User Equipment Energy Efficiency versus LTE Network Performance

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***Abstract*—The purpose of this article is to analyze the trade-off conditions between battery saving opportunities at the user terminal and Long Term Evolution network performance. To achieve the goal Voice over IP with discontinuous reception and a vast amount of different settings, including on duration, inactivity and discontinuous reception cycle timers, have been studied. An adaptive discontinuous reception with synchronizing the on duration time with the Voice over IP packet arrival has been proposed to minimize the delays caused by discontinuous reception. In addition, a channel quality indicator preamble time has been introduced to enable channel quality indicator update prior the on duration period. The quality of service and battery saving opportunities have been evaluated with a dynamic system simulator enabling detailed simulation of multiple users and cells with realistic assumptions. It can be concluded that high battery saving, i.e. increased talk-time opportunities, can be achieved without compromising the performance when discontinuous reception is properly adapted. Adaptive discontinuous reception and channel quality indicator preamble can effectively mitigate the capacity loss when more stricter DRX settings enabling higher energy efficiency at the terminal are applied.**

***Keywords*-DRX, VoIP, Battery savings, Energy Efficiency, Capacity, CQI, Preamble, Adaptivity**

I. Introduction

High peak data rates, low round trip times and high *Quality of Service (QoS)* enabled by current and upcoming wireless cellular technologies such as *Long Term Evolution (LTE)* [3][4] have driven the increase of wireless (data) subscribers to whole new levels. Despite of the fact that the growth is fueled by various innovative data services, the simple voice call service and especially *Circuit Switched (CS)* voice calls still remain as the main source of revenue for the cellular operators. However, the situation with CS voice is starting to change: Future systems, such as LTE, support only *Packet Switched (PS)* services meaning that voice calls would also have to be delivered via PS domain. Thus, this leads to situation where voice services are offered through Voice over IP (VoIP) protocols [5]. One of the benefits of sole PS system from the operator perspective is lower *Capital Expenditure (CAPEX)* and *Operating Expense (OPEX)* due to not having network elements for both CS (voice) and PS (data).

Generally, the requirement for successful penetration of IP based voice services, such as VoIP, is that the voice quality should be comparable to what is available using traditional CS voice [6]. There are numerous factors affecting VoIP QoS, which include, e.g., delay, packet loss and packet corruption. These performance indicators are challenges especially in the wireless domain due to more unreliable transmission media. Reliability in LTE networks is addressed through several radio resource management technologies such as *Hybrid ARQ (HARQ)*, *Link Adaptation (LA)*, *Channel Quality Indication (CQI)*, *Packet Scheduling (PS)* and short *Transmission Time Interval (TTI)* of 1 ms. The purpose of this article is to address LTE performance together with discontinuous reception and VoIP. Discontinuous reception cycles aim to improve the energy efficiency at the terminal by allowing possibilities to turn off the receiver circuitry during certain times. That kind of solutions are parallel as battery consumption at the terminal can very well become the limiting factor in providing satisfactory user experience along side of the network performance.

The rest of this article is organized as follows. Section II covers the motivation and related studies, which are followed by description of modeling and simulation assumptions related aspects in Section III. After those, simulation scenario is presented before simulation results and analysis. Conclusion is presented in Section V and finally in the Appendix reliability analysis of the used research tool and results is covered.

II. Motivation and Related Studies

Optimizing the VoIP over LTE performance in terms of QoS and the usage of radio resources has been studied in several articles [7][8][9]. From those it may be concluded that while the overall VoIP capacity may be control channel limited, the situation can be improved effectively by utilizing either packet bundling or semi-persistent packet scheduling. However, since the battery life of small hand-held devices might also very well become a limiting factor in providing satisfactory user experience, a prominent option to prolong the battery life is to use downlink *Discontinuous Reception (DRX)* cycles in conjunction with VoIP in LTE. DRX cycles, introduced by

Third Generation Partnership Project (3GPP) in [10] and [11], allow an idle *User Equipment (UE)* (i.e. UE that is currently not scheduled, i.e. neither transmitting nor receiving) to save battery by turning off the radio receiver for a predefined period (according to predefined, network-signaled parameters). This produces battery savings at the cost of somewhat reduced scheduling opportunities at the *Evolved Node-B (eNB)*.

Discontinuous reception has previously been studied both related to 3rd Generation systems as well as to LTE in several articles. In [12], the effects of DRX cycles and related timers to the queue lengths, packet waiting times, and the power saving factor were studied in Rel'99 wideband code division multiple access networks. The study showed quantitatively how to select appropriate DRX cycle values and the related inactivity timer for various traffic patterns. In [13] the scope is extended to consider DRX together with delay sensitive VoIP service over high speed downlink packet access, and the paper indicated that there are possibilities for high power savings but VoIP capacity can be compromised if improper parametrization is applied for DRX.

In [14] the DRX in LTE has been compared to DRX of 3rd Generation networks and it is concluded that LTE DRX is able to achieve more efficient battery usage through the use of short and long DRX cycles. In [15] an analysis of DRX with best-effort type of traffic over LTE networks was conducted. The paper showed with a single user simulations that a 95 % reduction of the UE power consumption with a moderate 10-20 % loss in throughput was achievable. In [16] the analysis is extended to a short DRX cycle and an inactivity timer. Both the short DRX cycle and inactivity timer aim to provide adaptibility to the variable traffic patterns. Both mechanisms improve the performance over a pure static DRX in terms of throughput and power consumption. However, short DRX with inactivity timer shows a gain of 0-3 times over DRX with just an inactivity timer. In [17] the DRX in LTE has been analyzed with video streaming and VoIP applications. It is concluded that DRX can save about 40-45 % of UE battery power without significantly impacting video quality; while for VoIP applications the saving can be approximately 60 %. However, the estimations are based on simple analytical calculations.

A part of the results in this article have earlier been published in conference articles [1] and [2]. In [1] we have studied DRX in a LTE network with high number of VoIP users. The focus was on the impact of DRX cycles and related timers on the system capacity as well as on battery saving opportunities. In [2] we proposed a CQI preamble for improving the VoIP performance with DRX. In this article, we have extended the work presented in [1] and [2] in several ways. We introduce an adaptive DRX, where the on duration time and VoIP packet arrival times are synchronized for buffering delay minimization. The CQI preamble scheme is analyzed with higher UE velocity where most of the CQI gains have been lost proving that most of the loss caused by DRX arise from the usage of out-dated CQI information. Finally, a statistical confidence analysis of the used simulation tool is presented at the end.

Our focus has been to study the combination of VoIP and DRX, since the performance degradation due to DRX is expected to be the highest with real-time delay sensitive traffic. Secondly, most of the previous work has focused on radio resource point of view of DRX and not on the battery saving opportunities. However, the DRX parameterization is clearly a trade-off between the capacity and battery savings. Finally, our analysis have been performed with a fully dynamic system simulator capturing the effects of dynamic nature of mobility.

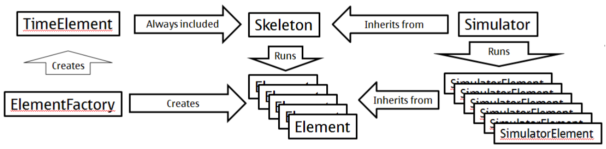

Fig. 1. Skeleton simulator

III. Modeling and Simulation Assumptions

The purpose of this section is to cover briefly the modeling issues related to dynamic system simulator used in these studies. Previously general modeling issues are presented briefly in [18] and VoIP specific issues, e.g., in [7]. In the following subsections the most critical aspects in terms of this paper are discussed.

A. Overview of the simulator

The general principle of all network simulators is quite much the same, where the simulation is configured through parameters, simulations are run with certain modeling assumptions and details and statistics are gathered e.g. by means of averages, cumulative distribution functions and time traces. For examples of other network simulators, see [19] and [20].

The simulator used for generating results is a fully dynamic system simulator, which means that the element of time passing is considered in details: channel conditions change, users move, traffic arrives at uplink and/or downlink buffer, scheduling happens and data is sent in downlink and/or uplink. The simulator works according to step-wise simulation principle: at each step, actions are executed in certain order before proceeding to the next step. The actions that are done depend on which features are turned on in the simulator (e.g. DRX can be turned off fully so that no UE uses it) and one simulation lasts for a certain number of predefined steps.

1) Simulator library: The simulator utilizes a library built for the purpose of enabling fast simulator development. The library is coded in C++, and contains many ready-made and tested implementations (i.e. sub-libraries) for e.g. propagation, channel, traffic and mobility models, as well as general purpose tools like scenario creation modules, parameter reader, random number distributions and simulation statistics collection utilities. At the heart of the library, there is also a so-called *skeleton simulator*: a built-in model of a simple simulator that dynamically loads simulator modules and executes them in the desired order. This is depicted in Fig. 1.

This kind of modularization of functionalities into standalone libraries enables code reuse in the future: For example, several simulators may use the exact same modules that do the same basic functions of the simulators, which enables easier comparison between such simulators. For example, [21], which shows a comparison of real network VoIP capacity for HSPA and LTE, was done with two such simulators, which enabled an easy comparison of just the system differences without a massive campaign of verification simulations ensuring the modeling is compatible between the simulators. Also new simulators can be created with small effort by taking the skeleton and adding the needed modules on top of that.

2) Simulator structure: The most important part of simulator is the *Signal to Interference plus Noise Ratio (SINR)* calculation engine: It is abstracted so that the SINR is always calculated between two radio objects (typically eNB and UE, but UE-to-UE is also possible). Since these objects also contain the information about the antennas, relative position and any UE-specific information (such as UE-specific random number sequences for determining the current channel conditions), the interference calculation can be abstracted quite easily. Further, there is a class called *Physical Resource Blocks (PRB)* manager that acts as an initiator for the calculation between the radios: Newly scheduled PRBs are inserted to the PRB manager, which then (at the end of each step) handles the calculation of C and I for those PRBs that currently exist. At the end of each TTI, the existing PRBs are destroyed, keeping the interference calculation machinery generic (i.e. easily maintainable and modifiable if need be) and safely isolated from the actual scheduling decisions.

The rest of the simulator consists of inter-working between modules:

- UEs and eNBs are modeled as entities with a *connection* object joining them together, representing the active *Radio Resource Control (RRC)* connection.
- The tasks of the UE are to monitor the relevant downlink channels (i.e. *Physical Control Format Indicator Channel (PCFICH)*, *Physical Downlink Control Channel (PDCCH)*, *Physical Downlink Shared Channel (PDSCH)* and *Physical Broadcast Channel (P-BCH)*) and transmit data in uplink when triggered by protocol stack and when scheduled to transmit.
- The UE also maintains measurements of serving cell and neighbor cells, which may trigger measurement report according to eNB-configured RRC reporting configuration. The UE may also notice a connection failure (called *Radio Link Failure (RLF)*) and take appropriate actions after that (see [10] for further details).
- The tasks of the eNB are to transmit downlink data to UEs when necessary, handle the scheduling for uplink and downlink and decide on handovers for UEs.
- The connection object contains information relevant to both UE and eNB, like scheduling assignments, UL/DL data generation and protocol stacks handling the data. The connection also maintains the linking between eNB and UE, enabling an easy process when handover happens: The linked eNB is simply exchanged for another and appropriate actions done separately within the UE and source/target eNBs, but there is no need to create/destroy all objects related to traffic models and data buffers since these common parts are handled within the connection object that remains.
- In general, many algorithms (such as DRX, CQI or handover measurements) are further separated to their own modules as much as possible: Keeping the simulator as object-oriented makes it relatively easy to maintain and extend.

B. VoIP Traffic

VoIP traffic is used in the simulations to model an IP based voice call. The traffic model used is closely based on AMR codec, and a figure illustrating the anatomy of a VoIP call is shown in Fig. 2. For more detailed description, see below.

- *A VoIP call consists of both downlink and uplink traffic*. The duration of each VoIP call is randomly distributed according to truncated negative exponential distribution. The mean, minimum and maximum value of the distribution are given as parameters.
- *A VoIP call can be in two states: Active or DTX*. The states have different packet generation patterns and the duration of each state is distributed according to parametrized negative exponential distribution. The relative time a user spends in Active state determines the *Voice Activity Factor (VAF)* of the call: For example, a 50 % VAF means that on average, a user spends half of its time in Active state and half in DTX state.
- *Only downlink direction is considered* in these simulations, but the simulator supports simultaneous traffic in uplink and downlink (e.g. synchronized so that DTX in uplink occurs when downlink is in Active and vice versa).
- *During Active period*, fixed-size packets (i.e. AMR voice packets) are generated at constant intervals. In this study, VoIP packet is assumed to be 38 bytes and the interarrival time between packets is 20 ms [22].
- *During DTX period*, fixed-size *Silence Descriptor (SID)* packets, used for generating comfort noise, are transmitted at constant intervals. In this study, the SID packet size is assumed to be 14 bytes and the SID packets are generated at 160 ms intervals.
- *Robust Header Compression (ROHC)* is not modeled explicitly but ideal ROHC is assumed by taken it into account in packet sizes.
- *The characteristics of a VoIP call are fully parametrized*, and can be varied between the simulations. It is also possible to have a mix of different types VoIP calls in the same simulation.

The traffic model described above is the same as described in [22], but could also be further enhanced by considering e.g the effect of explicit ROHC or jitter in packet arrival (i.e. the

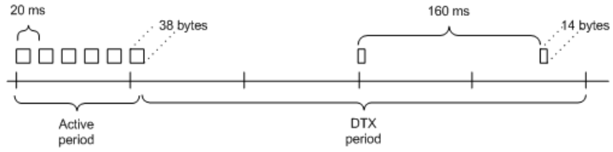

Fig. 2. Voice over IP traffic model

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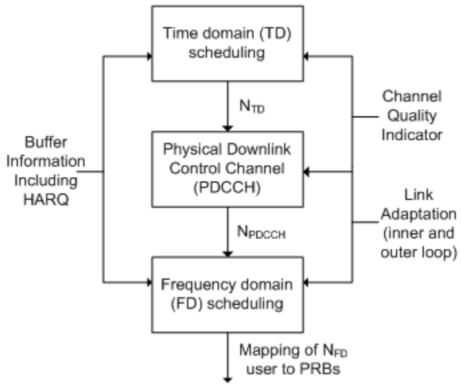

Fig. 3. De-coupled TD/FD-scheduler

packet arrival would not always be constant but could vary a little. However, in this paper, we concentrate on the basic model, to better account the basic interactions between DRX and VoIP.

C. Scheduling and Resource Allocation

In this study, we assume dynamic resource allocation for VoIP over LTE, i.e. we model a scheduler in the eNB that takes care of physical resource allocations for users. Each TTI, the eNB sends the scheduling allocations for users connected to the eNB in *Physical Downlink Control Channel (PDCCH)*, and UEs read the scheduling assignments and act accordingly (i.e. do nothing, transmit on uplink or receive in downlink). Since the scheduler is fully up to eNB implementation, there is no clear default behavior how the scheduling is done, but typically the scheduler assigns resources based based on each user's channel conditions: each user sends a *Channel Quality Indication (CQI)* report to eNB either at periodic intervals or when requested by the eNB.

Thus, the scheduler could vary the resource allocation of each user on a TTI basis. But this kind of fully dynamic scheduling of VoIP packets requires high amount of PDCCH resources, since each allocation for a UE consumes control channel resources each time it is signaled. Moreover, the scheduling assignments can be coded separately, i.e. they may consume different amount of resources depending on the selected coding scheme, so the limited availability of PDCCH resources also results in a varying amount UEs that can be scheduled per TTI. However, in general in this study we are assuming static amount of users (i.e., *Maximum Schedulable Users (MSU)*) that can scheduled per TTI, i.e., PDCCH is not explicitly modeled. Exclusion of explicit PDCCH modeling is done to better account the basic interactions between DRX and VoIP. The MSU value was chosen by estimating the average PDCCH capacity, though. Still, the impact of realistic PDCCH following modeling aspects from [23] and simulation principles from [24] are briefly addressed in this paper.

The scheduler used in these simulations has been a de-coupled *Time Domain (TD)-Frequency Domain (FD)* scheduler, presented in [18] and depicted in Fig. 3. This means that the scheduling is done in two stages: First, a TD-scheduler selects the candidates for the scheduling (up to MSU users). Next, a FD-scheduler chooses which resources (i.e. *Physical Resource Blocks (PRBs)*) to assign to which candidate. After this, the scheduling allocations are sent to the users. Note, that if PDCCH is explicitly modeled, then MSU in TD scheduler is not limiting the amount of scheduling candidates, but the PDCCH resource check is done in between TD and FD schedulers.

Scheduling decisions done in TD-scheduler are based on *Head-of-Line (HoL)* packet delay, i.e., the user with the oldest packet in the buffer (i.e. the packet with the largest delay) is selected first in order to prioritize users who have the worst-delayed packets. In FD-scheduler, the candidates from TD-scheduler are treated in the order of delay: The first candidate is allocated the best PRBs based on CQI information sent by that user, and then the same is done for the next candidate and so on. The PRBs are assigned until it is deemed that the user gets enough PRBs to empty its data buffer [1] or there are no more PRBs available or the maximum limit of allocated PRBs for one user is reached. Finally, it should be noted that both HARQ retransmissions and control message (e.g. handover command in downlink, measurement report in uplink) transmissions are prioritized by TD- and FD-schedulers since these types of traffic are considered critical for the call.

D. Performance Evaluation Criteria

While the simulation enables a wide variety of possible statistics, here we present the simulation results through a comparison of *Quality of Service (QoS) criterion* and *Battery Saving Opportunities (BSO)*.

1) The QoS Criterion: The QoS criterion, also called *system capacity* later in this paper, is defined as a combination of user and cell *outage levels*: A user is in outage if too many of its packets are dropped or have large enough delay, and a cell is in outage if too many of its users are in outage. More precisely,

- A cell is in outage if more than 5 % of its users are in outage.
- A single user is in outage if 2 % or more of the packets (monitored over the whole call) are not received correctly within 50 ms (one-way) time.

Note 1: In addition to monitoring delay at the receiving end, packets can also be discarded at the transmitting side if the delay of the packets in the buffer reach the discard delay threshold.

Note 2: The 50 ms delay limit is called the radio network *Delay Budget*, and is based on ITU e-Model requirements for good quality voice [25] as well as to slightly stricter benchmarking requirements of *Next Generation Mobile Networks (NGMN)* and 3GPP evaluations [26] for VoIP.

Since it is very difficult (and not even realistic) to achieve exactly the same load in each cell even within one simulation, the overall system capacity is interpolated from a large set of

[1]With some additional limitations: In this paper one user may be assigned resources so that it is able to send up to a maximum of two packets during one TTI. This is called *packet bundling*

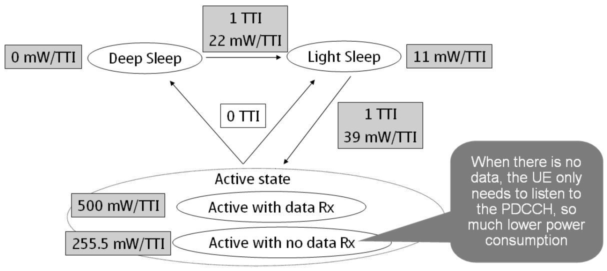

Fig. 4. Power Consumption Reference Model

simulated user amounts per cell (which lead different outage levels / cell). The target level for this interpolation is level where at most 5 % of users would be in outage, which is the absolute upper limit according to the QoS criterion described above.

2) Battery Saving Opportunity: The BSO is presented as the time a user spends in DRX state, i.e. the time during which the UE can be in reduced state of activity. The battery saving opportunities are calculated according to model presented in 3GPP contribution R2-071285 [27] and illustrated in Figure 4. Power consumption levels are calculated with and without DRX from which the relative power savings are finally calculated. In the power calculations one TTI is assumed to be the time used to receive one transmission. Time spent in active state, deep sleep and light sleep are collected for each call and the total 'Active with data Rx', illustrated in Figure 4, is calculated for each call in a following manner:

$$Rx_{active} = (N_{VoIPPackets} + N_{SIDPackets}) \times Tx_{mean}, \quad (1)$$

where Tx_{mean} is the average number of transmissions, $N_{VoIPPackets}$ and $N_{SIDPackets}$ represent the total number of VoIP/SID packets per call. $N_{VoIPPackets}$ and $N_{SIDPackets}$ are defined as follows:

$$N_{Packets} = (t_{call} \times \mu)/t_{IA}. \quad (2)$$

In Equation 2 μ represents the voice activity factor, t_{call} the total length of the call and t_{IA} interarrival time for packets (SID or VoIP).

E. Discontinuous Reception (DRX)

The discontinuous reception (DRX) feature was introduced to LTE as a network-configured feature (meaning it can be also turned off) that provides improved battery saving opportunities for the UE. DRX is specified at MAC level (see [11]), but is turned on by eNB by RRC (see [28]) signaling when eNB transmits the DRX parameters to the UE.

DRX consists of a cycle of alternating active period (called On Duration in MAC specification), during which UE functions just as without DRX, and an inactive period (also referred as DRX period), during which UE is not mandated to receive PDCCH (which means any scheduling assignment during that time would be lost so in practice eNB will not schedule the UE during that time) and can save power by turning off its receiver hardware. A set of timers, illustrated in Figure 5 and covered below, further control the operation of DRX cycle:

1) DRX Cycle Timer: specifies the periodic repetition of the on duration (active) time, which is followed by a possible period of inactivity time.

2) On Duration Timer (ODT): represents the minimum time in *Downlink (DL)* subframes that the UE is required to monitor the PDCCH at each DRX Cycle.

3) Inactivity Timer (IAT): specifies the number of consecutive subframes that UE shall stay active and monitor PDCCHs. Timer is (re-)started every time when the UE is scheduled and successfully decodes a PDCCH indicating new data transmission.

4) HARQ Round Trip Time (RTT): specifies the minimum amount of subframes before a DL HARQ re-transmission is expected by the UE. UE can enter to inactivity during RTT if not otherwise required to monitor the PDCCH.

5) Retransmission Timer (RTxT): specifies the maximum number of consecutive subframe(s) that UE waits for incoming retransmission after HARQ RTT. UE is not allowed to enter inactivity while retransmission timer is running in order to be able to receive the HARQ transmissions. However, when HARQ transmissions are prioritized, as the case is in this study, the retransmission timer does not have substantial impact. RTxT is stopped when retransmission is received.

F. CQI preamble concept

According to 3GPP specifications ([10], [11], [28]) UE only has to do measurements once during a DRX cycle, which means that the UE will typically do measurements (CQI or other) only during the active period. However, performing the measurements, processing and transmitting them and eNB receiving the measurements consumes time, so the active time may have passed before up-to-date CQI information is available in the e-Node B scheduler. Moreover, the lack of up-to-date information can lead to lowered performance. This procedure is illustrated in Fig. 6.

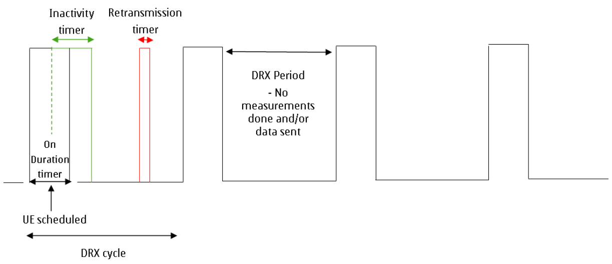

Fig. 5. Diagram of DRX operation

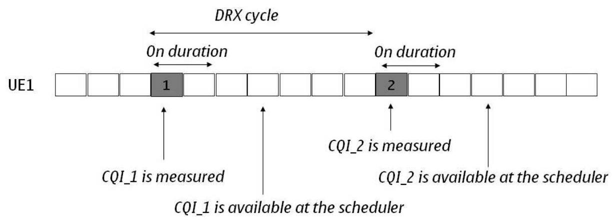

Fig. 6. Example of CQI measurement procedure with normal DRX. Assuming total CQI delay 3, on duration 2 and DRX cycle 7 TTIs

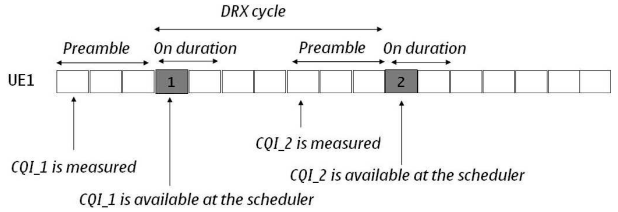

Fig. 7. Example of CQI measurement procedure with CQI preamble. Assuming total CQI delay 3, on duration 2 and DRX cycle 7 TTIs

To avoid possible performance loss, this paper considers a so-called CQI preamble scheme as a potential enhancement for the CQI measurement operation described above. With the CQI-preamble scheme, a CQI preamble time is applied before the actual on duration time takes place. During preamble time the UE turns its receiver circuitry on to perform and report the CQI measurements in addition to other possible *Radio Resource Management (RRM)* measurements. Naturally, when performing the measurements, the normal requirements, such as CQI measurement granularity and the CQI measurement period (i.e. minimum time since previous measurement), still apply. With the preamble scheme UEs could be scheduled with up-to-date CQI information for any potential DL data transmission as Fig. 7 illustrates. The downside of this operation is increased activity time, which leads to higher power consumption and shorter talk time from the UE/user point of view.

The current 3GPP specifications already allow this kind of improved operation. UE is allowed to do CQI measurements (and fall back to inactivity) before actual on duration. Though, according to [11] UE is not allowed to send the CQI report on PUCCH before the active time / on duration begins. Thus, from the UE side, CQI Tx part of the preamble scheme would be achieved through slightly prolonged on duration to allow the transmission. Changes could, however, be needed for the e-Node B scheduling: eNB should consider the time when the last CQI report has been received from a UE that has its on duration started / ongoing. Once CQI report is received during preamble time or within CQI requirements (e.g., period) UE becomes schedulable, not before. Also, changes could also possibly be needed in eNB implementation for evaluating and indicating the length of CQI preamble time for DRX purposes. CQI preamble time consists of the time before CQI is measured, transmitted, received and processed. In this paper preamble length is estimated to be as long as the total sum of CQI delay (defined through parameters) and the time that it takes to measure the CQI (1 TTI). Moreover, UEs are assumed to be active throughout the preamble time to better understand the 'worst-case' scenario.

G. Adaptive DRX

As described above, DRX operates in predefined cycles of active and inactive states. Moreover, different UEs can (and should) be allocated with slightly different offset from which their cycle timers start so that even amount of candidate set for scheduling remains balanced in the downlink. That is handled by eNB, which signals the DRX configurations

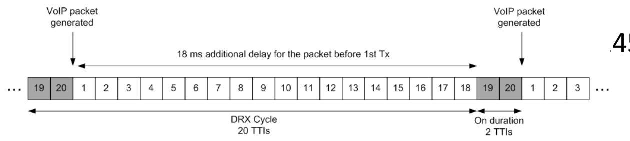

Fig. 8. Example of possible problems without adaptive DRX

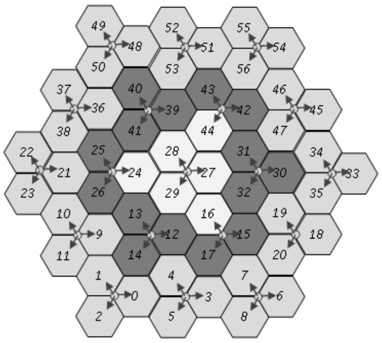

Fig. 9. Simulation scenario

to each UE. However, if the offset setting and timers are configured 'blindly', i.e. without considering the expected packet arrival times, possible problems could occur especially for delay critical services such as VoIP. Fig. 8 illustrates this through simple example: Blind offset setting can lead to situation where a single VoIP packet can have additional delay of 18 ms, which, in the context of the typical 50 ms delay budget, means that almost 40 % of the delay budget is already consumed before the first transmission, thus reducing the time for possible retransmissions.

To mitigate the negative effects of offset setting this paper shows that DRX offset could be adapted to the data flow timing. In terms of the example presented in Fig. 8 it would mean that instead of having the DRX cycle starting 2 TTIs before the packet generation (blind setting) the DRX would be adapted to start during the time when packets are generated. This could be achieved in real networks, e.g., by monitoring the data flow some time before configuring the DRX. Even though there can be some jitter for the packets in real networks, on average the adapted offset would not cause as high additional delays as the blind offset would in the worst case.

IV. Simulation Scenario and Results Analysis

Simulations were run in a hexagonal macro cellular scenario with three tiers, see Fig. 9. Scenario consists of 7 active base stations with *Inter Site Distance (ISD)* of 500 m. Each base station has 3 sectors resulting into layout containing 21 active cells. Statistics are collected from 6 middle cells. Third, i.e., the outer tier is simulated as interfering tier, which adapts to the load of the statistic cells. Users are not allowed to move to the third tier but only within two inner tiers. The main simulation parameters are shortly listed in Table I.

In the following subsections the performance of VoIP over LTE downlink is analyzed with respect to system capacity and power saving opportunity criteria covered in Section III-D. The analysis for the trade-off between increased talk-time opportunities and LTE performance is based on vast amount

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TABLE I
SIMULATION PARAMETERS.

Simulation time	1 million steps
Time resolution	1 step, i.e., 0.0714 ms
e-Node B Max. Tx power	46 dBm
Transmission Time Interval (TTI)	1 ms
Pathloss model	Modified Okumura-Hata [29]
Channel profile	Typical Urban (TU)
UE velocity	[3, 30] kmph
Handover	Hard, 3 dB threshold
MSU	[8, PDCCH]
CQI resolution	2 PRBs per CQI (fullband)
CQI delay	2 ms
CQI measurement period	5 ms
VoIP packet size	38 bytes [22]
VoIP packet interarrival time	20 ms
SID packet size	14 bytes
SID packet interarrival time	160 ms
VoIP call length	Negative exponential distribution, truncated, mean 20 s min 5 s max 60 s
Activity / Silence period length	Negative exponential distribution, mean 2.0 s
Layer 3 packet discard threshold	50 ms
Max. VoIP packet delay	50 ms
HARQ transmissions (max.)	7
HARQ RTT	8 TTIs
Retransmission Timer	10 TTIs
On duration timer	[1, 2, 3, 4] TTIs
Inactivity timer	[2, 10, 20] TTIs
DRX cycle timer	[10, 20, 40] TTIs

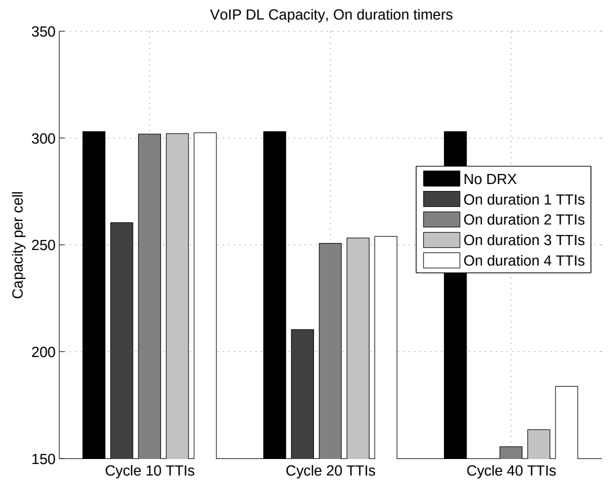

Fig. 10. VoIP DL capacity, ODTs, IAT 2 TTIs

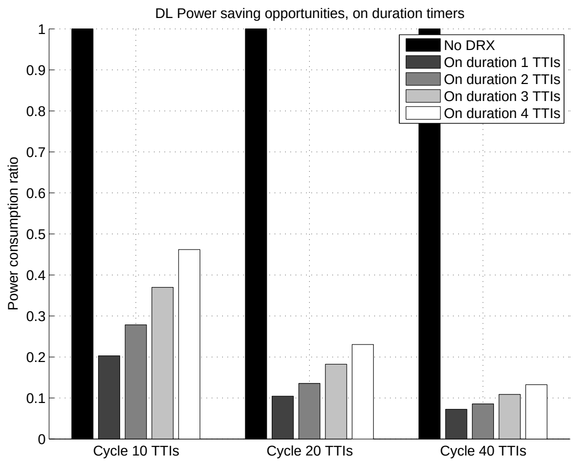

Fig. 11. DL power saving opportunities, ODTs, IAT 2 TTIs

of different DRX adjustments and enhancements, including on duration, inactivity and DRX cycle timers as well as CQI preamble scheme and adaptive DRX.

A. On Duration Timer Impact

Figure 10 shows the impact of on duration timers (fixed inactivity timer of 2 TTIs) to the LTE downlink performance in terms of maximum number of VoIP users that can be served per cell with acceptable QoS. The power saving opportunities for those cases are illustrated in Figure 11, respectively. As those Figures show, with DRX cycle timer 10 TTIs the on duration results in significant power saving opportunities with only minor impacts on DL capacity, providing that the timer value is higher than one TTI. Similar trend can be seen with 20 TTI cycle with the exception that the LTE performance numbers are lower than with 10 TTI but at the same time the power saving opportunities are higher (~75-90 % versus ~55-80 %). The reason behind the poor performance when the on duration is one TTI is that the scheduling opportunities are very scarce and with high probability there will be many users competing of that scheduling slot. Competition results into missed scheduling opportunities, which again leads to highly increased queuing delays for VoIP packets due to DRX cycles. Increased queuing delays lead to increased amount of discarded packets already at the transmitting end and thus to poor performance also from the system level perspective. Similar phenomena is seen and emphasized when the cycle length is very long. However, long cycles could possibly be taken into use when the cell is not fully loaded, assuming that DRX adapts to the different system loads.

B. Inactivity Timer Impact

The trade-off between VoIP DL capacity and DL power saving opportunities when inactivity timer is also varied on top of on duration and DRX cycle timers is shown in Figure 12 and 13. When compared to on duration timer results presented above the longer inactivity timer does not provide much higher capacity improvements, especially with cycles 10 and 20 TTIs. Power saving opportunities are also much lower when longer inactivity timer is used. With cycle 40 TTIs the inactivity timer can provide benefits as the cycle is so long that users will have multiple packets to be transmitted once they become active from DRX. Thus, longer inactivity timer allows users to deplete their packet buffers and possibly transmit new packets arriving their buffers while the inactivity timer is running. However, this combined effect of prolonged inactivity and on

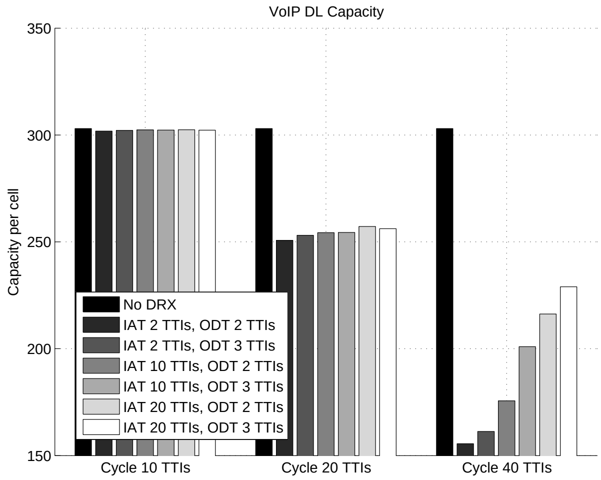

Fig. 12. VoIP DL capacity with different IATs and ODTs

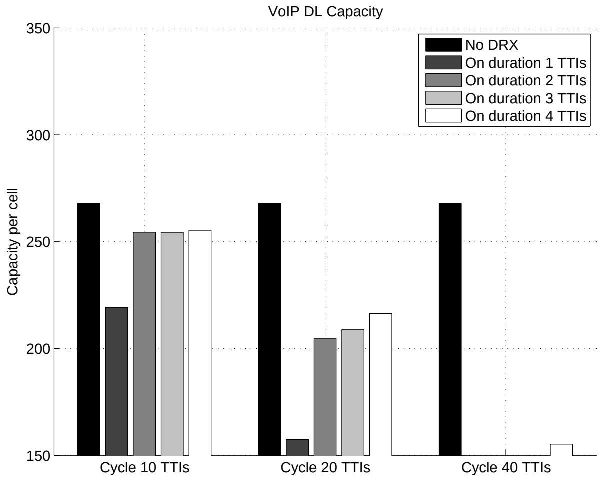

Fig. 14. VoIP DL capacity, realistic PDCCH

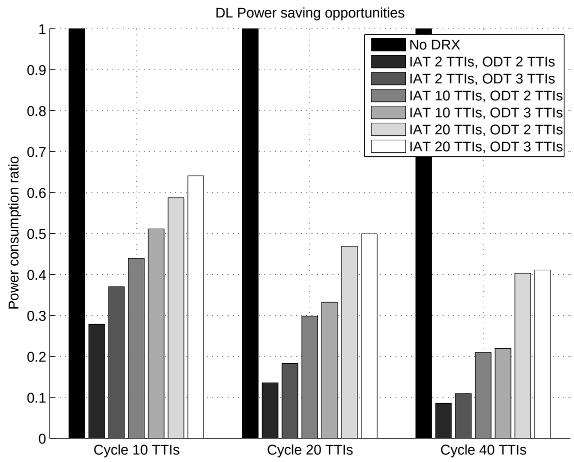

Fig. 13. DL power saving opportunities with different IATs and ODTs

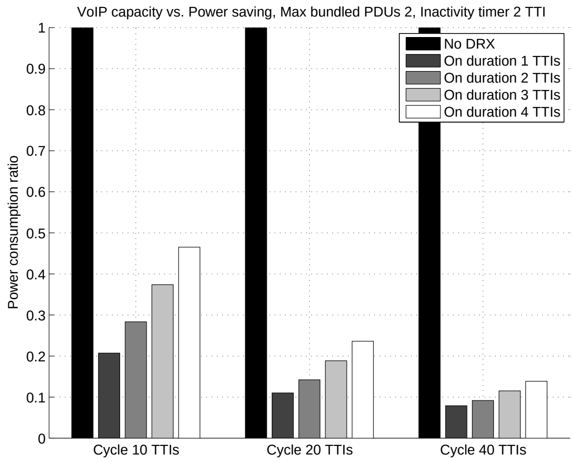

Fig. 15. DL power saving opportunities, realistic PDCCH

duration timer together with long cycle cannot reach significantly difference in power savings to justify the compromise in the system capacity. More optimal trade-off point can be achieved with timer settings described above.

C. DRX Performance with Realistic PDCCH

To further verify the trends presented above the performance of DRX is studied with realistic PDCCH modeling. This means that PDCCH resources can be exhausted even with a few users and PDCCH transmission can be erroneous leading to varying amount of users that can be scheduled per TTI. Previously presented results assumed fixed number of users that can be scheduled per TTI (MSU).

The performance of DRX with different activity timers and realistic PDCCH is illustrated in Figure 14 and 15. As the capacity Figure shows the absolute capacity numbers are on lower level, which indicates that the averaged number of schedulable users per TTI is actually a bit lower than the one that was assumed in this study as a basis (MSU 8). Apart from the absolute numbers the performance follows the same trends presented without detailed PDCCH modeling.

D. Performance with CQI Preamble

DRX and CQI preamble scheme (see Section III-F) performance in terms of VoIP capacity and power saving opportunities are illustrated in Figs. 16 and 17, respectively. In those figures three types of DRX scenarios are presented in addition to 'no DRX' case:

- *Ideal CQI*, which equals to the case where CQI is updated regardless of the DRX and power savings are unaffected. In reality this would not be possible but it is considered as a reference to benchmark the performance.
- *Normal DRX*, which equals to the case where normal DRX settings are used and thus CQI is updated only when UE is active.
- *Preamble 3*, which equals to the proposed scheme where UE wakes up before the actual on duration time to perform the measurements and to send them to e-Node B. Preamble length of 3 TTIs is assumed for this study.

When normal DRX operation is compared to the case with ideal CQI feedback (or no DRX case) it can be seen that the VoIP capacity is rather sensitive to the up-to-date CQI information availability. With cycle length of 20 TTIs the difference between those is around 15 % and with cycle of

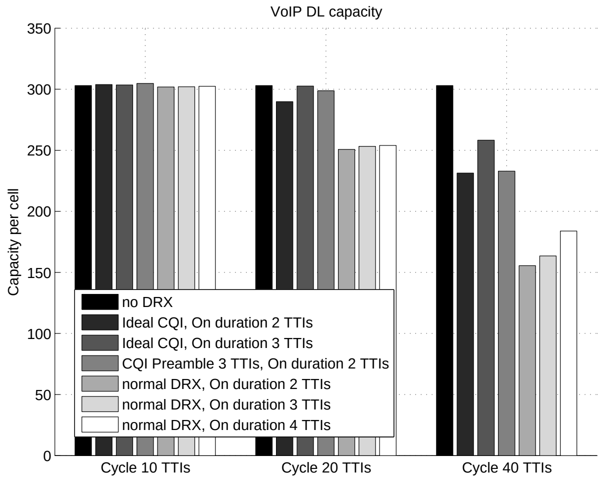

Fig. 16. VoIP DL capacity with and without DRX preamble, 3 kmph

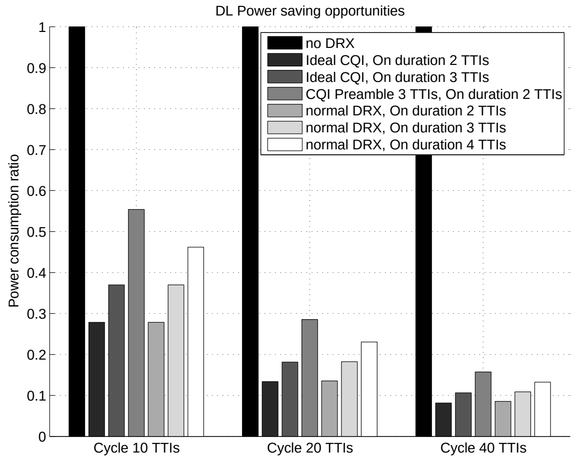

Fig. 17. DL power saving opportunities with and without DRX preamble, 3 kmph

40 TTIs even more. Moreover, as it can be seen from Fig. 16, mere increase of on duration time might not be adequate as UE can be scheduled at any point during that time, likely with outdated CQI information. This implies that some mechanism to guarantee newer CQI information for scheduling should be considered, CQI preamble scheme for instance.

When CQI preamble scheme is benchmarked against normal DRX cycle of 10 TTIs with different activity timer values it can be seen from Fig. 16 that preambles do not provide extra value as the capacity is not compromised with so short cycle. However, even though (normal) DRX cycle of 10 TTIs implies roughly 30-45 % power consumption versus ’no DRX’ the higher cycles imply possibilities for even higher power savings, as Fig. 17 shows. Thus, more focus should be paid on longer cycles, which could guarantee longer UE talk times.

With CQI preamble scheme and longer cycles of 20 or even 40 TTIs the deterioration in terms of VoIP capacity with DRX can be mitigated quite well. The gain from preamble scheme over normal DRX becomes higher when the DRX cycle length is longer, which is quite intuitive as then the CQI information available in the scheduler is older (without preambles). Preamble scheme can even outperform ’ideal CQI’ case in some situations due to preamble scheme forcing the periodic CQI measurements being synchronized with data transmissions. With ’ideal CQI’ the periodic reporting happens every 5 ms regardless of the data flow / DRX.

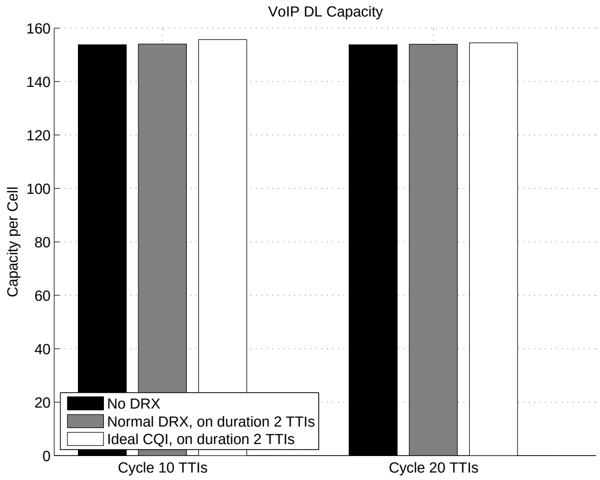

Fig. 18. VoIP DL capacity with and without ideal CQI, 30 kmph

In terms of downlink power saving opportunities the performance of CQI preamble scheme is expectedly lower than with normal DRX operation, as Fig. 17 implies. However, as the performance in terms of system capacity is much more robust against potential losses, the loss in battery savings with preambles can be considered as acceptable to guarantee more satisfactory service provision. Moreover, this paper evaluated only the scheme where UE stays active for the whole duration of preamble time but in principle after the UE has performed the measurements the UE could fall back to inactivity before actual on duration. By turning receiver circuitry off during those periods higher battery savings could be expected.

Finally, the findings and conclusions from CQI impact with DRX are confirmed in Fig. 18 where VoIP performance with all users moving with higher velocity is illustrated. As [30] indicates and this study confirms with higher UE velocity the frequency selectivity gain of CQI is lost to most extent and thus no additional gain could be achieved even with ’ideal CQI’.

E. Performance with Adaptive DRX

Finally, the purpose of this section is to cover how adaptive DRX presented in Section III-G affects to the performance. Figs. 19 and 20 illustrate the performance in capacity and power consumption ratio, respectively. As the capacity figure shows, adaptive DRX can provide noticeable gains, especially with longer cycles than 10 TTIs where practically no losses are seen if on duration is long enough. In terms of battery savings the adaptive DRX leads to slight increase in battery consumption. This due to the fact that blind offset setting could further induce the packet bundling and reduce the amount of retransmissions due to increased delays and thus reduce the time needed to keep receiver circuitry active.

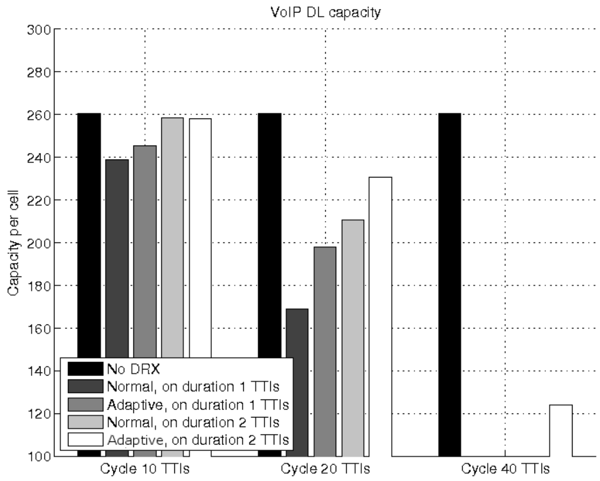

Fig. 19. VoIP DL capacity, adaptive DRX

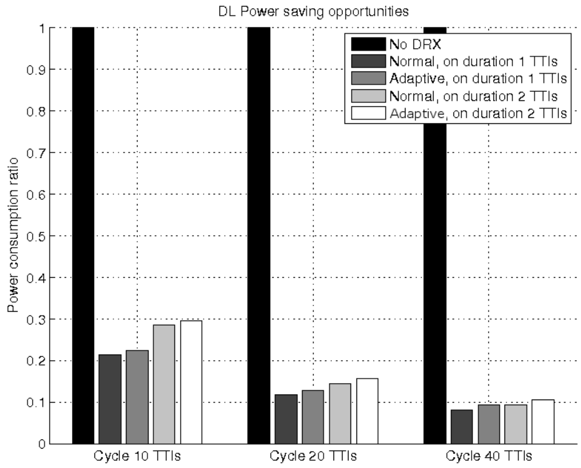

Fig. 20. DL power saving opportunities, adaptive DRX

V. Conclusion

The purpose of this article was to evaluate the trade-off conditions between energy efficiency at the user terminal and LTE performance. That goal is achieved by studying VoIP over LTE with various DRX related timers, which limit the scheduling freedom of users while increasing battery saving opportunities at the terminal. Increased power saving opportunities lead to increased talk-times for the terminals and thus more satisfactory user experience. The study was conducted with dynamic system simulator modeling LTE network with high level of detail.

This article indicates that for dynamic and PDCCH controlled scheduling, short DRX cycle timers together with appropriate on-duration timer is an attractive choice for LTE energy efficiency: Substantial power saving opportunities are achievable with minor trade-off in terms of maximum VoIP over LTE DL capacity. Regardless, this article also points out that in lower load situations different (more stricter) DRX adjustments could be used as then the capacity might not be compromised and the power savings would be higher. This article also shows that prolonging inactivity timer together with on duration and DRX cycle timers does not justify the slightly increased performance (capacity) as the trade-off in battery saving opportunities is too high.

TABLE II
Confidence intervals for interpolated VoIP capacity

	Capacity [UEs/cell]
MEAN	260.305
STANDARD DEVIATION	3.85448
CONFIDENCE INTERVAL, 90 %	± 0.44 %
CONFIDENCE INTERVAL, 95 %	± 0.52 %
CONFIDENCE INTERVAL, 99 %	± 0.69 %

VoIP performance in terms of capacity may, however, be reduced by some extent if sub-optimal DRX settings are chosen. One main reason for reduced performance, especially with long cycles, is linked to outdated CQI information. CQI preamble scheme, introduced in this paper, mitigates the reduced performance quite well in terms of VoIP capacity when dynamic user scheduling is assumed. Moreover, the improvements can be achieved with acceptable trade-off in terms of battery saving opportunities.

Finally, this study introduces concept where DRX (offset) would adapt the data flow. The result show significant improvement in terms of capacity in situations where blind DRX configuration show losses. Moreover, adaptive DRX brings only minor impact to the power consumption ratio.

VI. Acknowledgments

This study is a collaborative work between Magister Solutions Ltd., University of Jyväskylä, Nokia, Nokia Wireless Modem Research (nowadays a part of Renesas Mobile Corporation) and Nokia Siemens Networks. The authors would like to thank all of their co-workers and colleagues for their comments and support. Finally, special thanks go to Hannu-Heikki Puupponen from University of Jyväskylä for his contributions on providing confidence analysis results.

Appendix

Research tool used in this study was presented briefly above. This appendix is aimed to deepen the presentation by providing statistical confidence analysis for the used system level tool.

Statistical analysis is based on evaluating the performance with a few selected test cases, namely VoIP simulations with different random number generator seeds. Based on the seed all random generators are initialized, these include e.g. starting position and direction of the movement for the UEs. Even though, all of the simulation results depend on random processes, the results are reproducible with certain level of accuracy, which is defined in this appendix.

An interval estimation can be used to define a confidence interval, which means that the sample ϕ, is within a defined interval with a certain probability. This probability can be expressed as follows

$$P(a \leq \phi \leq b) = 1 - \alpha \quad (3)$$

where the interval $[a, b]$ is a $(1-\alpha) \times 100\%$ confidence interval of ϕ. A probability that the ϕ is not within the interval is

α. When the number of samples n is ≤ 30 the standardized normal distribution, $N(0,1)$, can be used to define confidential interval, which is

$$(\overline{x} - z_{\alpha/2} \times s/\sqrt{n}, \overline{x} + z_{\alpha/2} \times s/\sqrt{n}). \quad (4)$$

In Eq. 4 the $\overline{x}$ is the average value, $z_{\alpha/2}$ is the critical value taken from the standardized normal distribution $N(0,1)$, s is the standard deviation and n is the number of samples i.e. in this case the number of simulation runs.

The simulation environment used for confidence analysis is the same macro cellular layout used for DRX studies. Main parameters are as well similar to the simulations presented above with the exception that dynamic scheduling MSU is assumed to be 6. This is done so that simulations take PDCCH restrictions better into account.

Confidence intervals are calculated for radio system capacity i.e. at the point where 5 % VoIP users are in outage. Capacity is interpolated from different cell loads i.e. from another one where the system outage level is below 5 % and another where it is above that. Thus, the required simulation amounts for confidence analysis equal two times $n = 31$.

The results for dynamic LTE system level tool are shown in Table II. As that table shows the difference even with the highest confidence interval are very minor. Thus, this gives the confidence that the results produced with the tool for this study are also well within the required level of reliability and reproducibility.

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