Power consumption analysis of constant bit rate data transmission over 3G mobile wireless networks

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***Abstract*—This paper presents the analysis of the power consumption of data transmission with constant bit rate over 3G mobile wireless networks. Our work includes the description of the transition state machine in 3G networks, followed by the detailed energy consumption analysis and measurement results of the radio link power consumption. Based on these description and analysis, we propose power consumption model. The power model was evaluated on the smartphone Nokia N900, which follows a 3GPP Release 5 and 6 supporting HSDPA/HSPA data bearers. Further we propose method of parameters selection for 3GPP transition state machine that allows to decrease power consumption on the mobile device.**

I. Introduction

The number of mobile cellular subscriptions has been rapidly growing since the beginning of the 20th century, and now the rough estimation of it has already exceeded 4 billion [1]. Most of the phones are working in GSM, WiMAX and 3G networks. The last one is becoming ubiquitous. As wireless communication technology advances, 3G networks provide in new generation's mobile phones a large amount of various services including: high data rate internet access, videoconferencing, global positioning, high quality music and video downloading and gaming capabilities. As a consequence, all these features bring the power consumption of mobile phones to the level of desktop computers. Therefore, minimization of the power consumption of wireless devices becomes a great challenge, for the entire electronic industry, at all system levels. Hence, an intense research in the field of system design has been focused on power management.

One of the research areas is to optimize UMTS Radio Resource Control (RRC) state machine. As a User Equipment (UE) associates with UMTS core network, the network maintains RRC state machine and allocates the radio resources for the UE device. Meanwhile, the UE spends different amount of power consumption in each state as well. In order to minimize power consumption, UE should switch from high power consumption state to low power consumption state immediately once application traffic stops. However, unpredicted user traffic patterns may lead to massive transitions between two states, which increase signal overheads for radio access network, as well as yield additonal transmission delays for the UE. Inactivity timers are used to reduce the frequence of state transitions by controlling the timespan UE spends in each state. However, the open question is how to balance the tradeoff between power consumption and application performance on mobile devices, and signal overhead of the radio access network. Current statically configured parameters of RRC state machine causes slow adaption of the resources to application traffic patterns, which may lead ineffective usage of these resources. One work [2] analyses the impacts of the inactivity timer on energy consumption and reconnection cost, and proposes a parameter selection method based on analytical traffic models. Another work [3] investigates the optimization task of state machine parameter selection and explores the optimal timer values based on empirical results.

We are particularly interested in constant bit rate traffic such as video traffic on mobile devices, which will generate 4.2 exabytes data crossing the mobile network and account for 66 % of mobile data traffic by 2015 [4]. In this paper, we would like to find out how the energy consumption characteristics vary depending on the packet size and transmission interval, and also how to minimize the power consumption in case of constant bit rate data transmission. Thus, the main contributions of this paper are: 1) Power consumption of each RRC state is analyzed and we propose a power consumption model for one of the state. 2) We build a power model for proposed RRC transition state machine and present a parameter selection criteria taking signal overhead and transition delay into consideration to minimize power consumption of constant bit rate transmission on mobile devices.

Our paper starts with a presentation of the mobile transmission system in Section II, where we explain the idea of state machine applied for mobile phone and describe the transmitter and receiver. In Section III the state power model is given, in particular for two states - Cell_FACH (Cell Forward Access Channel) and Cell_DCH (Cell Dedicated Channel). We propose a model of energy consumption in Cell_DCH state and show that the energy consumption is intimately related to packet size and transmission interval. Further in Section IV we propose a method of parameters selection for 3GPP transition state machine that allows to decrease power consumption on the mobile device in case of constant bit rate data transmission.

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II. Mobile transmission system overview

3G systems provide a global communication with various services including telephony, messaging and access to Internet. 3G networks consist of three domains: Core Network (CN), UMTS Terrestrial Radio Access Network (UTRAN) and User Equipment (UE). UE interoperate with Base Station (called Node B). The Radio Resource Control (RRC) handles the control plane signalling between the UEs and the UTRAN.

A. State machine

In 3G, there are five power consumption states: Idle, Cell_FACH, Cell_PCH, Cell_DCH and URA_PCH. Cell_PCH and URA_PCH can be considered as low power states, which consume only around 30mW. The state of Cell_FACH consumes around 400mW and the state of Cell_DCH consumes around 800mW. URA_PCH is very similar to Cell_PCH, although some vendors have not implemented it in their solution. In our work, we consider the two states largely equivalent.

The power consumption in the Cell_FACH is roughly 50 % of that in the Cell_DCH, and the Cell_PCH states use about 1-2 % of the power consumption of the Cell_DCH state [5]. Each state is now described more in detail.

Idle. In this mode UE is not communicating with the network although it does listen for broadcast messages. So it does not have a RRC connection, but UE can still have an IP address and it can be reached by paging. In this state mobile phone consumes the least amount of power.

Cell_PCH (Cell Paging Channel). In this state the channel is shared by all mobile devices so the inclusion of an additional mobile phone does not really have any impact on the network. UE monitors paging messages from the Radio Network Controller (RNC). As in the Idle state, the power consumption is very small. In this state no dedicated physical channel is allocated to the UE, so no uplink activity is possible.

Cell_FACH (Cell Forward Access Channel). In the Cell_FACH the mobile phone is communicating with the network via a shared channel. Small bits of data can be transmitted at a relatively low data rate, or on the order of up to 16kbps in the uplink. The maximum amount of transmission data also depends on the overall loading of the common channels. At the same time the UE continuously monitors a FACH in the downlink. The mobile phone power consumption is higher than it is in Idle or Cell_PCH states.

Cell_DCH (Cell Dedicated Channel). The mobile phone is allocated a dedicated transport channel both in downlink and uplink. It is consuming the most network resources and the impact on the battery is also at the very high level.

B. Transmitter and Receiver

It is UE that always initiates the RRC connection, then the establishment and the release are handled by the RRC protocol. UE starts working in Idle state, when an RRC connection has not yet been established. Only one RRC connection is used at any time between the UE and the network. When an RRC connection has been established between UE and Node B together with RNC, the Idle state switches to the RRC Connected mode.

To be more precise, from Idle mode through establishment of an RRC connection with obtaining a dedicated traffic, the UE enters the Cell_DCH state. Further it can move by explicit signaling from Cell_DCH to other states. The UE does not generally listen to broadcast channel in this state. If the Node B allocates to UE a common or shared traffic channel (i.e., the channel is shared by several UEs), it enters the Cell_FACH state. The data communication activities can only be performed in these two states.

Depending on the activities of the UE and traffic volume, states could be changed. Signaling messages (radio bearer configuration messages) are sent between UE and Node B when states are changing. Three timers are used to detect when a mobile device should move to a lower power state in case of inactivity. These incativity timers T1, T2, and T3 (names established in WCDMA parlance) are managed by RNC.

T1 is used within the Cell_DCH state before the 3G device is sent to a lower power state, but it is being reset every time new traffic appears. T2 is an inactivity timer determining how long the 3G device should remain in the Cell_FACH state without any activity. T3 is used in Cell_PCH. After T3 seconds there (usually a very long timer), the RRC connection will be released and the state will be changed to Idle.s

III. Power consumption analysis of transition states

In this section, the power consumption of each state is analyzed. We focus on modeling the power consumption in Cell_DCH state. Then, our proposed model is compared with real measurements and reference model.

A. The influence of packet sending intervals and packet size on power consumption of Cell_DCH state

Each RRC state requires various power consumption to maintain operation and is in different roles of generating signals transferred between UE and RNC to establish, maintain, release connections as well as transmit/receipt data across air interface. Compared to Cell_FACH state, which is only applicable for transferring relative small quantities of data, Cell_DCH state gives potential for UE to transfer large quantities of data and thus, is the state where most of data communication happens as specifically described in previous section. As well, it is the most interesting state to examine the effect of packet sending intervals and packet size on power consumption of UE radio interface.

Generally speaking, the size of transport block decides the maximum payload can be transmitted once every Transmission Time Interval (TTI) and TTI decides the maximum packet sending or receiving rate. These two parameters together influent the maximum throughput and packets sending or receiving pattern in the Physical layer. From the Transport layer perspective, application's traffic pattern, namely packet sending or receiving interval and packet size, directly decides underlaying layer's behavior regarding the size of transport

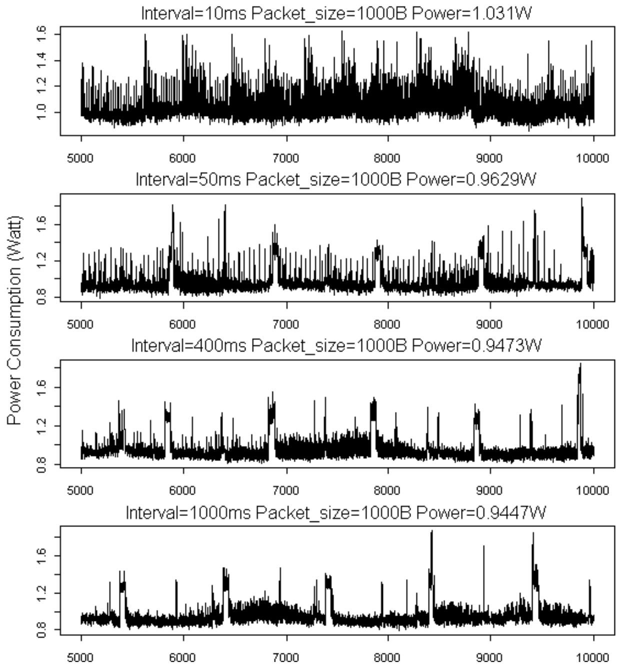

Fig. 1. Power Consumption of N900 in Downlink

block set and transmitting interval. Specifically, if the number of bits in a TTI is larger than the maximum size of one physical block can contain, segmentation is performed and the over-sized bits are sent during next TTI. If the packets are generated with an interval which is less than TTI, the transmitting interval is decided by TTI. Otherwise, it is decided by packet generate interval of application. Therefore, power consumption of radio interface is proportional to the number of transport block sets sent and received over radio interface [7].

Figure 1 demonstrates the power consumption of packet transmission on Nokia N900 in downlink. The traffic is UDP packets which were generated by a traffic generator in different intervals as shown in the figure. Each peak is corresponding to the power consumption of transmitting one transport block set. As we can see, the number of peaks directly decides the power consumption of radio interface. Faster receiving interval leads to larger number of peaks, thus higher power consumption. In our experiments, we also observed same phenomena in uplink on the N900. Among the peaks, wide peaks are due to the power consumption of daemon process of 3G modem and excluded from calculation in the following subsections.

B. Power Consumption Modeling of Cell_DCH state

Based on the description and analysis, we propose power consumption model in this subsection. The power consumption of sending or receiving packets in Cell_DCH state mainly consists of three sources, namely the power consumption of maintaining Cell_DCH state which is defined as P_{DCH} in watt, the power consumption of sending or receiving packets which is defined as P_{peak} in watt demonstrated as power peaks in Figure 1, and the power consumption of encapsulating or decapsulating packets which is defined as a function of packet size $P_{enc}(s)$, where s is the size of packet in bytes. Therefore, the power consumption of UE to send or receive packets in state Cell_DCH is returned in equation

$$P = P_{DCH} + P_{peak} + P_{enc}(s). \quad (1)$$

UE requires resource and power consumption to maintain the state. Thus, P_{DCH} is the minimal power consumption for the UE to stay in state Cell_DCH, which includes the power consumption of reception of control signals and is considered as an approximately fixed value since most of the traffic is data traffic.

Besides, we define I as packet sending interval in ms, which is the interval of sending packets from UE to Node B or the interval of sending packets from Node B to UE.

The power consumption for encapsulation or decapsulation $P_{enc}(s)$ for packet size s can be assumed as linear and the incremental power is proportional to the size of the packet since more computation power required to process bigger packet yields higher power consumption. Our practical experiments show that portion of encapsulation and decapsulation is only about 0.1% of total power consumption, which is yielded only by computation and considered as negligible compared with the power consumption of sending and receiving. Therefore, we exclude this power consumption component in our modeling.

The number of transport blocks needed for sending one IP packet is decided by the size of packet and specification related variables defined in different 3GPP releases. Here we define the number of transport blocks as

$$N = \left\lceil \frac{s}{MTBS} \right\rceil, \quad (2)$$

where MTBS is Maximum Transport Block Size.

Additionally, E_{peak} is defined as energy consumption of sending or receiving one peak in Joule.

As analyzed in previous section, the power consumption of peaks changes more or less linearly with the number of the transport blocks. When more than one transport block is needed for sending or receiving one IP packet, the time spent on processing this packet is $N \cdot \tau$, where τ is defined as the value of TTI. Normally, packet sending interval I is much larger than the packet processing time. Thus,

$$P_{peak} = \frac{N}{I} \cdot E_{peak}, \text{ when } I > N \cdot \tau. \quad (3)$$

Then taking into account (2) and (3), power consumption in CELL_DCH state can be written as

$$P = P_{DCH} + \frac{E_{peak}}{I} \left(\left\lceil \frac{s}{MTBS} \right\rceil \right) \quad (4)$$

Model (4) formulates the power consumption of one connection of uplink or downlink traffic. This model shows the power consumption can be decided by the number of peaks, in a way decided by packet sending or receiving interval I and packet size s, which is the main factor of power consumption of radio interface. This model can be extended to formulate the power consumption multiple connections by counting the

TABLE I
PARAMETERS APPLIED ON THE NOKIA N900

	Uplink	Downlink
UE Category	HSUPA Category 5	HUDPA Category 5
TTI	10 ms	2 ms
Maximum Transport Block Size (MTBS)	20000 bits	7298 bits
Data rate	2 Mbit/s *	2 Mbit/s
E_{peak}	0.4532E-3 J	0.4435E-3 J
P_{DCH}	0.8556 Watts	0.8478 Watts
*Note: The donwlink data rate is limited to 2Mbit/s due to the type of data packet. The maximum data rate is 3.65Mbit/s.		

amount of bits sent or received in a certain interval. As long as mobile devices are capable to record transmitted and received packet intervals and sizes, the proposed model can be extended to estimate power consumption of radio interface in runtime.

C. Experimental Setup

In order to keep enough measurement accuracy and uninterrupted power source, the battery of the N900 was replaced with a battery adapter, which was serially connected to a 4.1V DC power supply and a 0.1 Ohm resistor. NI cRIO-9215 was then used as a data logger to record voltage fluctuations of the N900 at sample rate of 1000 sample/second. A Linux traffic generator was also used to generate packets with various packet sizes and sending intervals. UDP traffic was generated instead of TCP to avoid TCP hand-shake and retransmissions. Besides, the packet sending interval ranges from 10ms to 1000ms to avoid UE switching to Cell_FACH state. Moreover, the packet size ranges from 10 bytes to 1500 bytes, which is the typical Maximum Transmission Unit (MTU) for Ethernet. When measuring the power consumption of sending packets, the UDP packets generated on the N900 were sent to Node B via uplink, then being forwarded to the Linux server. When measuring the power consumption of receiving packets, the UDP packets were generated on the Linux server and received by the N900 in downlink.

D. Evaluating of Power Models

The power model was evaluated on the Nokia N900, which follows a 3GPP Release 5 and 6 supporting HSDPA/HSPA data bearers. The measured average energy consumption of peak E_{peak}, average power consumption in Cell_DCH P_{DCH} and related parameters needed for equation (1) are listed in Table I. Finally inserting the measured values in equation (4), the power consumption of sending or receiving packets is thereby decided by data rate r and packet size s. Based on the equation, the minimum power consumption can be retrieved by finding optimum packet size when data rate is given.

As shown in Figure 2 and Figure 3, the values of interval and packet size are specified in a selection of interval ranging from 10ms to 1000ms and a set of two different packet sizes which are 100B and 1500B respectively. When the interval is given, the power consumption does not show too much difference for different packet size in both uplink and downlink. When the packet size is given, the power consumption is mainly decided by packet sending or receiving interval.

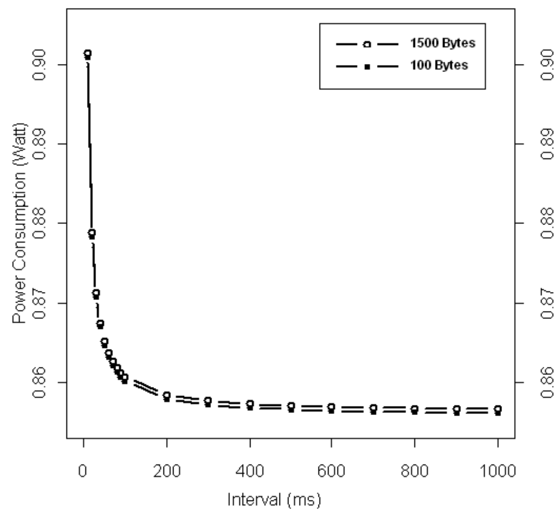

Fig. 2. Power consumption of uplink when packet sizes are 100 Bytes and 1500 Bytes

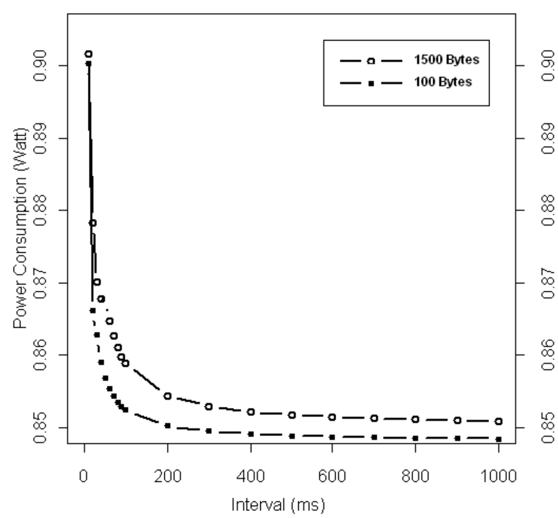

Fig. 3. Power consumption of downlink when packet sizes are 100 Bytes and 1500 Bytes

In order to evaluate our model, we give another power consumption model, which is based on the assumption that power consumption is linear to data rate r [6]. The referenced model considers the energy consumption of UDP-type session as a function of data rate, which is expressed as

$$E = t \cdot (a + b \cdot r) + c, \quad (5)$$

where b is the energy consumption rate for data, a is power consumption, r is data rate and c is a constant value. By dividing by time t, the power consumption can be formulated into a linear equation as follows.

$$P = \alpha \cdot r + \beta \quad (6)$$

We compared the fitted values of two power models with the measured values from experiments. Mean Absolute Percentage

Error (MAPE) of the Interval-based model are 24.6% and 10.2% in uplink and downlink, and MAPE of the Datarate-based model are 27.2% and 20.9% in each case respectively.

IV. Uplink power consumption analysis of transition state machine

This section is directed to uplink power consumption analysis of transition state machine (TSM) described in section II.

In related work [9] the Poison source traffic model is analyzed. This model is good for HTTP-like data source. In this paper we consider the uplink power consumption in case of constant bit rate sources. This assumption is hold in case of video (audio) data transmission which are compressed in constant bit rate mode. In this case it is easy to predict source rate and use this information for minimization of the uplink power consumption.

A. Power consumption for ideal transition state machine

Let us denote P as uplink power consumption of mobile station, r as data source bit rate, c as channel bit rate. Then optimal transition state machine has to correspond to the following optimization task:

$$\begin{cases} \text{minimize } P \\ c \geq r \end{cases} \tag{7}$$

Let us define B_{RLC} as uplink data buffer of UE, B_{RLC}^T as buffer threshold and t_{inact} as inactivity time. Then the following ideal TSM can be introduced:

TABLE II
IDEAL TRANSITION STATE MACHINE

State 1 (Cell_PCH).
If activity detection, then go to State 2,
else go to State 1.
State 2 (Cell_FACH).
If $B_{RLC} > B_{RLC}^T$, then go to State 3,
else if $t_{inact} > T_2$, then go to State 1,
else go to State 2.
State 3 (Cell_DCH).
If $B_{RLC} = 0$, then go to State 2,
else go to State 3.

Let us define p_1, p_2 and p_3 as power consumption in State 1, State 2 and State 3 accordingly and c_2 and c_3 as channel rate in State 2 and State 3. Then power consumption of this TSM depending on data source bit rate r can be described as follows. If data rate $r = 0$, then UE is always working in State 1 and power consumption is p_1. If $0 < r \leq c_2$, then UE is always working in State 2 and has power consumption p_2. If $r \geq c_3$, then UE is always working in State 3 and has power consumption p_3. If $c_2 < r < c_3$ then we will have buffer accumulation in State 2 and buffer emptying in State 3. Accumulation time in State 2 is

$$t_2 = \frac{B_{RLC}^T}{r - c_2}. \tag{8}$$

Emptying time in State 3 is

$$t_3 = \frac{B_{RLC}^T}{c_3 - r}. \tag{9}$$

Finally, power consumption for ideal TSM is:

$$P = \begin{cases} p_1, \text{ if } r = 0, \\ p_2, \text{ if } 0 < r \leq c_2, \\ \dfrac{t_2}{t_2 + t_3} \cdot p_2 + \dfrac{t_3}{t_2 + t_3} \cdot p_3, \text{ if } c_2 < r < c_3, \\ p_3, \text{ otherwise}. \end{cases} \tag{10}$$

Theorem 1. Proposed state machine is solution of optimization task (7) for data source bit rate $r \in (c_2, c_3)$.

Proof. From (10) it is follows that for ideal TSM the channel rate $c = r$ for $r \in (c_2, c_3)$. Let us assume that another TSM with power consumption $P' < P$ is exist. It is possible only if accumulation time t_2' in State 2 for this TSM is more than accumulation time t_2 in State 2 for ideal TSM. But in this case channel rate c' for this TSM will be less than r. It means that this TSM does not exist.

B. Power consumption for 3GPP transition state machine

The ideal TSM can be used for selection of the parameters for 3GPP TSM [7]. Let us define these parameters as B_{RLC}^T and T_3. Then 3GPP TSM can be described as follows:

TABLE III
3GPP TRANSITION STATE MACHINE

State 1 (Cell_PCH).
If activity detection, then go to State 2,
else go to State 1.
State 2 (Cell_FACH).
If $B_{RLC} > B_{RLC}^T$, then go to State 3,
else if $t_{inact} > T_2$, then go to State 1,
else go to State 2.
State 3 (Cell_DCH).
If $r < c_3$ more than T_3 sec, then go to State 2,
else go to State 3.

If data rate $r = 0$, then UE is always working in State 1 and power consumption is p_1. If $0 < r \leq c_2$, then UE is always working in State 2 and has power consumption p_2. If $r \geq c_3$, then UE is always working in State 3 and has power consumption p_3. If $c_2 < r < c_3$ then we will have buffer accumulation in State 2 and buffer emptying in State 3. Finally, equation (10) with accumulation time in State 2

$$t_2 = \frac{\min\{B_{RLC}^T, (c_3 - r) \cdot T_3\}}{r - c_2}, \tag{11}$$

and emptying time in State 3 $t_3 = T_3$ is power consumption model for 3GPP TSM.

From Theorem 1 follows that if parameters T_3 and B_{RLC}^T of 3GPP TSM satisfy to equation

$$B_{RLC}^T = (c_3 - r) \cdot T_3, \tag{12}$$

then 3GPP TSM is identical to ideal TSM and it is solution of optimization task (7) too.

Figure 4 shows power consumption for TSM with typical parameters and parameters selected by using (12) for constant bit rate data. This figure illustrates that proposed parameters selection allows to significantly decrease the uplink power consumption of UE.

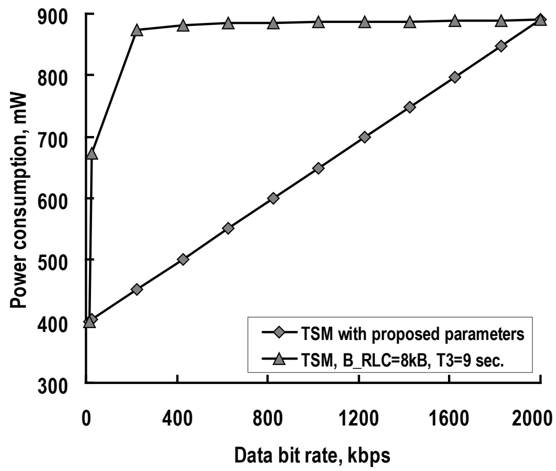

Fig. 4. Uplink power consumption for transition state machine for constant bit rate data transmission, $c_2 = 16$ kbps, $c_3 = 2000$ kbps, $p_2 = 400$ mW, $p_3 = 890$ mW

C. Parameters selection taking signaling traffic into account

As mentiond before, one of the problem for 3G is the increasing amount of the signalling traffic [3], [10], [11]. In this subsection we show the possibility of controlling the total signalling traffic on base station.

Let us define n_{23} as number of signals which is needed to transit from State 2 to State 3 and n_{32} as number of signals which is needed to transit from State 3 to State 2 and n_s as number of signals per second for UE. Then optimization task (7) can be modified as follows:

$$\begin{cases} \text{minimize } P, \\ c \geq r, \\ n_s \leq N_s^*, \end{cases} \tag{13}$$

where N_s^* is required number of signals per second for UE.

If $c_2 < r < c_3$ the UE works in State 2 and State 3 only and number of signals is

$$n_s = \frac{n_{23} + n_{32}}{t_2 + t_3} \leq N_s^*. \tag{14}$$

Combining (8), (9) and (14), it follows:

$$B_{RLC}^T \geq \frac{(n_{23} + n_{32}) \cdot (r - c_2) \cdot (c_3 - r)}{N_s^* \cdot (c_3 - c_2)}. \tag{15}$$

And maximum needed B_{RLC}^T is

$$\max_r B_{RLC}^T = \frac{(n_{23} + n_{32}) \cdot (c_3 - c_2)}{4 \cdot N_s^*}. \tag{16}$$

From (16) follows that 3GPP TSM is a solution of (13) if

$$\begin{cases} B_{RLC}^T = \dfrac{(n_{23} + n_{32}) \cdot (c_3 - c_2)}{4 \cdot N_s^*} \\ T_3 = \dfrac{B_{RLC}^T}{c_3 - r} \end{cases} \tag{17}$$

In case of constant bit rate data transmission the equation (17) allows to control the total network signaling traffic on the base station by selecting N_s^*.

D. Parameters selection taking states transition delay into account

As discussed above, the other issue in 3GPP networks is states transition delay. For example, State 2 to State 3 transition delay is around 1.5 sec, and from State 3 to State 2 is around 0.5 sec [3], [8]. It means that to provide low latency real-time video transmission the TSM has to work in State 3 only and it is not possible to save power consumption by tuning timer T_3 and buffer threshold B_{RLC}^T.

On the other hand for bit rate-controlled data sources like video surveillance or extracted data from scalable bit stream under bit rate constraints which don't require low latency it is possible to take into account states transition delay in the following way.

Let us define d_{23} as State 2 to State 3 transition delay and d_{32} as State 3 to State 2 transition delay. Then buffer size after transition from State 2 to State 3 is

$$B_{RLC} = B_{RLC}^T + d_{23} \cdot (r - c_2). \tag{18}$$

It is easy to proof that if parameters T_3 and B_{RLC}^T of TSM satisfy

$$B_{RLC}^T + d_{23} \cdot (r - c_2) = (T_3 + d_{32}) \cdot (c_3 - r), \tag{19}$$

then 3GPP TSM is identical to ideal TSM and it is a solution of optimization task (7). Thus, as a result, we can take into account transition delays during power consumption minimization of the UE.

V. Conclusion

In this paper we have analized the data transmission over 3G networks for smartphones. The first part of the analysis is related to the states in RRC in general. We have proposed the power consumption model based on our experimental results, taking into account packet sending intervals and packet size. This power model was further evaluated on the smartphone Nokia N900. Our model shows better approximation to the experimental results than referenced model based on data rate, that we took for the comparison. The second part of the paper discusses the uplink power consumption analysis of the transmission state machine. Our results here show that proposed parameters selection allows to significantly decrease the uplink power consumption on the mobile device taking signalling traffic and latency restrictions into account.

VI. Acknowlegements

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References

[1] ITU press release, “International telecommunication union“, available on: http://www.itu.int/newsroom/press_releases/2008/29.html, Sep. 2008.
[2] J.H. Yeh, J.C. Chen, and C.C. Lee, “Comparative Analysis of Energy-Saving Techniques in 3GPP and 3GPP2 Systems“, *IEEE transactions on vehicular technology*, 58(1):432438, Jan 2009.
[3] F. Qian, Z. Wang, A. Gerber, Z.M. Mao, S. Sen, and O. Spatscheck, “Characterizing Radio Resource Allocation for 3G Networks“, *in Proc. of the 10th annual conference on Internet measurement*, 2010.
[4] Cisco Visual Networking Index, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 20102015“, website: www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705 /ns827/white_paper_c11-520862.html, Feb. 2011.
[5] H. Haverinen, J. Siren, P. Eronen, “Energy Consumption of Always-On Applications in WCDMA Networks“, *Proceedings of the 65th Semi-Annual IEEE Vehicular Technology Conference*, 2007.
[6] K. Mahmud, M. Inoue, H. Murakami, M. Hasegawa, H. Morikawa, “Measurement and usage of power consumption parameters of wireless interfaces in energy-aware multi-service mobile terminals“, *15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2004.
[7] C. Johnson , “Radio Access Networks for UMTS: Principles and Practice“, *John Wiley & Sons, Ltd*, 2008.
[8] M. Sauter, “Hspa state change measurements“, available on: http://mobilesociety.typepad.com/mobile_life/2008/11/hspa-state-change-measurements.html, Nov 2008.
[9] K.H. Lee, J.H. Park and J.S. Koh, “User Experience Analysis of Smartphone Web Surfing in UMTS Networks“, *2010 IEEE 72nd Vehicular Technology Conference*, 2010.
[10] P. Willars, “Smartphone traffic impact on battery and network“, available on: http://www.labs.ericsson.com/developer-community/blog/smartphone-traffic-impact-battery-and-networks.
[11] Signals Research Group, “Smartphones and a 3g network“, available on: http://www.signalsresearch.com.