

Performance Analysis of Dynamic PUCCH Allocation Algorithm in LTE Network

Maciej Czerniecki, Jacek Wszolek, Marek Sikora and Wieslaw Ludwin

Abstract—The aim of the presented paper was to verify the impact of Dynamic PUCCH Resource Allocation Algorithm of the LTE cellular system on the maximum uplink cell throughput and call setup success rate - CSSR. Paper includes the laboratory testbed description and presents the results of an experiment confirming the improvement of both key performance indicators KPIs. Apart from the presentation of the Dynamic PUCCH Resource allocation algorithm, the paper also includes a description of legacy LTE uplink (PUCCH and PUSCH) channels dimensioning process thus filling the gap of such a tutorial in the available literature.

Keywords—LTE, optimization, planning, PUCCH dimensioning, network planning, network optimization, Self-Organizing Networks, SON, Dynamic PUCCH allocation, Static PUCCH allocation

I. INTRODUCTION

PLANNING and optimization process of the LTE cellular network [1], apart from many steps, requires also suitable PUCCH (*Physical Uplink Control CHannel*) dimensioning [2], [3]. PUCCH dimensioning process [2] relies on assigning the appropriate number of radio resource blocks (RB) in the uplink for PUCCH control channel and on the configuration of the maximum frequency (periodicity) of SR (*Scheduling Request*) messages and CSI (*Channel State Information*) reports [4]. During PUCCH planning process operator can also assign dedicated PUCCH RBs for special purposes like for sending HARQ (ACK/NACK) and SR only [4]. While the PUCCH configuration is vendor dependent, the standardized configuration results are broadcasted with the aid of System Information Block Type 2 (SIB2) [4].

The amount of radio resources in the LTE uplink depends on the system bandwidth, which can vary from 1.4 up to 20 MHz and division duplex strategy, which can be either TDD (*Time Division Duplex*) or FDD (*Frequency Division Duplex*) [5]. All LTEs uplink radio resources can be allocated either for PUCCH [3] or for PUSCH (*Physical Uplink Shared Channel*) [3]. PUCCH is a control channel dedicated to carry UE specific L1/L2 signalling including scheduling request, hybrid ARQ messages and Channel State Information (CSI) which can be composed of Channel Quality Indicators (CQI), Rank Indicator (RI) and Precoding Matrices Indicators (PMI) [4]. On the other hand PUSCH is a channel which carries uplink user data.

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The channel bandwidth defines the number of available RBs. When the LTE system serves 20 MHz channel, it has 100 RBs available for schedule. In order to maximize the number of contiguous PRBs that can be allocated for the PUSCH conveying user traffic, PUCCH resources are located on the extreme ends of the bandwidth (Fig. 1). (Note that up to Release 10 only continuous bandwidth could be allocated to terminals). To provide frequency diversity gain for the PUCCH transmissions UEs hop between the bandwidth edges (intra subframe hopping) [5].

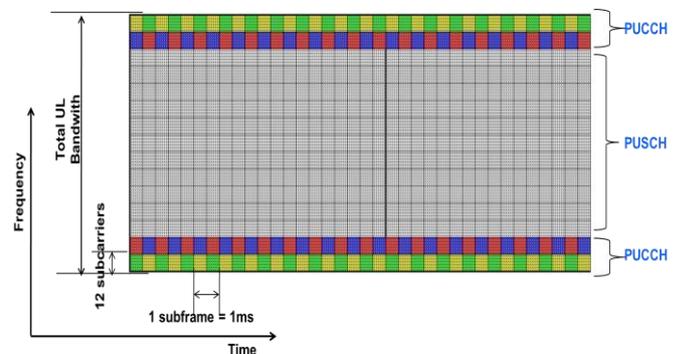


Fig. 1. PUCCH resource in time and frequency domain.

Each UE in the *RRC Connected mode* (connected to the LTE network and transmitting data) is obliged to send L1/L2 control signalling on PUCCH periodically [6]. The configuration of a given eNodeB (base station) determines the periodicity of sending both SR messages and CSI reports. The configuration is most often the result of an optimization process [1], [2]. Frequent and accurate reporting of CSI and the ability to send SR messages frequently requires a large amount of radio resources on the PUCCH channel, which limits the maximal number of active users, but on the other hand, improves the quality of services offered by the LTE network [1], [2].

One of the most important parts of the PUCCH L1/L2 signalling is transmission of a Scheduling Request SR. The *RRC connected* UE, which is willing to transmit data, sends scheduling request indicator (SRI) to the eNodeB [4]. If the base station has enough radio resources, it replies to a scheduling request by giving the mobile uplink grant. Terminals are also having other possibilities to get uplink resources like sending BSR (*Buffer Status Report*) MAC control signalling [6] or they can just receive some proactive uplink grants [7], [8].

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Nevertheless during PUCCH dimensioning process SR resources must be reserved for each connected user [1], [2], [4]. Each UE, which is in the *RRC Connected* state, must also have reserved resources on the PUCCH channel for sending Hybrid ARQ (HARQ). It is absolutely necessary for positive or negative acknowledgement of downlink traffic. Therefore, the maximal number of connected UEs in the cell depends on the amount of resources dedicated to PUCCH.

High SR periodicity increases the likelihood of more frequent allocation of radio resources to a selected user, and thus reduces the delay. In turn, more accurate reporting of the radio channel state increases the efficiency of the AMC (*Adaptive Modulation and Coding*) [9], [10], [11] and CAPS (*Channel Aware Packet Scheduling*) algorithms [12], [13], which translates into reduced packet loss and increased spectral efficiency [1].

As a rule of thumb, L1/L2 control signalling messages are sent via the PUCCH channel. Despite the fact that, clustered SC-FDMA technique for UL transmission, which allows non-contiguous groups (clusters) [3] of subcarriers to be allocated to a single terminal in one TTI (*Transmission Time Interval*), were introduced in Release 10, even today most terminals do not support that feature. Therefore most UEs are not capable of sending both PUCCH and PUSCH simultaneously. When the UE is scheduled an uplink grant and in a meantime is also obligated to transmit L1/L2 control signalling it can send them both using the PUSCH channel. However, from this paper's point of view, it does not matter much, because regardless of whether these messages are sent via PUCCH or PUSCH, they occupy radio resources and increase a signalling overhead.

When optimizing selected cell for the maximum uplink throughput [1], it is best to allocate the maximum number of RBs to the PUSCH channel, thus limiting the signalling overhead (PUCCH) to the necessary minimum. On the other hand, limiting the number of radio resources allocated for the PUCCH channel translates into a reduction in the maximal number of users in *RRC Connected mode*.

Both the maximum number of users in the *RRC Connected mode* and the maximum uplink throughput are Key Performance Indicators (KPI) of the LTE network.

The paper is organized as follows. A short introduction to PUCCH Dimensioning is presented in Section I. Section II contains a static PUCCH planning and optimization basics. In Section III, a dynamic PUCCH allocation algorithm is described. Section IV contains description of test environment while the analysis of the obtained results are shown in Section V. The paper is finalized with a Summary and Conclusions.

I. PUCCH DIMENSIONING

The process of dimensioning and optimization of the PUCCH channel is a trade-off among the maximum uplink throughput, the maximal number of *RRC Connected* UEs and the quality of service measured by QoS indicators, such as latency or throughput. Therefore, from the network optimization point of view, the PUCCH region needs to be planned in order to get an appropriate balance between amount of radio resources dedicated to signalling and user data. Optimal PUCCH area configuration should reduce probability of UE rejection caused by the lack of uplink L1/L2 signalling resources, provide maximum possible user data uplink throughput and assure high

service quality level [1], [2]. As a result of the PUCCH planning and optimization process following parameters are determined:

- The number of RB assigned to PUCCH (PUCCH area)
- SR Periodicities
- CSI Periodicities

The process of dimensioning the PUCCH channel is further complicated by periodic fluctuations in LTE network traffic load. For example, during busy hours (BH) it is important to have a possibility to serve as many users as possible and decrease the rejection probability. Otherwise Call Setup Success Rate CSSR KPI can become significantly degraded. Therefore, from the maximal number of connected UEs point of view, it is worth allocating more resources for the PUCCH channel.

On the other hand, after busy hours, when the traffic load is small, a large amount of resources allocated for the PUCCH channel translates into limiting the maximum uplink bandwidth. In this situation, a better solution is to limit the amount of resources allocated to the PUCCH channel.

Until now, the LTE network operator, could periodically assign the number of RBs for the PUCCH channel and determine the periodicity of SR and CSI messages. There is a possibility to repeat this process very often, although in practice, updates in the PUCCH configuration were performed relatively rarely, almost only when selected KPIs (e.g. Call Setup Success Rate - CSSR) exceeded the quality threshold. Static PUCCH dimensioning is a complex process. Moreover, it is not possible to find optimal PUCCH area because it depends on number of UEs in *RRC connected state* which fluctuates in time.

II. STATIC PUCCH PLANNING AND DIMENSIONING

As described above, dimensioning of the PUCCH area is very important process. If too small amount of resources is dedicated to PUCCH a poor call setup success rate is usually observed. On the other hand, overestimation of PUCCH implicate higher signalling overhead which causes lower user data throughput. Therefore in order to achieve appropriate balance between control and data traffic resources the PUCCH size needs to be planned.

TABLE I
PUCCH FORMATS

PUCCH Format	Usage	Bits	Modulation
1	Scheduling Request	N/A	ON/OFF Keying
1a	1-bit HARQ-ACK & SR	1	BPSK
1b	2-bit HARQ-ACK & SR	2	QPSK
2	CQI/PMI or RI report	20	QPSK
2a	CQI/PMI or RI report & 1-bit HARQ-ACK	21	QPSK+BPSK
2b	CQI/PMI or RI report & 2-bit HARQ-ACK	22	QPSK+BPSK

The PUCCH is located at the lower and upper band edges of the UL system bandwidth (Fig. 1). RB carrying CQIs (PUCCH format 2/2a/2b - Table I) are located at the outermost part of the uplink bandwidth, while the SR and the HARQ ACK/NACKs

PUCCH RBs (format 1/1a/1b - Table I) are located at the innermost PUCCH resource blocks [3].

A. PUCCH Format 1/1a/1b

When using PUCCH formats 1, 1a and 1b (Table I), the mobile modulates the bits onto one symbol, using BPSK for a one-bit acknowledgement (PUCCH format 1a) and QPSK for a two-bit acknowledgement (PUCCH format 1b). It then spreads the information in the time domain using the orthogonal sequence, usually across 4 symbols, (3 symbols in slots which support an SRS - Sounding Reference Signal). The mobile then spreads the information across 12 sub-carriers in the frequency domain using the cyclic shift. Having 3 orthogonal sequences and 12 cyclic shifts it is theoretically possible to schedule $12 \times 3 = 36$ UEs in a single RB. However in practice it is not recommended to schedule more than 18 UEs in one PUCCH RB [5].

TABLE II
MAX NUMBER OF UES SCHEDULED IN A SINGLE PUCCH RB

PUCCH Format	Purpose	Bits	Multiplexing capacity UE/RB
1	Scheduling Request	N/A	36, 18 ¹ , 12
1a	1-bit HARQ-ACK & SR	1	36, 18 ¹ , 12
1b	2-bit HARQ-ACK & SR	2	36, 18 ¹ , 13
2	CQI/PMI or RI report	20	36, 18 ¹ , 13
2a	CQI/PMI or RI report & 1-bit HARQ-ACK	21	12, 6 ¹ , 4
2b	CQI/PMI or RI report & 2-bit HARQ-ACK	22	12, 6 ¹ , 4

¹ recommended maximal value.

The PUCCH format 1/1a/1b capacity is calculated as follows:

$$\text{MultiplexingCapacity}(18) * \text{SRPeriodicity} \quad (1)$$

Where value of MultiplexingCapacity is taken from Tab. 2 and the SRPeriodicity defines the admitted Scheduling Request periodicity in the cell. For example, with SRPeriodicity=20ms scheduling capacity is:

$$18 [\text{users per RB}] * 20 [\text{ms}] = 360 \text{ Users.}$$

B. PUCCH Format 2/2a/2b

Format 2/2a/2b is capable of conveying 5 symbols per slot which gives 20 coded bits plus ACK/NACK per subframe. The PUCCH resource blocks for PUCCH format 1/1a/1b and format 2/2a/2b can be allocated either separately or mixed according to LTE specification [3].

The PUCCH format 2/2a/2b carries CQI/ PMI and HARQ ACK/NACKs. Every UE with established SRB1 (*Signalling Radio Bearer 1*) is obligated to send CQI reports periodically [5], which means that every UE requires format 2/2a/2b resource assignment. Table II presents PUCCH formats 2.x, multiplexing capacity. It is possible to allocate 4, 6 or 12 UE per single RB, however it is not recommended to exceed 6 UE/RB. In real life network total capacity for format 2.x in a cell is defined by the number of dedicated PRBs, cyclic shifts (6) and CQI periodicity. In the opposite of format 1.x for format 2 nCQIRB parameter (Number of Physical Resource Blocks that are reserved for PUCCH formats 2/2a/2b) defines how many

RBs should be assigned for format 2/2a/2b. The PUCCH format 2.x capacity is calculated by:

$$1[\text{RB}] * 6[\text{CyclicShifts}] * [\text{CQIPeriodicity}] * n\text{CQIRB} \quad (2)$$

For example, to serve 840 UEs in a cell with CQIperiodicity = 20ms, the following number of RB for format 2.x is needed:

$$840 / (6 \text{ UEs per RB} * 20 \text{ ms}) = 7 \text{ RB} \quad (3)$$

III. DYNAMIC PUCCH ALLOCATION ALGORITHM

In real network, applying frequent updates in the PUCCH region manually as well as introducing changes in periodicities of SR and CSI in such a way is almost unfeasible. Hence dynamic PUCCH algorithm was developed, that enables the modification of the number of physical resource blocks (PRBs) allocated to the physical uplink control channel (PUCCH). Adaptation is made proportionally to the number of UEs in *RRC connected state* in a cell (cell load). Using appropriate parameters operator can define both, PUCCH and PUSCH channels adaptations areas (Fig. 2) and have control on the range of dynamic PUCCH allocation algorithm.

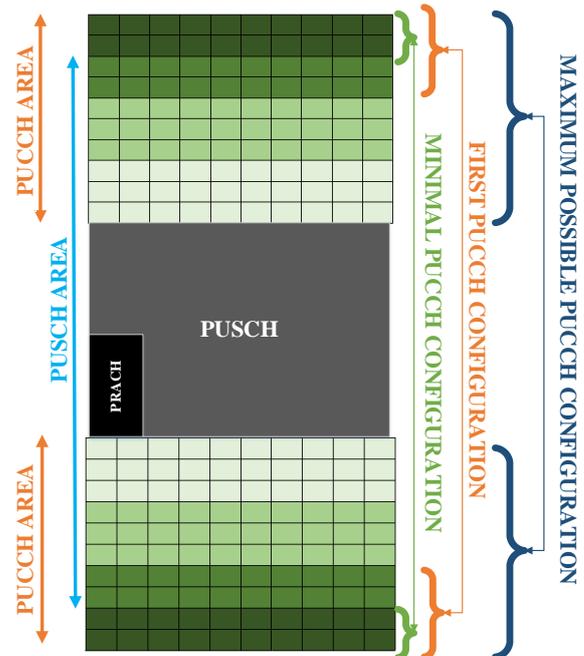


Fig. 2. PUCCH adaptation areas.

Moreover, algorithm can adjust scheduling request (SR) and channel state information (CSI) periodicities dynamically. When using dynamic PUCCH resource allocation algorithm, adaptation of PRBs assigned to PUCCH is more efficient and swift because PUCCH size is adequate to the number of UEs connected to the cell.

When governed by the dynamic allocation algorithm, the PUCCH size can be expanded or compressed. In the dynamic algorithm, two procedures have been implemented. First procedure defined as PEP (*PUCCH Expansion Procedure*) is responsible for expanding PUCCH region. Oppositely to PEP, second procedure named PCP (*PUCCH Compression Procedure*) reduces PUCCH region.

During PEP procedure, new RBs are assigned to PUCCH channel, with the same periodicities of SR and CSI. It allows to increase cell capacity significantly, which is measured by maximum UEs in *RRC Connected state* per cell. It is possible to calculate analytically the PUCCH capacity with specified number of assigned RBs and periodicities of SR and CQI.

The PEP procedure can be controlled by two parameters:

- Upper threshold UEs in *RRC connected*,
- Countdown timer SIB modification by PUCCH expansion.

The first parameter is defined as a percentage of the number of UEs in *RRC connected* state. It defines threshold which triggers expansion, so adding next RBs to the PUCCH channel. By default, it is set to 80% of maximum number of UEs which can be served (PUCCH capacity) for a given PUCCH configuration.

To avoid ping-pong effect between PUCCH configurations which means contiguous reconfiguration of the number of RBs assigned to PUCCH region, the second parameter was introduced. It is defined as a counter which defines how long it takes to make next PEP procedure. Default value of the countdown timer for changing the number of RB allocated for PUCCH is 10 minutes.

The base station informs UEs about PUCCH configuration via SIB2 (*System Information Block Type 2*) [4], which contains radio resource configuration information that is common for all UEs, and is periodically broadcasted by base station. Every UE which is in *RRC connected* or idle state must receive and process all SIBs information [4], [5].

The PCP procedure compress radio resources assigned to PUCCH. The mechanism is similar to PEP procedure in terms of corresponding steering parameters. In the opposite to PEP the PUCCH compression procedure needs much more attention. However, it needs to be pointed that there are some potential complications during PUCCH region compression like:

- Connection rejection caused by lack of radio resources for signalling for some already connected UEs,
- Risk of unsuccessful relocation during PUCCH resource reconfiguration event

Therefore, in the PCP procedure steering parameters has much higher values than in the PEP procedure. The *Countdown timer SIB modification by PUCCH* compression is set to 60 minutes by default and the number of UEs requiring reconfiguration must be limited to avoid unnecessary repositioning. Similarly the *Lower threshold UEs in RRC connected* by default is set to 50%.

The algorithm reacts when number of UE change, every PUCCH configuration can support certain number of UEs in *RRC connected state* which is calculated by the eNodeB. During expansion when *Upper threshold UEs in RRC connected* exceed, the eNodeB decides to perform reconfiguration and add next RBs for the PUCCH channel. The number of RBs which are added to expand PUCCH region is not constant and depends on the eNodeB configuration (MIMO, Carrier Aggregation, eICIC (enhanced Inter-Cell Interference Coordination), etc.) [14].

In some specific cases, after PUCCH reconfiguration, the number of UEs in *RRC Connected* state can change immediately. Such situation requires dynamic PUCCH algorithm response. If PUCCH expansion is triggered and the number of SIB modification per interval is higher than SIB update rate threshold, PUCCH size is reconfigured to the maximum allowable value. On the other hand, if compression procedure is triggered and the number of SIB modification per interval is higher than SIB update rate threshold, PUCCH compression procedure is aborted and put off to the next countdown expiration.

IV. THE TESTBED ENVIRONMENT

Experiments were carried out in a laboratory environment which is depicted in Fig. 3. The laboratory environment consisted of the ET emulator, a hardware emulating multiple UEs behaviour, the real eNodeB hardware of the LTE system, the EPC (Evolved Packet Core) emulator and the TGRs Traffic Generators. The Multi-UE-Emulator was attached to both the uplink traffic generator and the eNB. The eNodeB under the test was configured as a three sectored cell serving a bandwidth of 20 MHz per each sector. Each sector was configured for dynamic open loop 2x2 MIMO without carrier aggregation and enhanced intercell interference cancelation (eICIC) features.

The EPC part including MME (*Mobility Management Entity*), PGW (*Packet Data Network Gateway*), SGW (*Serving Gateway*) was emulated using Nokia proprietary software EPC emulator configured to support large number of UEs (2520 UEs). In all experiments performed during the test campaign, the constantly full-buffer model of UDP data stream was used. The input traffic stream for the whole group of UEs was generated by TGRs (*Traffic Generators*), serving the traffic to the ET emulator for the uplink direction. The role of the ET emulator was to evenly distribute traffic streams among N independent radio transmissions. As a results of the distribution N different virtual EUs were created each transmitting a full-buffer UDP traffic on the default radio bearer (best effort traffic). The ET emulator was connected with the eNodeB via waveguide with a 40 dB attenuator, which has to reduce signal power to a correct level. In order to make the results free from the influence of the radio propagation environment no channel emulation were used in the test setup.

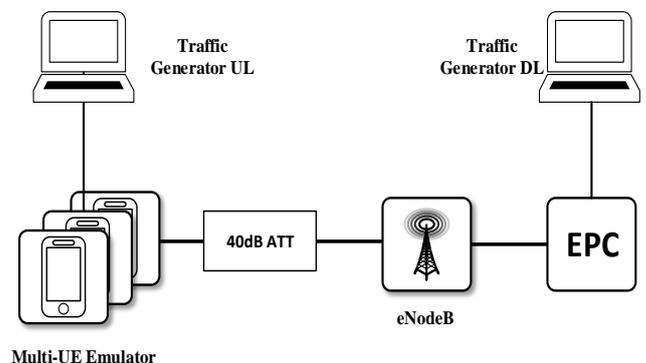


Fig. 3. Simplified testbed environment schematic

V. THE EXPERIMENT

The experiment was conducted with an eNodeB configured for 20 MHz bandwidth. The aim of the experiment was to

evaluate the influence of dynamic PUCCH allocation algorithm on the basic cell's uplink performance indicators including maximum uplink throughput (*MaxCellULThroughput*) and call setup success rate CSSR.

Four different base station configurations were used during the experiment. In the first configuration, the allocation of the PUCCH cell resources was controlled by the algorithm which dynamically adjusted the periodicity of the SR and CQI. The rest three static configurations are treated as a baseline. Detailed information concerning baseline configurations are collected in Table III.

TABLE III
 BASELINE CONFIGURATIONS WITH STATIC PUCCH ALLOCATION

Number	PUCCH allocation algorithm	Number of PRB allocated to PUCCH
1	Dynamic PUCCH	4 - 8
2	SR: 20 ms, CQI: 80 ms	8
3	SR: 40 ms, CQI: 40 ms	10
4	SR: 20 ms, CQI: 40 ms	10

During all experiments UEs were configured to offer traffic exceeding the total theoretical capacity of the eNodeB regardless of number of the UEs (full-buffer traffic model). The experiment was divided into six stages for each of which, in all four configurations, presented in Table III, the number of the UEs attached to the eNodeB was increased. The number of the attached terminals was increased from 50 through 100, 300, 500, 700 up to 840, where 840 was a maximum number of terminals supported by the eNodeB.

During the experiment the value of the maximum uplink cell throughput averaged over a 10 seconds intervals and the number of resource block reserved for the PUCCH by the dynamic resource allocation algorithm were collected. Additionally during the last stage with 840 UEs attached the CSSR was also monitored.

The maximum cell uplink throughput achieved during experiments is presented in the Fig 4. After quick analysis of the Fig. 4 it can be concluded that the maximum achievable uplink throughput decreases with the growing number of UEs attached to the eNB. This phenomenon is a clear consequence of increasing amount of resources devoted to serving signalling needs of active UEs.

The variability of maximum achievable uplink throughput is most significant for the first scenario where the number of resource blocks designated to PUCCH channel was governed by the adaptive algorithm. In case of the three baseline scenarios the decrease in maximum uplink throughput was significantly smaller due to the constant number of resource blocks designated to form a PUCCH channel. The number of resource blocks devoted for PUCCH channel in baseline scenarios remained constant despite of variability in a traffic load. As a consequence for the low values of the traffic offered by UEs, most of the signalling channel resources were wasted. On the other hand when the traffic offered by UEs approaches a cell capacity, not only the whole number of resource blocks devoted to the PUCCH channel are utilised, but additionally some of the PUSCH resource blocks are used to convey the signalling information.

Closer look at the Fig. 4 reveals that highest increase of the uplink throughput can be observed for the case of dynamic PUCCH resource allocation. The lower the number of the UEs the higher was the gain in maximum uplink throughput. For the 50 terminals case, depending on configuration the gain varied between 5% and 8% which was caused by reallocation of the unutilized resource blocks designated formerly to PUCCH to the traffic channel PUSCH.

The number of the resource blocks allocated for PUCCH by the dynamic PUCCH allocation algorithm were collected in Table IV. The case of the 50 terminals is an interesting example of the PUCCH resource allocation. For the case of the static PUCCH resource allocation the number of 4 RBs allocated for the uplink signalling would be connected with strong risk of the drastic reduction of the cell capacity during the traffic busy hours. Such a conservative allocation of the PUCCH resources would in the static allocation case limit the maximum number of active UEs in a cell to approximately 100. With the dynamic PUCCH resource allocation the risk of reduction of the cell capacity can be avoided since with the increase in number of the active UEs the dynamic PUCCH allocation algorithm will instantly increase the number of resource blocks designated to PUCCH thus avoiding a risk of the cell blockage.

TABLE IV
 NUMBER OF RESOURCE BLOCKS DESIGNATED TO PUCCH CHANNEL

Number of active UEs in the cell	Number of RBs allocated for PUCCH			
	Dynamic PUCCH	Static PUCCH		
		SR: 20ms, CQI: 40ms	SR: 40ms, CQI: 40ms	SR: 20ms, CQI: 80ms
50	4	10	10	8
100	6	10	10	8
300	6	10	10	8
500	6	10	10	8
700	8	10	10	8
840	8	10	10	8

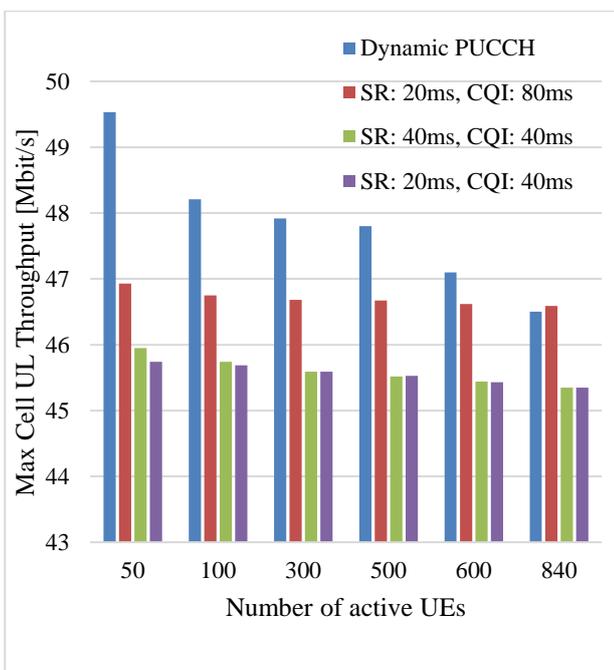


Fig. 4. Maximum cell uplink throughput

VI. THE SUMMARY

The Table V summarizes the selected values of counters and performance indicators collected as part of research experiments for the eNodeB LTE base station serving up to 840 active users. For comparative purposes, two scenarios were considered: a static and dynamic PUCCH configuration where the last one was governed by the dynamic PUCCH allocation algorithm.

TABLE V

SELECTED VALUES OF COUNTERS AND KPIS FOR THE ENODEB SERVING UP TO 840 ACTIVE UES FOR STATIC AND DYNAMIC PUCCH RESOURCE ALLOCATION

KPI/ Counter name	Dynamic PUCCH	Static PUCCH
RRC CSSR	100%	42.86%
SIGN_CONN_ESTAB_FAIL_PUCCH	0	480
SIGN_CONN_ESTAB_COMP	840	360

In case of the static PUCCH allocation the eNodeB under the test was able to serve up to 360 active UEs which reflected the value of the call success rate counter of 42,86% being totally unacceptable for the commercial network.

Contrary to the static case the introduction of the dynamic PUCCH resource allocation algorithm enabled the eNodeB to serve up to 840 active UEs. It's worth noting that such a large number of active UEs subtly decreased the uplink throughput comparing to the static allocation case.

The decrease in maximum achievable uplink throughput was caused by the increase of the number of RBs designated for the PUCCH signalling purposes, resulting from the increased number of active users.

VII. CONCLUSIONS

Evaluating dynamic PUCCH allocation algorithm from the mobile network operator perspective, it is an especially beneficial technology for those operators who are reaching the uplink capacity limits in their networks. Introduction of presented algorithm allows operators to increase the uplink throughput by up to 8%, which is especially important now, when the demands for uplink are growing significantly. This is caused mostly by social networking which has a high uplink demands as users actively create content [16].

Moreover, dynamic PUCCH algorithm is a part of SON (Self-Organizing Networks) [17], [18], which allows operator to optimize OPEX (Operating Expenses). It also simplifies the network dimensioning process and therefore decrease TTM (Time to Market) as well.

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