPDDCH can be categorized into two namely; how to select the EPDCCH-RBs pairs from the PDSCH-RBs and the effective utilization of the ECCEs. We proposed CQI reporting mechanism for selecting the best subband or RBs pairs for the mapping.

One of the most popular methods for EPDDCH-RBs mapping is the combinatorial index method; the combinatorial index based method has the following signaling [5].

- **Size indicator**: used to indicate the number of RB pairs for the EPDCCH sets.

- **Combinatorial index**: contains the location of the n used RB pairs where n is indicated by size indicator. The combinatorial index is defined as;

$$indx = \sum_{0}^{m-r} \langle^{N-r_i}_{m-i}\rangle \tag{1}$$

  where

$$\langle^q_p\rangle = \begin{cases} \binom{q}{p} & q \geq p \\ 0 & : q < p \end{cases}$$

- The range of combinatorial index is from 0 to $\binom{N}{M} - 1$. N is the number of downlink RBs. M is the maximum supported number of RB pairs for an EPDCCH set. r_i is the index of the ith RB for the configured EPDCCH set.

3.3   Proposed Mapping Method

Because of the importance of DCI message(s) to UEs, it is worthwhile to map EPDCCH-RBs sets to subcarriers with better SINR. This is to ensure robust control channel. Basically in the downlink, the eNB transmits reference signal (downlink pilot) to UEs. These reference signals are used by UEs for the measurements of the channel quality indicator (CQI).The UEs periodically send CQI reports to their serving eNB, a higher CQI value infers better channel condition. The CQI measurement interval and reporting mechanisms are configurable parameters in LTE. The granularity of CQI report can be based on; wideband, subband or RBs. Leveraging the subband and RBs CQI reports, eNB(s) can identify the best subband and RBs to be chosen for EPDCCH-RBs mapping for distributed and localized transmission respectively. This way, the reliability of the selected RBs for EPDCCH-RBs sets can be guaranteed.

The CQI for each kth RB differs and can be computed as follows[6];

$$CQI_{UE}(k) = \Delta_{cqi}\left(\frac{SINR_{UE}(k)}{\Delta_{cqi}}) + 0.5\right) \tag{2}$$

Δ_{cqi} is the quantization step. Successful ranking of the RBs or subband based on the measured CQI in equation (2) will help in indicating the best RB pairs for mapping EPDCCH. k RBs out of N^{RB}_{DL} RB pairs can be earmarked for potential EPDCCH-RBs mapping, and then a total of $\binom{N^{DL}_{RB}}{N^{EPDCCH}_{RB}}$ EPDCCH sets can be formed. To inform UEs of the EPDCCH set pattern index, $log_2\binom{N^{DL}_{RB}}{N^{EPDCCH}_{RB}}+2$ bits are required for respective EPDCCH set as proposed in[7]. Having indicated

the RBs or subband with best SINR we can ignore the RBs pairs with lower SINR for mapping the EPDCCH sets. Hence, the bits required can be reduced to; $\log_2 \binom{N_{RB}^{SINR}}{N_{RB}^{EPDCCH}} + 2$,(note that $N_{RB}^{SINR} \ll N_{RB}^{DL}$ where N_{RB}^{SINR} is the number of RBs with better SINR), this will not only reduce the number of bits required for indicating the EPDCCH set pattern index but also minimize the computation overhead for the EPDCCH mapping.

4   EPDCCH Resource Utilization

4.1   Resource utilization

The efficiency of procedure for EPDCCH allocation to UEs determines the degree of resource utilization, i.e. a robust scheme that maximizes the resource allocation would yield a better utilization results. The generic procedure for resource allocation is as follows: for an aggregation level η, the eNB looks for unallocated ECCE candidate with the best CQI report for the prospective UE. The eNB decides the required SINR threshold ($SINR_{threshold}$) with a target BLER of 1% for the DCI transmission. The available ECCE candidate at the lowest aggregation level, which has equal or greater SINR than the ($SINR_{threshold}$) is chosen for allocation. The possibility of blocking UEs that could not find any available candidates after repeated blind decoding (BD) attempts cannot be ruled out, this could be as result of search space overlap or insufficient resources within the EPDCCH-sets, or (ii) extensive blind decoding that would consume UEs power or (iii) underutilization of the ECCE candidates. Hence, there is need for optimal solution to balance the trio factors. The concept of search spaced has being under investigation to strike a good balance for the trio.

4.2   Related work for optimizing ECCE Utilization

Overt time, several attempts have been proposed for EPDCCH search space design. Search space design pattern can basically be divided into two: dynamic and semi-static. Each of these methods employed hash function that randomized the search spaces. The metrics for computing EPDCCH search space is also in agreement with that of legacy PDCCH to ensure downward compatibility, thus the relation in equation 3 for computing the search space size is maintain for EPDDCH too.

$$SS_{LTE} = \eta\{(Y_k + m)mod\lfloor\frac{N_{CCE}}{\eta}\rfloor\} + i \tag{3}$$

where $Y_k = (A * Y_{k-1} mod D)$ $i = 0,.,...\eta - 1$ and $m = 0, 1, ...M^{(\eta)}) - 1$; $M^{(\eta)}$ is the number of PDCCH candidates to monitor at η in a given search space. Where $Y_{-1} = n_{RNTI} \neq 0$ $A = 39827$ $D = 65537$ and $k = \lfloor\frac{n_s}{2}\rfloor$ is the slot number within a radio frame. The cardinal difference in the two methods lies in the number of RB pairs chosen for applying the hash function. In semi-static concept, the hashing is performed on the total entire RBs designated for the EPDCCH; and a fix number of RBs are earmarked for EPDCCH in each subframe irrespective of DCI demand. This method encourages radio resource wastage. On the other hand, in dynamic method the number of RBs to be designated for EPDCCH is proportional to DCI demands. See figure 3 for illustration. As a principle to maximize resource utilization, all unused RBs designated for EPDCCH should be returned for PDSCH scheduling. In every case, there is still need for further improvement on
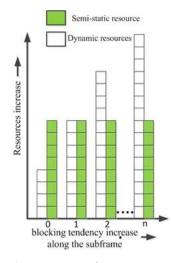
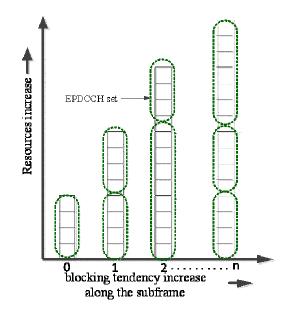Fig. 3: resource designations for semi-static and dynamic

Fig. 4: Dynamic design with EPDCCH set splitting

dynamic method to ensure the search spaces are well packed to avoid unnecessary wastage, in response to this phenomenon authors in[8] have proposed search space interleave to maximize the resource utilization and [9] proposed subdividing the UE's search space into two for distributed transmission, so that UEs can only explore one in most cases provided it could find available unused ECCE candidates to reduce the BD overhead, or modified hash function for localized transmission. However, these methods still employs the semi-static technique, which cannot guarantee optimum resources utilization especially when the control channel is lightly loaded. Another approach by[10] apply the dynamic method while similar work in[11, 12] adopted the dynamic method with search space splitting as depicted in figure 4. Each of these methods can be described by equation 3 with modification of m and N_{CCE} . They achieved better results compare to semi-static methods. Nevertheless, there is no account for proper rule to guard against search space overlap for UEs that belongs to the same EPDCCH sets.We have herein proposed a simple rule in mapping UEs' search spaces to avoid overlaps. The basic requirements to meet

our objective function for optimum resource utilization are;

$$\sum_{k=1}^{K} \eta_k \leq |S_i| \forall U_k \in S_i \tag{4}$$

Where η_k is the aggregation level for user k and $|S_i|$ is the size of EPDCCH set S_i then the resource utilization for each EPDCCH set can be given as;

$$\beta_{s_i} = \frac{\sum_{k=1}^{K} \eta_k}{|S_i|} \forall U_k \in S_i \tag{5}$$

from equation 5, cumulative resource utilization can be deduced. (ii) Assuming the number of ECCEs for any given EPDCCH set is R_{s_i}, then resource distribution among UEs should satisfy;

$$\begin{cases} \bigcup_{k=1}^{K} \eta_k \leq R_{s_i} & U_k \in S_i \\ r_k \cap r_{k+1} = \emptyset & \forall k \neq k+1 \end{cases} \tag{6}$$

Where r_k is the ECCEs occupy by k^{th} UE. If the EPDDCH candidates assign to a set is equal or less than the number of ECCE therein, we expect that the blocking probability in that set should be zero. However, there may be a tendency of collision/ overlap if the start points for UEs are not properly configured, the blocking becomes even more worst if the aggregation levels and start points for the UEs are similar, hence, there is need to rearrange the start points to reduce the blocking tendency. We derive a new pattern as a solution for the overlap. Assuming the ECCE resources in each EPDCCH set are indexed from $0, 1, 2, ...n$, we map the start point of the first UE to 0th ECCE and determine the start point of subsequent UEs using the algorithm in figure 5;

$$for \; \forall u \; \in s_m$$

$$sp_{u_1} = sp_{u_1}^{ini} mod \; sp_{u_1}^{ini}$$

$$sp_{u_2} = \left\{ \left(sp_{u_1} + \eta_{u_1} \right) mod \; n \right\}$$

$$.$$
$$.$$
$$.$$

$$sp_{u_k} = \left\{ \left(sp_{u_{k-1}} + \eta_{u_{k-1}} \right) mod \; n \right\}$$

$$end$$

Fig. 5: search remapping algorithm

Next is how to allocate the UEs to the EPDCCH sets; the objective is how to maximize β_{s_i} for each EPDCCH set. We proposed the algorithm in table 2 for the allocation procedure;

Table 2: EPDCCH reallocation algorithm

Steps	actions
1.	*M= No. of EPDCCH sets*
2.	*for m=1:M*
3.	*find UE with minimum η and place it at point 0 in figure 6*
4.	*arrange the remaining UEs in a tree as shown in figure 6*
5.	*find the sum of for the UEs along all possible paths starting from the point 0*
6.	*choose the sum that is most closet to No. of ECCEs in S_m and satisfy the first condition in equation 6*
7.	*assign the user in step 7 to S_m*

Note: the numbers in the diagram in figure represents UE index not the aggregation levels.
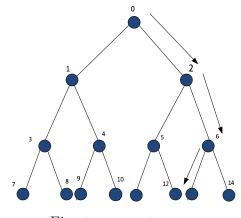

Fig. 6: remapping tree

5   Simulation and Evaluation

5.1   EPDCCH set resource mapping

In this subsection, we provide the result of our proposed algorithm using computer simulation. Firstly, we conduct simulation to compare the signaling overhead for indicating EPDCCH-RB sets to UEs. As shown in figure 7, the number of bits use for signaling remain unchanged in case of using bitmap to identify the prospective EPDCCH-RBs pairs sets, this is because the number of bits is always the same with number of available RBs for the bandwidth. Hence the effect of CQI report did achieve any gain. On the contrary, using the combinatorial method explained in section 3.3, we observed that the signaling overhead was significantly reduced. Further reduction was observed after combining combinatorial index method with channel quality indicator (CQI) report.
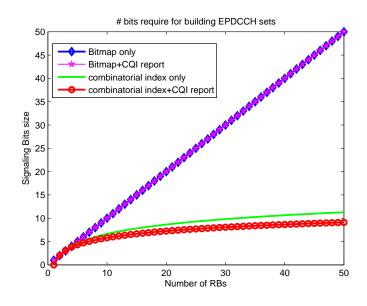
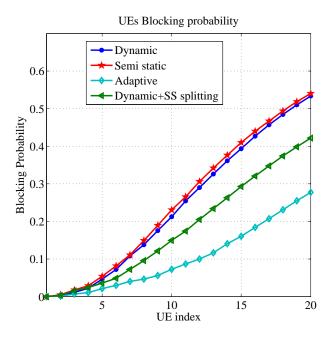Fig. 7: Signaling bit size for indicating EPDCCH-RB pairs

Fig. 8: UEs blocking probability

5.2   Blocking Probability and Resource utilization

In this subsection, we investigate the effectiveness of our method, by comparing the performance with traditional resource allocation methods. Resource utilization and users' blocking probability are used as the performance metrics. The blocking probability is estimated as proportion of UEs that successfully decode their respective DCI message(s) to the total scheduled UEs, this is similar to PDCCH's evaluation formula. On the contrary, the same formula that is been used for PDCCH resource utilization evaluation cannot be applied for EPDCCH, this is because the number of EPDCCH resources varies from sub-frame to sub-frame and depend on other factors stated in [13]. In this paper, the metric of resource utilization in evaluated as average ECCE utilization per

UE index. Figure 8 and 9 shows the blocking probability and cumulative distribution of ECCE utilization by the UEs respectively.
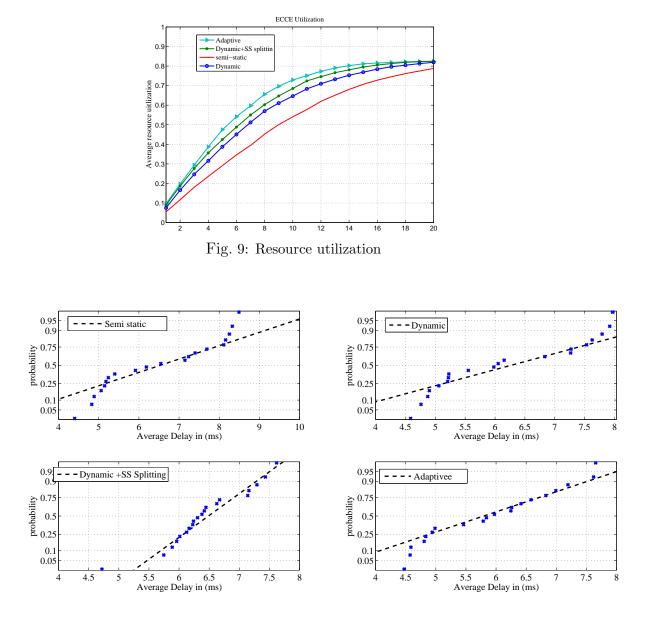

Fig. 9: Resource utilization

Fig. 10: Latency distribution compared with normal distribution

Lastly, variation in latency is also important factor and need to be accounted for. Figure 10 depict the degree of variance for each of the algorithms we considered compare to normal distribution. semi-static and dynamic algorithms appear to have the worst performance case compare to dynamic search splitting and our proposed algorithm. This is because no effort has been put in place to limit the blind decoding process in the former scenarios.

6   Conclusion

A new simplified algorithm is herein proposed for efficient resource scheduling for enhanced physical downlink control channel (EPDCCH), our propose scheme combined the method of dynamic

search space technique and start point remapping to fashion resource allocation for UEs' search spaces during scheduling. Also, we adopted the channel quality indicate (CQI) reports received from UEs to ease the indication of the best resource blocks pairs for mapping the EDPCCH-RB sets, through simulation we have established the gain of our proposed algorithm compare to existing ones. The gains includes improve resource utilization and reduced latency and blocking probability during blind decoding.

References

[1]   Y. Sigen, W. Shin Horng, and C. Worrall, "Enhanced physical downlink control channel in LTE advanced Release 11," Communications Magazine, IEEE, vol. 51, pp. 82-89, 2013.

[2]   3GPP, "TS 36.211, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 10) V10.7.0," in Physical control format indicator channel, ed: 3gpp, 2013.

[3]   M. Einhaus, C. Wengerter, J. Ohlhorst, and S. Feng, "Performance Study of an Enhanced Downlink Control Channel Design for LTE," in Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th, 2012, pp. 1-5.

[4]   3GPP, "Executive summary Release 11; Understanding the standards for HSPA+ and LTE-Advanced Enhancements," ed, 2013.

[5]   3GPP, "R1-125335, NTT DOCOMO, HTC, Huawei PRB Indication for EPDCCH," ed, 2012.

[6]   3GPP, "PRB pair Configuration for EPDCCH Sets," in TSG RAN WG1 Meeting 71, ed, 2012.

[7]   N. Kolehmainen, J. Puttonen, P. Kela, T. Ristaniemi, T. Henttonen, and M. Moisio, "Channel Quality Indication Reporting Schemes for UTRAN Long Term Evolution Downlink," in Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE, 2008, pp. 2522-2526.

[8]   3GPP, "PRB Indication for EPDCCH," in TSG RAN WG1 Meeting 71 R1-125335, ed. New Orleans, USA: NTT DOCOMO, HTC, Huawei, 2012.

[9]   Y. Wang, H. Zhou, and J. Wu, "The search space design for enhanced Downlink Control Channel in LTE-advanced system," in Wireless Communications and Mobile Computing Conference (IWCMC), 2012 8th International, 2012, pp. 322-326.

[10] L. Liu, M. Qin, K. Takeda, and C. Lan, "Search space design of enhanced physical downlink control channel for long term evolution advanced system," in Wireless Communications and Networking Conference (WCNC), 2013 IEEE, 2013, pp. 3323-3328.

[11] 3GPP, "Fujitsu "Motivation, Requirements and Design for ePCFICH" TSG RAN WG1 Meeting 69 , R1-122261," ed, 2012.

[12] 3GPP, "Samsung, "Enhanced PCFICH,"RAN1 69 meeting, R1-122261, ," ed, May 2012.

[13] M. Qin, L. Liu, C. Lan, and K. Takeda, "Search Space Design in Enhanced Physical Downlink Control Channel for LTE-Advanced," in Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, 2013, pp. 1-5.