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Fast Control Channel Decoding for LTE UE Power Saving

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***Abstract*—This work examines the energy saving potential of powering down RRC_connected but unscheduled User Equipment (UE). The idea is to power down energy consuming circuits in RF and BB, when it is determined by Fast Control Channel Decoding (FCCD) that the UE is not scheduled to receive downlink data in the current TTI. The cost is that some reference signals are not received leading to a degraded channel estimate. Calculations show that this causes an SINR degradation of approximately 0.5 dB, which will result in maximum 4 % throughput loss. Comparing this with energy saving potentials of 5 %-25 % it is concluded that the FCCD method is a valuable aid to prolong LTE phones' battery lifetime.**

The results are generated using a two state Markov chain model to simulate traffic and scheduling, and verified mathematically. The work also includes an examination of various data traffic types' on/off relation and an evaluation of how the relation affects power consumption. The FCCD method can complement DRX sleep mode since it is applicable when the signal is too aperiodic or fast switching for DRX.

I. INTRODUCTION

Today mobile phone users are experiencing limitied battery lifetime, and the situation is not improving because the gap between mobile phone complexity and battery capacity increases [1], [2]. One reason is that the users run more power and data demanding applications. The Third Generation Partnership Project developed the Long Term Evolution (LTE) standard [3] to deal with the demand for higher data rates and lower latency, but this caused the phones to become even more complex in terms of number of antennas and processor speed [4]. During the standardization process less attention was paid to how long the phones can utilize LTE before the battery is discharged, and therefore we now deal with a problematic relationship between required and available energy.

In previous work researchers have tried to maximize the available energy, minimize the energy consumption, [5], and harvest energy [2]. Minimizing the phone's energy consumption requires optimization of the hardware (HW) and/or software (SW). A less obvious minimization option is to adjust network controlled parameters that affect the phone's modem as described in [6]. The energy consumption of the phone's HW can be reduced by developing energy efficient components and by applying power management. In LTE Discontinuous Reception (DRX) [7] have been standardized to enable energy saving sleep modes [8]. The problem is that DRX requires a data traffic pattern with periodic trends, and furthermore it increases the control message overhead of the network and complicates the scheduling. In this work a micro-sleep mode, [9], which can be applied in traffic that does not fit DRX, is examined. The idea is to perform Fast Control Channel Decoding (FCCD) and then power down energy consuming circuits, when the phone is RRC_connected in the current TTI, but not scheduled. The objective is to determine whether the FCCD is feasible for various data traffic patterns, and if energy can be saved, but it is out of scope to present a specific power down implementation.

First we describe LTE control channel decoding, the inherent SINR degradation, the UE power model and the Markov chain traffic generator. Then we present simulation results, a mathematical verification, and finally the conclusion.

II. APPLYING FCCD TO SAVE ENERGY

A. Fast Control Channel Decoding

The Physical Downlink Shared Channel (PDSCH) carries individual user data and is configured on a Transmit Time Interval (TTI) basis. The channel is shared among the users and therefore the network notifies the users of when and where in time and frequency their data is located. This procedure is known as resource block allocation. A Resource Block (RB) consists of 12 subcarriers, each 15 kHz wide, spanning one TTI, which is 1 millisecond i.e. 14 symbols, when the normal cyclic prefix is applied, [10].

The UE will initially receive one of seven different Downlink Control Information (DCI) data blocks on the Physical Downlink Control Channel (PDCCH). The DCIs are contained in Control Channel Elements (CCE) and used to determine the PDSCH's modulation format and the assigned RBs. The UE is required to blindly decode several CCEs in each TTI to check if it contains a relevant DCI, [9]. Therefore the Physical Control Format Indicator Channel (PCFICH) indicates the number of OFDM symbols, used for PDCCH in the current TTI. The PCFICH is located in the first OFDM symbol of a TTI while the PDCCH occupies the first 1-3 symbols.

Usually the UE buffers PCFICH & PDCCH, and while it decodes those channels it buffers PDSCH to ensure that it does not lose any data. Buffering PDSCH, when the user is not scheduled is a waste, because the decoding will fail since the data was not intended for the UE. The proposed idea is thus to power down energy consuming circuits in Radio Frequency (RF) and Base Band (BB), when it is determined by decoding of PCFICH & PDCCH that the UE is not scheduled to receive

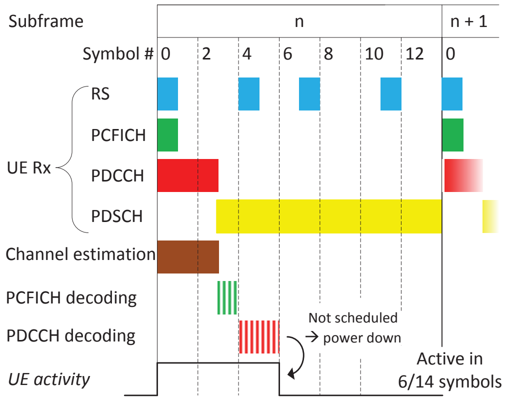


Fig. 1. Power down based on Fast Control Channel Decoding (FCCD).

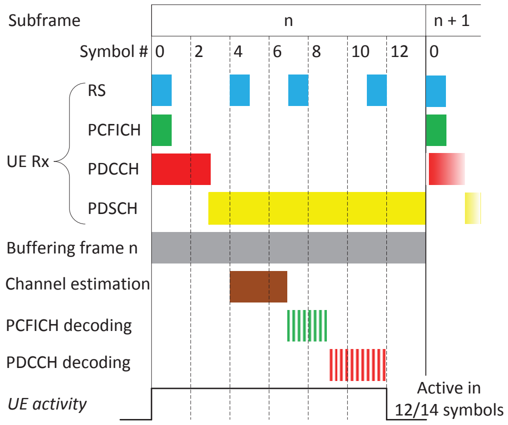


Fig. 2. Power down based on full frame buffering.

downlink data in the current TTI, as illustrated in figure 1. Note that a fast decoding of the two control channels is crucial. The DCIs are transmitted on PDCCH using CCEs composed of 9 Resource Element Groups, which again are composed of 4 Resource Elements (RE), [4]. A RE is one subcarrier and one symbol, and since PDCCH is QPSK modulated a CCE is $9 \cdot 4 \cdot 2\,\mathrm{bit} = 72\,\mathrm{bit}$. Note that the DCIs only comprise 40-50 bit. The DCI search space is composed of 16 UE specific and 6 common CCE candidates, [11] thus the UE must Viterbi decode $2 \cdot (16+6) \cdot 72\,\mathrm{bit} = 3168\,\mathrm{bit}$ to determine if it is scheduled. The factor of 2 is due to the UE decoding both UL and DL DCI formats, but it is an estimate since some DCIs have equal size, hence they can be decoded together. The number is low compared to the 150 kbit the UE can Turbo decode per TTI and therefore the FCCD is deemed plausible.

The FCCD is compared with a regular method, where the entire subframe is buffered. Here the UE decodes the control channels later and is therefore unable to power down. Instead it discards data and saves energy by not processing useless, not decodable data as illustrated in figure 2.

The FCCD method has several advantages as compared to DRX. First of all it is much more flexible than DRX since it does not require a periodic data traffic pattern. Furthermore the network does not need to schedule sleep mode users and transmit control messages regarding the sleep mode settings i.e. the overhead is reduced because the method is applied individually by each UE. Actually the method is fully independent of DRX, which means they can co-exist.

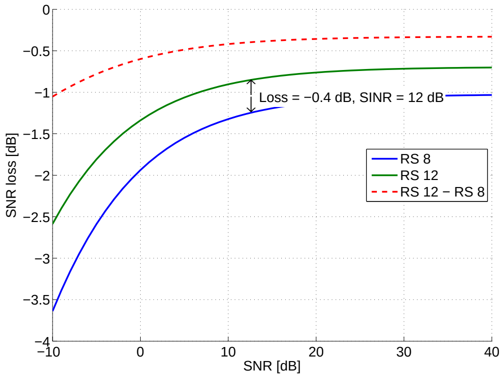


Fig. 3. SNR loss as a function of downlink Reference Signals (RS).

B. *SNR Degradation due to fewer Reference Signals*

The Reference Signals (RS), which are transmitted in symbol 0, 4, 7, and 11 of every subframe, as shown in figure 1, and spread across the subcarriers according to a mapping scheme, consist of a predefined symbol sequence enabling the UE to estimate the transmission channel(s), [10]. Using the power down technique in figure 1 will entail that the RS in frame *n* are not available for channel estimation if the UE is scheduled in frame *n+1* as compared to figure 2. This is interpreted as a Signal-to-Noise Ratio (SNR) degradation and therefore also a throughput loss.

In LTE the number of RS per RB's effect on the SNR was examined to determine a reasonable relationship between channel estimatation quality and overhead. The effective SNR based on channel estimation is [12]

$$\mathrm{SNR}_{\mathrm{ch.Est}} = \frac{\mathrm{SNR}}{1+\frac{1}{d}+\frac{1}{d\cdot\mathrm{SNR}}} \tag{1}$$

where SNR is with perfect channel estimation, and d is the number of RS used to generate the channel estimate. The assumption is that the channel is flat in frequency and time during one resource block.

The UE will receive 8 RS per antenna port per RB, [10] and if the UE is active in consecutive frames it is furthermore assumed that it can utilize the last half (time wise) of the RS in the previous TTI, achieving a total of 12 RS. Figure 3 illustrates the SNR loss, which is the difference between the original SNR and $\mathrm{SNR}_{\mathrm{ch.Est}}$ for 8 and 12 RS. Furthermore the loss caused by using 8 instead of 12 RS is also plotted.

To comply with the assumption that the RB is flat in time the maximum UE speed is calculated. As a rule of thumb we set the wave length λ to $1/20$ of the original wave length λ_c:

$$\lambda = \frac{\lambda_c}{20} = \frac{1}{20}\cdot\frac{c}{f} = \frac{3\cdot 10^8\,\mathrm{m/s}}{20\cdot 2\cdot 10^9\,\mathrm{Hz}} = 0.0075\,\mathrm{m} \tag{2}$$

$$v_{\mathrm{UE}} = \lambda/t = 0.0075\,\mathrm{m}/0.001\,\mathrm{s} = 7.5\,\mathrm{m/s} = 27\,\mathrm{km/t} \tag{3}$$

where c is the speed of light, f is the carrier frequency, and t is 1 TTI. Most users are indoor hence v_{UE} is high enough for the SNR degradation assumptions to be applicable.

Note it is assumed that PDCCH is encoded so well that it can be received properly even though some RS are missing.

TABLE I

UE POWER MODEL, [13]. VALUES ARE RELATIVE TO P_{ACTIVE}

Description	**Variable**	**Relationship**
Active with data reception	$P_{\text{active}} = 500\,\text{mW}$	1
Active, FCCD power down	P_{ccd}	[0.4,0.5,0.6]
Active, full buffering	P_{buf}	[0.7,0.8,0.9]

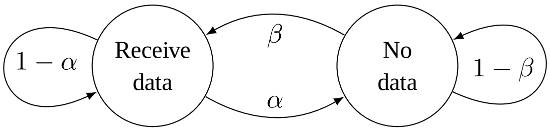


Fig. 4. Two-state Markov chain model.

TABLE II

RECEIVE PATTERNS. H/L INDICATES HIGH/LOW PROBABILITY.

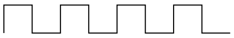
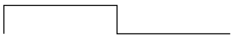
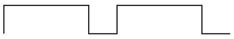
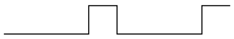
α	β	**AF**	**Receive pattern examples**	
H	H	50 %	1	Rx data No data 
L	L	50 %	2	Rx data No data 
L	H	> 50 %	3	Rx data No data 
H	L	< 50 %	4	Rx data No data 

TABLE III

ESTIMATED ACTIVITY FACTORS FOR SELECTED APPLICATIONS.

		Network load			Real Time
		Low	Medium	High	Constraint
Applications	Heartbeat	≤1	≤1	≤1	None
	Voice	5	5	5	Hard
	H.264 film	30	50-60	80-90	Easy
	FTP	80-100	80-100	50	None

C. UE Power Model

The structure of the subframe allows the UE to decode the control channels and then power down if data is not scheduled. As mentioned earlier this work introduces the FCCD method, but not a specific implementation. Implementing the method should however not pose problems, because a phone utilizes power domains i.e. it can power down circuits individually. Furthermore most circuits can power down/up fast, and in [8] the wakeup time is estimated to $2\,\mu$s. This excludes the synthesis which requires $\approx 300\,\mu$s to settle. Among the envisioned sleeping circuits are Low Noise Amplifiers, Programmable Gain Controls, mixers, and analog-to-digital converters.

To evaluate the energy saving potential the UE power model from [13] is applied. The model is based on relative values and one arbitrary power level. In [13] and the DRX focused article [14], there is no sensitivity analysis of the relative values, but as shown in table I this work includes such an analysis to give a broader perspective of the energy saving potential.

Because the FCCD power down happens after the 6th symbol, as shown in figure 1, the power consumption is estimated to be half of P_{active}. Using the full buffering method is not as efficient because the decoding occurs later, and processing first stops after the 12th symbol, see figure 2.

Note that the power model does not include uplink transmission and state transition power consumption.

D. Traffic Generation & Packet Scheduling

One of the main objectives is to evaluate the energy saving potential for various traffic patterns. The traffic is generated using a two-state Markov chain [15], where the two states represent the UE's mode. In the first mode the UE is scheduled and receiving data, and in the second mode it is RRC_connected, but not scheduled as illustrated in figure 4. The Markov chain, which only depends on the previous state, has two parameters α & β. The probability to change from a state where the UE is receiving data to not receiving is α, while the probability to continue being in a receiving data state is $1-\alpha$. Likewise with β for the state "no data". Small α & β results in a pattern with long consecutive blocks whereas large α & β will result in a rapidly switching pattern. Table II contains four examples of the relationship between α, β and the resulting receive pattern. The ratio between "receive data" and "no data" in figure 4 is defined as the Activity Factor (AF), and it is estimated for the patterns in table II. Notice that the AF is equal for the first two patterns even though α & β are not equal. Pattern 1 results in an SNR degradation four times as often as pattern 2, hence the troughput will be different. Because of this throughput difference, simulations are made for various configurations of α & β even though they result in the same AF.

Defining the transition probablity matrix P for the Markov chain in figure 4 as

$$P = \begin{bmatrix} \text{Rx} & \text{Rx} \rightarrow \text{No data} \\ \text{No data} \rightarrow \text{Rx} & \text{No data} \end{bmatrix} = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix}$$

the stationary probability mass function $\boldsymbol{\pi}$ is [16, Eq. 9.18b]

$$\boldsymbol{\pi} = \boldsymbol{\pi} P = \begin{bmatrix} \pi_0 & \pi_1 \end{bmatrix} \tag{4}$$

That is the probability of a given state approaces a steady state independent of the initial probability. Noting that $\sum_i \pi_i = 1$

$$\begin{bmatrix} \pi_0 & \pi_1 \end{bmatrix} = \begin{bmatrix} \pi_0 & \pi_1 \end{bmatrix} \cdot \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix} \tag{5}$$

$$\pi_0 = \frac{\beta}{\alpha+\beta} \qquad \pi_1 = \frac{\alpha}{\alpha+\beta} \tag{6}$$

where π_0 is the probability of being in state 0 (receive state) and π_1 is the probability for state 1 (not scheduled state). Since AF equals π_0 it can be calculated using α & β.

The AF can be related to real traffic generating applications by determining the applications' data rate and latency requirements. Table III gives estimated AFs for four selected applications with diverse requirements. Heartbeat applications do not impose hard time constraints, neither do they require a lot of data, and therefore the AF is estimated to be $\leq 1\,\%$ for all network loads. The voice applications usually generate very small packets (<40 bytes), but they have a hard real time constraint. Because the packets arrive every 20 ms, [4], the AF is set to 5 % independently of the network load. DRX is expected to be applied to both heartbeat and voice applications.

Video is available in many different qualities and frame rates. In [17] a H.264 high quality video configuration with a

TABLE IV
SIMULATION PARAMETERS.

Parameter	**Value**
Allocated PRBs	8 (180 kHz per PRB)
Simulation time	120 s
SINR	12 dB
Num. RS for first/consecutive TTI(s)	8, 12
α, β	[0.01:0.04:0.09 0.1:0.4:0.9]
Block Error Rate (BLER)	10 %
Receive patterns	100 per α & β set
Channel	TU20 SISO

frame rate equal to 25 Hz is presented. The resulting bitrate is 3.6 Mbps and since the authors mention that IP and UDP adds 30 % overhead the required rate is $1.3 \cdot 3.6\,\text{Mbps} = 4.68\,\text{Mbps}$. Assuming the SINR to be 12 dB the spectral efficiency is $\approx 1.7\,\text{b/s/Hz}$ for a TU20 SISO channel. In the low network load scenario the user is estimated to get 50 PRBs resulting in a throughput equal to 15.3 Mbps. The AF is $\frac{4.68}{15.3} \approx 30\,\%$. The allocated bandwidth reduces as the network load increases and therefore the activity factor increases in order to maintain the frame rate. The FTP application does not impose any time constraints and therefore the activity factor solely depends on the allocated resources. When the network load is low the user can be active every TTI, but as the load increases the user may not be scheduled every TTI hence the AF decreases.

In summary table III shows how diverse the AF can be for traffic generated by LTE users, and therefore the simulations are made for $1\,\% \leq \text{AF} \leq 100\,\%$.

E. Simulation Setup

The simulation parameters are given in table IV. The simulations are initialized by generating a 120 s receive pattern using the Markov chain and a α & β set. Then a BLER of 10 % is added. This is achieved by randomly inserting 10 % extra receive-periods. These periods do not add to the total throughput, but they entail that the RS are received in the given TTI. Next the throughput using 8 (FCCD) and 12 RS (full buffering) are calculated based on the SINR and the number of PRBs. Finally the energy consumption is determined using the generated pattern and the power model from section II-C. The simulations are made on 100 patterns per α & β set.

The simulations do not include protocol specifics such as TCP's slow start. Furthermore LTE DRX [7] is not implemented, but the authors are aware that DRX will be applied for low AFs, leading to a lower power consumption [14]. Long DRX has a minimum cycle of 10 ms, [18] and if the UE is active in one TTI the maximum AF is 10 %. Short DRX has a minimum cycle of 2 ms i.e. the maximum AF is 50 %.

III. SIMULATION RESULTS

The SNR degradation described in section II-B will entail a reduced throughput. The loss is calculated as the achieved throughput, when the UE is always active, minus the achieved throughput, when the UE is using FCCD. The simulated result is plotted in figure 5 and the average loss is 1.04 % and the maximum loss is 3.68 %. These are negligible numbers hence FCCD is applicable for all AFs from a throughput point of view. The loss decreases as the AF increases because the FCCD is applied less and less. The loss fluctuates because the simulations are made for different combinations of α & β. If e.g. the AF is 50 % the two set of probabilities $[0.9, 0.9]$ and $[0.01, 0.01]$ are applicable, but they will result in different patterns. When α & β are large the UE will change state rapidly leading to a larger SNR degradation as compared to smaller α & β which will entail a slowly changing pattern with minimal SNR degradation.

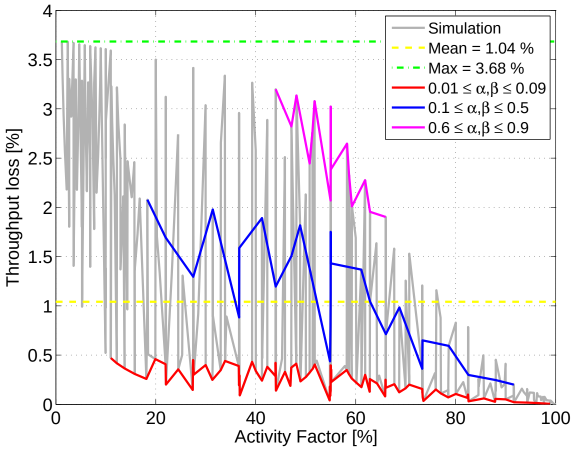


Fig. 5. Throughput loss as a function of AF.

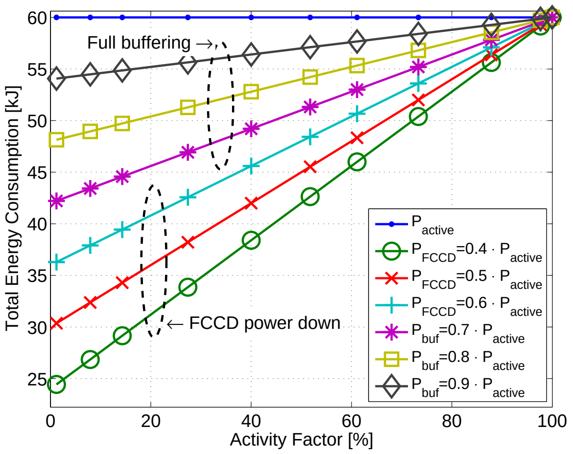


Fig. 6. Energy consumption as a function of AF.

The simulated energy consumption for the three UE modes is illustrated in figure 6. The power model sensitivity analysis (table I) is represented in this plot by the three lines per sleep mode. As expected the average energy consumption is constant for the always active mode, while it decreases for decreasing AF for the two other modes. The reason is that the number of "no data" periods increase, when the AF decreases and therefore the UE is able to be in a sleep mode more often.

Figure 7 shows the energy saving when using FCCD relative to full buffering. Notice that the FCCD method is applicable for AFs that are too high for DRX. The biggest energy savings are obviously obtained for lower AF and for AF$= 20\,\%$ they are between 10 % and 45 %. When AF$\geq\ 80\,\%$ the energy savings are below 10 % for all combinations. The result for $P_{\text{ccd}} = 0.5 \cdot P_{\text{always active}}, P_{\text{buf}} = 0.7 \cdot P_{\text{always active}}$ shows savings between 5 % and 25 % in the applicable AF interval. Note that

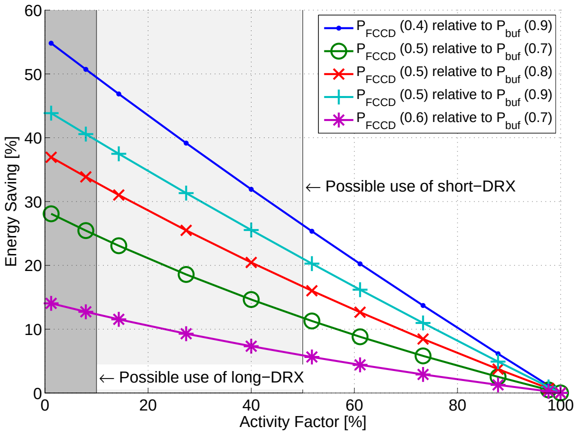


Fig. 7. Energy savings when using FCCD instead of full buffering as a function of AF. The values in ( ) denotes the power relative to the always active power. The grey areas indicate possible DRX use based on [18].

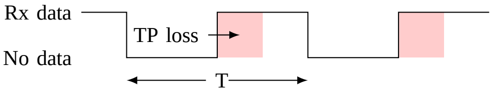


Fig. 8. Receive pattern defining T and throughput loss.

there is a throughput loss when using FCCD as compared to full buffering, but as shown in figure 5 it is less than 4 %.

IV. VERIFICATION

In this section the energy saving and the throughput loss are verified mathematically by equations that only depend on the time period T and the AF. Since the Markov chain's α and β are not used, the equations are based on periodic patterns. The average power consumption of pattern 1 (50 % AF) and 3 (75 % AF) in table II is

$$\begin{aligned} P_1 &= (P_{\text{active}} \cdot 4\,\text{TTI} + P_{\text{FCCD}} \cdot 4\,\text{TTI}) \,/\, (8\,\text{TTI}) \\ P_3 &= (P_{\text{active}} \cdot 6\,\text{TTI} + P_{\text{FCCD}} \cdot 2\,\text{TTI}) \,/\, (8\,\text{TTI}) \\ &\Downarrow \\ P_{\text{avg}} &= P_{\text{active}} \cdot \text{AF} + P_{\text{FCCD}} \cdot (1 - \text{AF}) \qquad (7) \end{aligned}$$

Using the power values from table I the total energy consumption for AF$= 40\,\%$ is

$$\begin{aligned} E_{\text{tot}} &= t_{\text{sim}} \cdot P_{\text{avg}} = t_{\text{sim}} \cdot (P_{\text{active}} \cdot \text{AF} + P_{\text{FCCD}} \cdot (1 - \text{AF})) \\ &= 120\,\text{s} \cdot (0.5\,\text{W} \cdot 0.4 + 0.25\,\text{W}\,(1 - 0.4)) = 42\,\text{kJ} \end{aligned}$$

Similar calculations can be made for the other AFs and they are in accordance with the results in figure 6, which thereby is verified. By replacing P_{FCCD} with P_{buf} the energy saving using the buffering method can be calculated.

The throughput loss occurs in the first receiving TTI after a period, where the UE has not been scheduled, as shown in figure 8 and therefore the loss is determined by

$$\text{loss} = (b_{\text{active}} - b_{\text{noRS}}) \,/\, (\text{AF} \cdot T \cdot b_{\text{active}}) \qquad (8)$$

where T denotes one period i.e. a single receive period and the corresponding no data period as illustrated in figure 8. The upper bound is $\text{AF} \cdot T = 1$. Using the PRB, SINR, and RS parameters in table IV $b_{\text{active}} = 2267$ bit and $b_{\text{noRS}} = 2183$ bit meaning that the throughput loss is 3.7 %. This corresponds well with the simulation results shown in figure 5.

V. CONCLUSION

In LTE scheduling information is transmitted in the Physical Downlink Control Channel on a subframe basis. The channel's format is declared in the same subframe using the Physical Control Format Indicator Channel. By fast decoding of the two control channels the receiver can be powered down within the subframe, if it is not scheduled for data reception in that subframe. In this work a Fast Control Channel Decoding method is proposed and the results show an energy saving potential of 5 %-25 %, when compared with a regular buffering method in which the control channels are decoded slower and power down is not possible. The cost is that some Reference Signals are not received thus the channel estimate is less good, but calculations show it only entails a throughput degradation of 1 %-4 %.

The LTE Discontinuous Reception (DRX) sleep mode technique will be applied when the downlink data traffic activity factor is below 10 % and 50 % for long and short DRX respectively. The proposed method can however complement DRX, when the traffic is too aperiodic or rapidly switching for DRX and furthermore it is applicable for all acitivity factors. Contrary to DRX the method is applied individually in each UE thus it does not introduce a control message overhead and affect the network scheduling.

ACKNOWLEDGEMENT

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REFERENCES

[1] IMS-Research, "Handset power requirements dramatically outpacing capacity," 2009.
[2] S. Cordova, "Harvesting the future of mobile," in *IQ Magazine*, vol. 9, no. 3, 2010, pp. 26–29.
[3] 3GPP, "Long Term Evolution," http://www.3gpp.org/article/lte, 2010.
[4] H. Holma and A. Toskala, *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access*. John Wiley & Sons, Ltd., 2009.
[5] J. Öfversten, "Mobile internet battery life," Forum Nokia Webinar, 2009.
[6] M. Lauridsen, A. R. Jensen, and P. Mogensen, "Reducing lte uplink transmission energy by allocating resources," in *Vehicular Technology Conference Fall, 2011 IEEE 74th*, Sep 2011, pp. 1 –5.
[7] 3GPP, "MAC protocol specification," TS 36.321 V8.9.0, 2010.
[8] K.-C. Ting, H.-C. Wang, C.-C. Tseng, and F.-C. Kuo, "Energy-efficient drx scheduling for qos traffic in lte networks," in *Parallel and Distributed Processing with Applications , IEEE International Symposium on*, 2011.
[9] R. Love, R. Kuchibhotla, A. Ghosh, R. Ratasuk, B. Classon, and Y. Blankenship, "Downlink control channel design for 3gpp lte," in *IEEE Wireless Communications and Networking Conference WCNC*, 2008.
[10] 3GPP, "Physical channels and modulation," TS 36.211 V8.9.0, 2010.
[11] ——, "E-UTRA, Physical layer procedures," TS 36.213 V8.8.0, 2009.
[12] Ericsson, "Ue specific reference signal pattern," 3GPP R1-080506, 2008.
[13] Nokia, "Drx parameters in lte," 3GPP R2-071285, 2007.
[14] T. Kolding, J. Wigard, and L. Dalsgaard, "Balancing power saving and single user experience with discontinuous reception in LTE," in *Wireless Communication Systems. IEEE Int. Symp. on*, 2008, pp. 713 –717.
[15] A. Adas, "Traffic models in broadband networks," *IEEE Communications Magazine*, vol. 35, pp. 82–89, 1997.
[16] A. Leon-Garcia, *Probability and Random Processes for Electrical Engineering*, 2nd ed. Addison Wesley, 1994.
[17] T. Wirth, L. Thiele, T. Haustein, J. Brandenburg, and B. Stabernack, "Scalable video broadcasting trials in 4g cellular deployments," in *Future Network and Mobile Summit, 2010*, june 2010, pp. 1 –7.
[18] 3GPP, "RRC protocol specification," TS 36.331 V8.14.0, 2011.