Performance Study of an Enhanced Downlink Control Channel Design for LTE

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Abstract—**The expected extensive use of new transmission schemes and network deployment paradigms for 3GPP Long Term Evolution (LTE) systems will significantly increase the pressure on the downlink control channel structure. More users than before will be scheduled within a single transmission interval by the base station due to extensive use of multi-user multiple-input multiple output (MU-MIMO) transmission and cross-carrier scheduling. In order to meet these requirements, new control channel designs facilitating frequency-selective allocation and precoding for the transmission of downlink control information are currently discussed in 3GPP. In this paper we discuss the features of such an enhanced downlink control channel design and provide a detailed performance comparison between the conventional control channel design and the enhanced one by means of stochastic system level simulations.**

I. INTRODUCTION

Since the first release, the 3GPP Long Term Evolution (LTE) specification has been designed in order to meet the ever growing capacity demand of mobile users. The downlink of the according air interface is based on orthogonal frequency division multiplexing (OFDM), which supports frequency selective resource allocation in combination with adaptive modulation and coding scheme (MCS) selection and multiple-input multiple output (MIMO) techniques. The latter is supported in form of different transmission schemes, ranging from transmission diversity over beamforming to multi-layer transmissions to single or multiple users [1]. Since the resource allocation in LTE is network controlled, the base station (enhanced NodeB, eNB) periodically informs the user equipments (UEs) about resource allocations on a subframe basis. For this purpose, the radio channel is divided into subframes of 1 ms in the time domain, and resources are assigned to UEs in form of sets of physical resource blocks (PRBs) each comprising 180 kHz in the frequency domain. LTE basically supports duplexing in both frequency (FDD) and time domain (TDD). We focus in this paper on the downlink of an FDD system where downlink and uplink are located on different frequency channels.

Each downlink subframe comprises a control region in the first OFDM symbols and a user data region in the remaining part. User data is transmitted in form of physical downlink shared channels (PDSCH) that are indicated by downlink control information (DCI) transmitted on a physical downlink control channel (PDCCH) within the control region. Further DCI is also required for indicating uplink user data transmissions in form of physical uplink shared channels (PUSCH) in subframes on the uplink channel.

The current PDCCH structure was designed for the first version of LTE (Release 8), which was mainly standardized between 2005 and 2007, and has in principle not been modified since then. However, the requirements have changed quite a lot since that time. The introduction of new features like cross-carrier scheduling for carrier aggregation [2] and the expected grows in usage of multi-user MIMO transmission schemes [3] will yield a significant increase in the amount of DCI that has to be transmitted per subframe [4]. The reason for this is that in the current LTE design each PDSCH or PUSCH allocation requires the transmission of an individual corresponding PDCCH that conveys the DCI.

Additionally, new deployment paradigms like heterogeneous networks (HetNets) consisting of macro and pico cells with cell range expansion (CRE) are currently discussed within 3GPP. Pico cells are formed by low power eNBs that are placed at traffic hotspots in order to offload traffic from macro cells. CRE has been introduced within this context as a means to increase the throughput performance in such deployments [5]. It means that UEs connect to a macro eNB only if the received power is at least K dB larger than the received power from the strongest pico eNB, where K is the semi-statically configured CRE bias. Typical values are expected to range from 0 to 20 dB [6].

It has been shown that HetNets can significantly increase the spectral efficiency of an LTE system due to load balancing, but these deployments will also inflict further pressure on the control channel structure since more UEs than in case of homogeneous network deployments have to be served under conditions of very low SINR levels.

In the current LTE downlink control channel design, a PDCCH is distributed across the whole channel bandwidth at the beginning of each subframe in a pseudo-random manner in order to provide diversity within a PDCCH transmission concerning both channel fading and inter-cell interference. However, that design is expected to hinder the fulfillment of the described requirements concerning capacity and coverage. This is based on the following disadvantages:

- Large resource allocation granularity
- Large control region overhead
- No support of frequency selective resource allocation and precoding
- No support inter-cell interference coordination (ICIC)

The details of the mentioned drawbacks will be discussed within this paper. Based on that observation, a new enhanced physical downlink control channel (E-PDCCH) design with finer resource allocation granularity and support of more efficient transmission schemes is deemed to be essential for meeting the requirements for future LTE releases. The design should support both frequency selective resource allocation and precoding for the control channel [4]. We will discuss a specific E-PDCCH proposal and provide a comprehensive downlink performance comparison between the conventional PDCCH and the E-

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PDCCH under consideration of detailed inter-cell interference modeling in a typical HetNet deployment with CRE.

In the next section we describe the LTE Release 8 downlink control channel design and the proposed enhancements in detail. This is followed by a performance comparison by means of stochastic system level simulations of both control channel designs. The paper ends with concluding remarks and an outlook on future activities.

II. DOWNLINK CONTROL CHANNELS

A. Basic Design

In LTE, the following three downlink control channels are currently defined and transmitted in each downlink subframe [7]:

- Physical Control Format Indicator Channel (PCFICH)
- Physical Hybrid-ARQ Indicator Channel (PHICH)
- Physical Downlink Control Channel (PDCCH)

In order to receive information about PDSCH and PUSCH resource allocations, a UE first needs to decode the PCFICH that is distributed in frequency domain across the first OFDM symbol of a downlink subframe. The PCFICH carries information on the control region size in terms of OFDM symbols on which the PDCCHs are mapped. The size ranges from one to three OFDM symbols at the beginning of each subframe. After successful decoding of the PCFICH, an UE searches for PDCCHs addressed to itself within the control region.

The PHICH carries ACK/NACK feedback for PUSCH transmissions. Due to the small overhead caused by PCFICH and PHICH compared to PDCCH, and since this paper focuses on the performance evaluation of PDCCH and E-PDCCH, the impact of PHICH and PCFICH overhead is neglected.

B. PDCCH Details

The PDCCH conveys downlink control information (DCI). An individual DCI is transmitted for each PDSCH or PUSCH allocation, which facilitates highly dynamic UE scheduling depending on traffic load, UE priorities and channel conditions. The DCI basically contains information on allocated PRBs, used modulation and coding scheme (MCS), precoding, and on hybrid automatic repeat request (HARQ) status. The DCI size is basically determined by the system bandwidth. For a typical system bandwidth of 10 MHz the DCI size ranges for example from 43 to 65 bits depending on used transmission scheme and various system configuration parameters [8].

In order to transmit the DCI efficiently, link adaptation by means of transmit power control and code rate adaptation are used in LTE. Each DCI is encoded with a tail-biting convolutional code that is rate-matched to $n \times 72$ code bits with $n = 1,2,4$ or 8. The code bits are mapped onto resource elements (REs) with QPSK modulation. An RE describes a single subcarrier within an OFDM symbol, and a set of 36 REs form a control channel element (CCE) that defines the resource allocation granularity for the PDCCH. The code rate adaptation is implemented by aggregating multiple CCEs as defined in the table below.

Table 1: CCE aggregation levels

CCEs	REs	Code Bits	SINR [dB]
8	288	576	-4.9
4	144	288	-1.8
2	72	144	1.8
1	36	72	6.9

The switching points for the aggregation level (number of CCEs) selection for the control channels adaptation used in the performance study in Section III are also given in Table 1. The switching point is the minimum SINR level for reception with an error rate of less than 1%, determined here with link level simulations for a DCI size of 59 bits. Aggregation level selection and transmit power adaptation on eNB side are based on the channel quality feedback transmitted by UEs on the uplink. Detail on channel quality estimation and control channel scheduling as used for the control channel performance evaluation are described in Section III.

Each UE applies blind decoding on a specified number of CCEs that are candidates for PDCCH transmissions within the control region. The set of these candidate CCEs (also known as search space) is UE dependent [1].

The total number of available CCEs per subframe depends primarily on system bandwidth, number of transmit antennas and control region size. In case of a 10 MHz system and two transmit antennas as evaluated in this paper, a control region size of one, two and three OFDM symbols corresponds to 9, 26 and 42 available CCEs, respectively. Due to this coarse granularity, some CCEs may remain unused depending for example on scheduling algorithm and control region size selection, which means that time-frequency resources (REs) would be wasted.

Since each PDCCH CCE is interleaved and distributed in frequency domain across the system bandwidth in a cell specific pseudo-random manner, this provides diversity against frequency selectivity of the radio channel in order to achieve very low control channel error rates with reasonable code rates and transmit power levels. In case of more than one transmit antenna at the eNB the reliability of the PDCCH is furthermore improved by making use of transmit diversity by means of space-frequency block codes (SFBC).

The simplified PDCCH structure ignoring PCFICH, PHICH and reference signals is depicted in Fig. 1. It can be seen how each PDCCH is distributed over the first OFDM symbols of a subframe. The figure also shows exemplarily how some REs are wasted due to the strict time domain separation of control and data region.

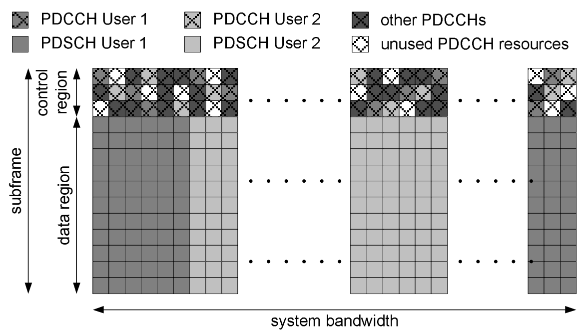

Fig. 1: PDCCH structure

C. E-PDCCH

Due to the shortcomings of the current PDCCH design, as mentioned in the introduction, different conceptual enhancements are discussed within 3GPP at the moment. The majority of the E-PDCCH concepts focus on transmission scheme and physical channel mapping, whereas DCI formats and link adaptation (by transmit power control and CCE aggregation) are assumed to be unchanged. The E-PDCCH presented in this paper comprises the following key components:

- Precoding and spatial multiplexing
- Frequency selective mapping

- Resource block sharing between E-PDCCH and PDSCH

Precoding and frequency selective mapping target the SINR improvement by means of beamforming and allowing inter-cell interference coordination (ICIC) in frequency domain, which is especially beneficial in HetNet deployments in order to reach UEs in the CRE area. Both is not possible in case of PDCCH, since precoding is not supported and the cell specific pseudo-randomly interleaved CCE allocation does not allow coordination of transmit beams on PDCCH level. Moreover, the proposed new design supports exploitation of multi-user diversity by frequency selective scheduling of E-PDCCH transmissions, as already done in case of PDSCH.

Resource sharing between E-PDCCH and PDSCH within PRBs intend to reduce the overhead in terms of REs compared to the strict separation between control and data region in case of PDCCH. The support of precoding furthermore facilitates the possibility to transmit E-PDCCH and PDSCH at the same time on different spatial layers.

The simplified structure of the E-PDCCH (ignoring PCFICH, PHICH and reference signals) is shown in Fig. 2. As mentioned above, the time domain separation of subframes into control and data region disappears and no REs are wasted since the E-PDCCH is multiplexed with the PDSCH in both time and frequency domain. For the sake of backwards compatibility, PCFICH and PHICH still have to be transmitted on certain REs in the first OFDM symbols, but the impact is expected to be minimal from overhead perspective.

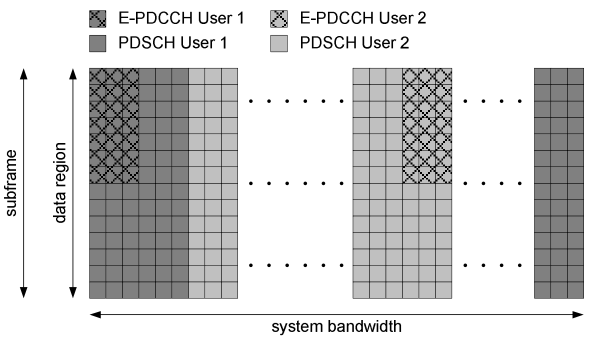

Fig. 2: E-PDCCH structure

III. PERFORMANCE EVALUATION

A. Simulation Scenario and Model

In the following, we investigate the performance of both PDCCH and E-PDCCH in a typical hexagonal HetNet deployment. The scenario consists of 57 macro cells (each cell corresponds to a 120° sector) and four randomly placed pico cells per macro cell with omni-directional antenna patterns and fixed CRE bias of 12 dB. 25 UEs are uniformly dropped into each macro cell (sector area) as specified in [10]. An excerpt of such a scenario is shown exemplarily in Fig. 3.

In order to facilitate efficient PDSCH transmissions for pico cell UEs that make use of CRE, the concept of almost blank subframes (ABS) has been introduced in 3GPP [9]. An ABS is a downlink subframe that is not used for PDSCH transmissions by a macro eNB yielding reduced interference to pico cell UEs. The ABS ratio describes the ratio between almost blank and regular downlink subframes. The term almost blank subframe stems from the fact that the subframe is not completely empty since cell-specific reference signals (CRS) have to be transmitted in every subframe.

It is known that the system level performance in such a scenario is in principle determined by the combination of CRE bias and ABS ratio setting [6]. Since that dependency is not in the focus of the performance study presented in this paper, we use a fixed ABS ratio of 50 % and a CRE bias of 12 dB, which has been proven to be an appropriate combination in order to maximize the system throughput for the investigated deployment. The uniform UE dropping in combination with the used CRE bias setting results in a fraction of 53 % of UEs associated to the pico eNBs in the given scenario.

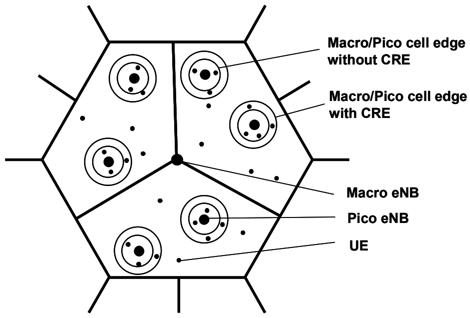

Fig. 3: Exemplary HetNet deployment with two pico cells per macro cell

We evaluate a 10 MHz system (corresponding to assignable 50 PRBs) at 2 GHz with macro eNB inter-site distance of 500 m. Pathloss and shadowing are modeled according to 3GPP Model 1 for macro-pico HetNet scenarios as described in detail in [10]. The model takes into account different channel characteristics for macro and pico cells (e.g. line of sight / non line of sight probabilities). The impact of frequency selectivity of the radio channel and precoding on the transmitter side is considered for both signal and interference power calculations throughout the simulations by using the ITU Urban Macro spatial channel model [10]. The transmission power of macro and pico eNBs is 46 and 30 dBm, respectively and we assume two TX antenna ports at both eNB types, and two RX antenna ports on UE side.

The PDSCH transmission scheme is codebook based closed-loop single user 2x2 MIMO with fast rank adaptation [1]. The eNB can choose between single layer beamforming and dual layer spatial domain multiplexing on subframe level, and specification-conform MCS selection is taken into account; LTE supports for PDSCH transmissions QPSK, 16QAM and 64QAM with different code rates for turbo coding, and retransmissions are handled by HARQ. A detailed description of degrees of freedom in LTE resource scheduling can for example be found in [11]. Regarding traffic model, full transmission buffers are assumed for all downlink connections to UEs, and the resource scheduling is done with a typical proportional fair (PF) scheduler implementation for OFDMA systems [12], constrained by the control channel capacity as described in the next section. The allocation granularity in frequency domain is one PRB.

The effective SINR of both control channels and PDSCH is determined with exponential effective SNR mapping (EESM) based on link level simulations.

B. Control Channel Scheduling and Adaptation

It has been shown in [13] and [14] that the throughput performance of an LTE system does not only depend on the PDSCH scheduling algorithm itself but also on the PDCCH resource scheduling strategy. As described in Section II, the UEs are informed about PDSCH and PUSCH resource allocations by the control channels (PDCCH or E-PDCCH). Hence, scheduling and adaptation of these channels can have severe impact on the UE throughput distribution. If a UE cannot receive/detect a control channel, it will also not be able to receive the according PDSCH. It is therefore in general very important to ensure low control channel error rates. Fairness between different UEs regarding PDSCH throughput can only be provided if it is also facilitated by the control channel resource allocation strategy.

In case of PDCCH, the control channel region is adapted in each subframe depending on the control channel resource requirement in order to fulfill the PF scheduling decisions for the PDSCH. The E-PDCCH is scheduled on the PRBs with highest estimated SINR level within the PDSCH allocation. In addition to the PRB selection, rank and precoder selection has to be considered for the E-PDCCH. We use the same rank and precoding as periodically proposed by the UE feedback for PDSCH transmissions. Details on the reporting scheme can be found in [1].

The feedback loop for SINR level reports is based on channel quality indicator (CQI) levels for PDSCH transmissions. In the evaluated system setting, minimum and maximum CQI levels correspond to -7 and 20 dB SINR, respectively. Here it has to be taken into account that the CQI reports from UEs are based on the assumption of a certain proposed transmission rank and precoder [1]. In this performance study we assume for all simulations a reporting delay of 5 ms and the arrival of new reports (rank, precoder and CQI) every subframe. To compensate for the mismatch between reported PDSCH SINR level and expected control channel SINR level, an SINR adaptation is applied on eNB side. This adaptation is done in form of an SINR offset by which the reported SINR level is reduced for aggregation level selection; a positive offset means that the control channel SINR is assumed to be lower than the reported PDSCH SINR. This SINR adaptation is used for adjusting the control error rate.

Concerning search space settings as described in Section II we do not consider restrictions throughout the simulation study, neither for PDCCH nor for E-PDCCH transmissions, since it is assumed that the expected effects are negligible.

In addition to the aggregation level selection, we consider also dynamic power allocation and power sharing in case of PDCCH transmissions. Depending on the selected aggregation level, the transmission power is boosted or de-boosted in order to meet the expected SINR level of the aggregation level switching point. A PDCCH, and therefore the respective UE, cannot be scheduled if either not enough resources (CCEs) are available or if the required transmission power cannot be provided. In the E-PDCCH case, transmit power control and sharing is not applied.

C. Simulation Results

First we evaluate in Fig. 4 the dependency of the effective SINR on the control channel types. It shows the according cumulative distribution functions comprising SINR samples of both macro and pico UEs.

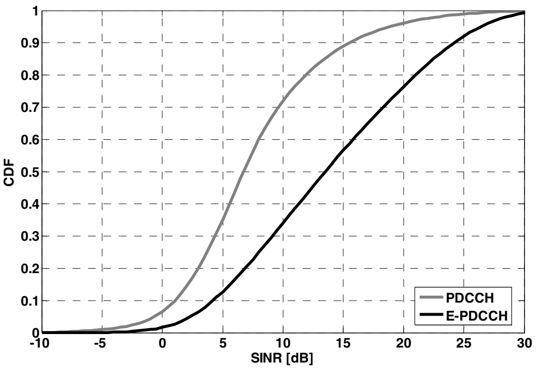

Fig. 4: SINR distribution of control channels

The results basically reveal two effects: (a) the E-PDCCH design provides a significant average SINR gain compared to the PDCCH due to frequency-selective scheduling, and (b) the E-PDCCH usage increases at the same time the SINR variance due to the increased impact of channel fading and interference fluctuations (flash-light effect) based on the narrow-band transmission structure of the E-PDCCH.

In order to study the different impacts of the control channel design in detail, Fig. 5 shows the probability density function of the SINR margin for both control channel types for two exemplary SINR offset values of 0 and 5 dB. The SINR margin metric describes the difference between the SINR level during control channel reception and the minimum SINR level of the chosen aggregation level as given in Table 1. Control channel receptions with an SINR margin smaller than zero correspond to an error probability of more than 0.01 (error rate of 1%).

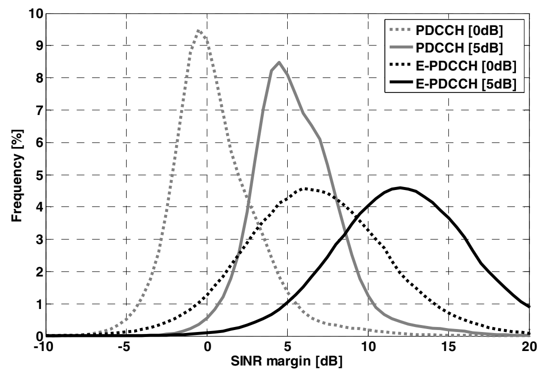

Fig. 5: SINR margin of control channels

The impact of the E-PDCCH design can be clearly seen; it significantly increases the SINR margin due to the combination of frequency selective resource allocation and precoding for beamforming. These large average SINR margins yield a significantly lower error rate than in case of PDCCH usage with the same SINR offset. But the result also shows how the E-PDCCH usage increases the variance of the SINR margin, which is based on the increased uncertainty due to the stronger interference flashlight effect compared to the PDCCH case. The reason for this effect is that the proposed E-PDCCH design is not based on pseudo-random distribution of control channel resources. The basic difference between PDCCH and E-PDCCH is that the first one maximizes diversity within a single DCI transmission while the E-PDCCH maximizes diversity between different candidates for DCI transmission due to the frequency selective allocation. The results of the SINR margin evaluation furthermore suggest that the transmission with higher order modulation schemes (e.g. 16QAM) could be used to further increase the spectral efficiency of the E-PDCCH.

One of the crucial performance metrics from system perspective is the UE throughput that is evaluated in Fig. 6 and in Fig. 7. The curves show the dependency between average and cell-edge UE throughput, respectively, and the control channel error rate. As cell-edge throughput we consider here the 5th percentile of the cumulative UE throughput distribution.

The evaluation of the UE throughput distribution basically suggests three conclusions. The first one is that the E-PDCCH clearly outperforms the PDCCH for all control channel error rates. The second conclusion is that there is a tradeoff between control channel error rate and UE throughput for both control channel schemes. The reason for this is that the achievement of low control error rates requires the use of high CCE aggregation levels, which increases the amount of resources needed for control channel transmission. Hence, the achievement of very low control channel error rates comes in both cases along with noticeable reduction of both average and cell-edge UE throughput. And the third conclusions is that a certain degree of UE throughput fairness can be provided by both control channel designs independent of the control error rate; a reduced control error rate reduces both average and cell-edge UE throughput at the same time, which means that the control channel resource allocation supports in both cases the PF scheduling of the PDSCH transmissions.

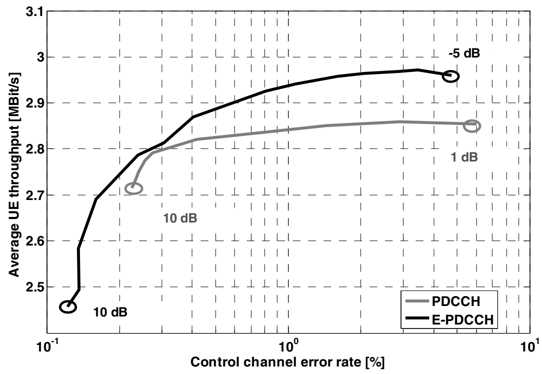

Fig. 6: Average UE throughput depending on control error rate

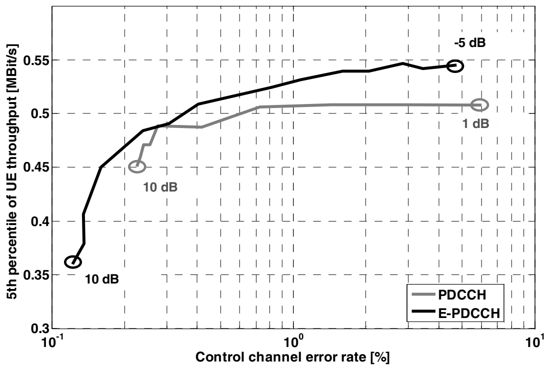

Fig. 7: Cell-edge UE throughput depending on control error rate

The important question is here which maximum control channel error rate is acceptable from system point of view in order to be able to provide sustainable operation. We present in Table 2 detailed results for an operation point at 3% control error rate since we deem this a reasonable assumption. In addition to the previous evaluation we show here also the results for 50 UEs per macro cell area. Next to the UE throughput metrics, the table furthermore contains the average number of CCEs per control channel transmission in the investigated scenario and the average number of UEs scheduled per subframe at an eNB. The rather small number of UEs scheduled per subframe stems from the fact that the overall number of UEs per macro cell area is shared between five eNBs (one macro and four pico eNBs).

Table 2: Concluding control channel performance evaluation

		PDCCH	E-PDCCH
25 users	Average UE throughput [Mbit/s]	2.86	2.97
	Cell-edge UE throughput [Mbit/s]	0.51	0.55
	CCEs per control channel	2.4	1.6
	UEs per subframe	2.3	2.3
50 users	Average UE throughput [Mbit/s]	1.53	1.62
	Cell-edge UE throughput [Mbit/s]	0.27	0.29
	CCEs per control channel	2.4	1.5
	UEs per subframe	3.4	3.5

The results show that the E-PDCCH significantly reduces the average number of CCEs used for a single control channel transmission (about 35% reduction). The average number of UEs scheduled per subframe is more or less the same with both control channel designs, which shows that the fairness between the UEs is basically not affected by the control channel design. The UE throughput gains are 4% and 6% for the average UE throughput in case of 25 and 50 UEs, respectively; and 7% for the cell-edge UE throughput with both UE numbers.

IV. Conclusion and Outlook

In this paper, we presented a detailed performance comparison between the conventional LTE downlink control channel (PDCCH) and an enhanced design proposal (E-PDCCH) that is currently discussed in 3GPP. We described the motivation for such an enhancement based on the disadvantages of the current PDCCH. The results of the simulation study show that the E-PDCCH outperforms the PDCCH due to the combination of frequency selective resource allocation and precoding. The results of the SINR margin evaluation also suggest that further UE throughput improvements with the E-PDCCH can be expected if higher modulation schemes (e.g. 16QAM) would be supported for the control channel since that could furthermore reduce the amount of required resources for the control channel.

An open topic that should be investigated is the impact of search space configurations on the performance of both control channel designs and the possibility to apply multiplexing of E-PDCCH transmissions by means of multi-user MIMO schemes. The impact of non-full buffer traffic models (e.g. FTP) should here also be taken into account. A further potential study topic is to evaluate the separation of UEs into PDCCH and E-PDCCH served sets, depending on average SINR level and UE mobility.

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