Balancing Power Saving and Single User Experience with Discontinuous Reception in LTE

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***Abstract* — The UTRAN *long-term evolution* (LTE) provides flexible means to achieve micro-sleep operation for *user equipment* (UE) even though it is in active mode and running a service. By means of a *discontinuous reception* (DRX) framework pauses in transmission due to natural traffic characteristics or network prioritization can be utilized. However, the optimum setting of parameters must be provided as a compromise among reaction latency, user throughput, power consumption, and network performance. Using a realistic RF modem power consumption model for the UE, we investigate different algorithms for optimizing the balance among user throughput and power saving using a web-browsing session as the reference. We show that with proper configuration of the DRX parameters we can optimally achieve a 95% reduction of the UE power consumption with only a moderate and acceptable 10-20% loss of experienced throughput.**

I. INTRODUCTION

In current and next generation wireless networks a common feature for high spectral efficiency is to grant a user wide access to the radio channel during those time instances where the channel is most favorable. Hence, users transmit with very high peak data rates, but only for short time bursts. This kind of scheduling behavior is tightly coupled to the multi-user diversity concepts [5] as well as the general requirement for short latency and real-time services.

For such networks it is easily understood that the ability to predict when *user equipment* (UE) will be active, and reversely when it can be asleep, is a key mechanism to allow for very low UE power consumption without penalizing the experienced throughput or *quality of service* (QoS). In this context we address specifically the power consumption of the RF modem and discard other consuming entities as the display and baseband/digital processing. Unfortunately there are many time-varying characteristics of the traffic source as well as the load in the network that impairs the ability to fully predict when a UE should be available for transmission or not. Some services are more suitable for prediction than others; e.g. *voice over IP* (VoIP) is an almost trivial case since the packets are received and transmitted with a very predictable pattern. In this paper, we address bursty packet data services and use the web-browsing traffic model from [1] for investigation.

We will base our studies on the evolving wireless system in 3GPP: The UTRAN *long-term evolution* (LTE). LTE introduces a very flexible *discontinuous reception* (DRX) framework for controlling the balance between QoS and power saving for each UE [2][3]. In this paper we start by introducing the LTE DRX concept as well as a simple representative model for the RF modem power consumption. After this we introduce different network algorithms for adapting the DRX parameters according to the available data for a UE, and we show how efficient power saving can be achieved with careful setting and adaptation of the parameters. We will consider connected mode optimization only, although the combined use of paging and connected mode DRX is another way to optimize performance. Finally, we generalize our conclusions.

II. LTE AND THE DRX CONCEPT

In LTE the scheduling of users in both uplink and downlink is tightly controlled by the network scheduling algorithms. A user reads a special shared *physical downlink control channel* (PDCCH) in the downlink sent every 1 ms to find out whether reources are allocated in either downlink or uplink. Specifically for downlink, if a first transmission fails, the UE will send a NACK in the uplink, and a retransmission will take place HARQ RTT ms later or when the UE gets priority by the scheduler.

A major design criterion for LTE is to provide effective power consumption performance for all attached equipment. In principle, if the network could predict when a certain user needs to be scheduled, a UE only needed to be awake at such specific time instances. Such a prediction is very complex due to the bursty nature of Internet traffic, use of advanced opportunistic scheduling, and multi-user QoS and prioritization considerations. However, in LTE a DRX framework has been devised to quickly adapt to change in conditions while facilitating robustness of the network. DRX is important for the performance of the LTE system since it basically defines when a UE listens to the PDCCH and, hence, when the network is able to schedule a user.

The main part of the LTE DRX framework is illustrated in Figure 1 and consists of the following parameters that are configured by the network and communicated by means of higher layer (RRC) signaling to each UE in the cell.

- *DRX cycle* denotes the time distance between which the UE is active (indicated by “highs” in transition diagram in Figure 1) and again active. The optimal periodicity of the

DRX cycle depends on QoS requirements; especially the maximum latency.

- *On-duration* denotes the time for which the UE shall stay awake whenever it comes out of DRX (e.g. each DRX cycle). The On-duration is part of the DRX cycle and allows for the network to define a window for reaching each UE so that multi-user priorities can be considered. A longer setting allows the network to benefit from channel quality measurements from the UE in the scheduling. The on-duration allows for the network to tightly share the time among DRX users and to effectively configure control channel resources (particularly uplink ones).
- *Inactivity timer* denotes the time after the last scheduling (DL or UL) that a UE shall remain awake. Hence, this parameter provides means for the network to keep a UE awake beyond the On-duration period when data is buffered. One disadvantage of using inactivity timers is that they trigger worst-case reservation of control channels (particularly in uplink) which makes that joint consideration of On-duration and the Inactivity timer should be considered.

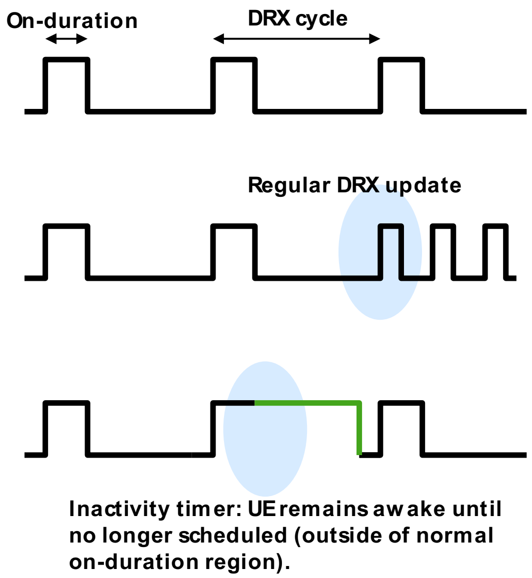

Fig. 1. Illustration of the LTE DRX framework.

The DRX settings can be set and/or updated for a certain UE by means of (RRC) signaling. Higher update rates cost control signaling overhead, but allows for faster adaptation to changing traffic conditions and thus optimized UE power consumption performance.

In practice any pending retransmissions are taken outside the DRX configured range. Hence, if some first transmissions are lost within the On-duration region, the UE will need to wake up for the first possible retransmission time and remain awake until it receives a retransmission (or until a timer, the DRX Retransmission timer, will time out).

It was mentioned that the configuration of the control channels is an important issue when setting the DRX parameters. A UE will not be given any dedicated uplink resources for *channel quality indication* (CQI) reporting when being asleep. In case of usage of not only the On-duration, but also the inactivity timer, it is non straightforward to estimate how often the UE can be given the limited number of uplink resources, since the time the different UEs keep awake depends on the actual scheduling instants. This can lead to longer delays of the CQI information, which degrades the system level performance.

In these studies, the impact of these specific effects are ignored thus assuming a very low mobility environment. Not used in this study either, but part of the 3GPP DRX specification, is the Short DRX and the DRX Short Cycle Timer which offers additional optimization possibilities.

III. The UE Power Consumption Model

We have modeled the UE power consumption with the simple model from [4] in which relative power consumption figures are used and compared to arbitrarily chosen maximum power consumption for UE in active downlink reception mode. Three different states of UE activity are selected: Active, Light sleep, and Deep sleep including applied fixed state transition times and power consumption during the state transitions as shown in Figure 2.

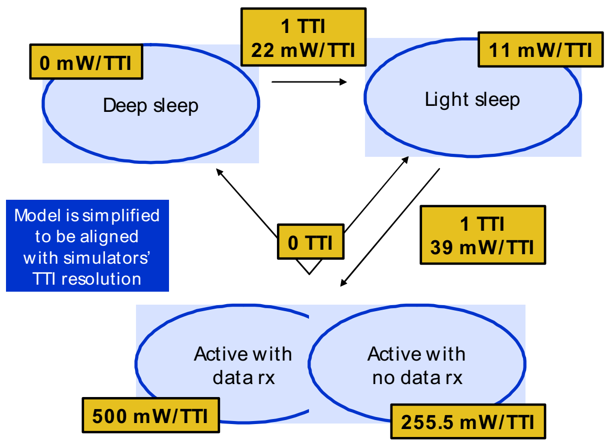

Fig. 2. State diagram for UE power consumption model [4].

In active mode we distinguish the cases when UE is being scheduled for receiving data (i.e. actively scheduled) or when the UE just receives and decodes the control channels without being scheduled. The value of 500 mW as absolute power consumption for UE in active reception mode is chosen as arbitrary value. State transitions are aligned with the simulator resolution for convenience.

We utilize this information together with collecting the knowledge about the length of time in TTIs the UE was in each state, to calculate an overall estimate of the UE power consumption by using the system model, traffic flows, and the different DRX algorithms described next.

IV. System Model

The system model and used simulation tool consider a single user model only with multi-user aspects indirectly considered. The UE's instantaneous radio performance in the downlink is extracted from detailed system level simulation tool and reflects the performance for a UE in 5-MHz bandwidth, two receive antennas with maximum ratio combining, 3 km/h velocity, and a ratio of average intracell to othercell interference and noise of 0 dB, i.e. the considered UE is located close to the cell edge. Outer loop link adaptation is employed to keep the average *block error rate* (BLEP) of the first transmission at 10%. The packet scheduler is assumed to use frequency domain scheduling with K denoting the number of users that simultaneously share the radio channel. The probability of a user being scheduled in a given subframe when being active and with data buffered for transmission is denoted by P_{ps} and is assumed uncorrelated among successive subframes. With these parameters, we are able to study two “extremes” from a DRX and system optimization perspective: One case where a DRX user is given maximum priority (K=1, P_{ps}=1) to optimize performance/power and a more balanced case where a DRX user is given same priority as the other users when in the active set (K, P_{ps} <1) for optimum system capacity. While modeling the multi-user aspects, we only specifically monitor the same user as defined above. Uplink control signaling is not considered. HARQ is modeled explicitly with retransmission being conducted after a delay of 8 subframes. The 2nd transmission is assumed to always be received correctly given a tight outer loop link adaptation target.

The DRX algorithms are described in the following section and determine when a UE is in a certain power state as described in the last section. For algorithms that rely on RRC signaling, an RRC signaling delay of 0 or 40 ms from transmission until hand-shake is received from UE side is assumed.

The traffic is modeled according to the web traffic model in [1]. The Internet round-trip time (RTT) is set to 20 ms assuming relatively fast access to the server. The traffic flow to a certain user is highly bursty as reading time has a wide distribution and each packet call often contains multiple packets. TCP slow-start is modeled with MSS equal to 1500 bytes and a receiver window of 64 kilobytes. The duration of each web session is set to at least 2 hours (depending on required statistics for simulation point).

V. DRX Algorithms

We have studied different approaches for having DRX implemented for the abovementioned web-browsing user. In general we have considered three different approaches:

1. *Static DRX:* In this configuration we keep the DRX parameters DRX cycle and on-duration static during the whole session time. The inactivity timer has been disabled. The advantage is that no RRC DRX update signaling is needed, but performance is sub-optimum as there is no adaptation according to the traffic flow and time-varying user conditions.
2. *Semi-Static DRX:* DRX cycle is kept constant, but we use an adaptation algorithm to optimize the on-duration parameter by investigating the buffer and radio channel dynamics on the fly. To keep the RRC signaling at bay we introduce a maximum RRC signaling rate in the system. The Inactivity timer is disabled. The algorithm is detailed below.
3. *Dynamic DRX:* In this setup we introduce the Inactivity timer and set on-duration to only a single TTI. We assume that there is CQI signaling in order to have same radio performance as for other methods which means worst-case reservation of PUCCH resources for the DRX user. No signaling is used, as in the *static DRX* method, to update the parameters, i.e. the inactivity timer and on-duration are kept constant during a session.

While methods (1) and (3) are straight forward implementations of the standard DRX concepts introduced earlier, method (2) introduces an adaptation algorithm as shown in Figure 3 (implements earlier discussed aspects).

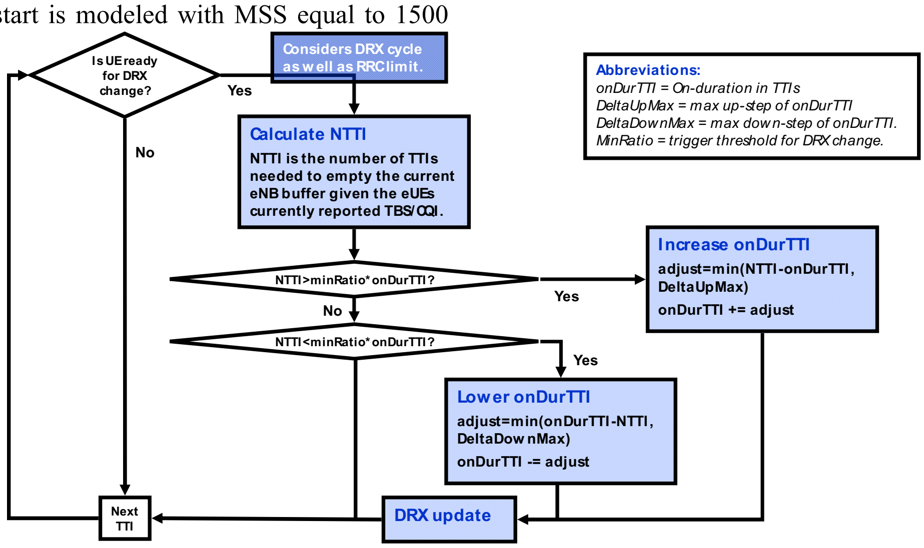

Fig. 3. Illustration of the Semi-Static DRX algorithm.

The algorithm adjusts the on-duration based on the time needed to empty the buffer (*NTTI*). If NTTI indicates that more than *minRatio* on-duration periods are needed to empty the buffer, the on-duration is increased. Otherwise the on-duration is decreased. The algorithm is run for a certain maximum rate in order to limit the RRC signaling and in order to avoid large changes it limits the maximum change to *deltaUpMax* and *deltaDownMax*. The values used in this study for these parameters are 20 and 10 TTIs, while *minRatio* is set at 2.

VI. RESULTS AND DISCUSSION

We first show results for *Static DRX* in Figure 4, where the average HTTP packet call throughput for a user at the cell border in a 5 MHz bandwidth versus power consumption is shown for the case of a 1 TTI on-duration and different DRX cycles. The different points in the figure correspond to different DRX cycles. Also the case with optimal but fixed On-duration and different DRX cycles is shown. It can be seen that use of on-duration allows for about 10% throughput increase for the same power consumption over a 1 TTI on-duration. Note that in the optimal on-duration over a 1 hour WWW session is difficult to pre-set in a real network since it requires a priori knowledge of the traffic pattern.

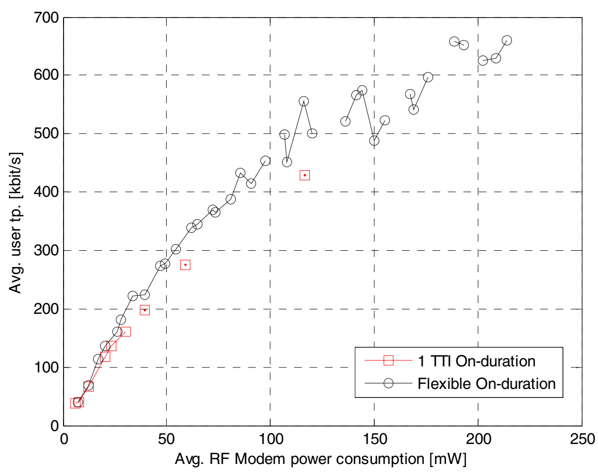

Fig. 4. Average user session throughput vs. average power consumption for static DRX with 1 TTI on-duration and optimal on-duration for optimal DRX cycle.

To have more realistic adaptation to traffic patterns without a priori knowledge, we consider next the *Semi Static DRX* scheme. This is shown in Figure 5 where the user throughput vs. power consumption is plotted for different maximum signaling rates. It is seen that the user throughput is nearly doubled compared to *Static DRX* for the same power consumption level (e.g. 50 mW). For lower maximum signaling rates the improvements are lower, but still significant. Note that no delay of applying the new settings is considered.

The effect of having this delay is shown in Figure 6, where 40 ms is used as delay value. It can be seen that the delay only has an effect for very high signaling rates, i.e. for 10 Hz. The results for the other update rates do not change significantly. The reason for this is that 40 ms is very short compared to 1 or 10 s. Even with the delay included, the semi static DRX results still outperform those of static DRX.

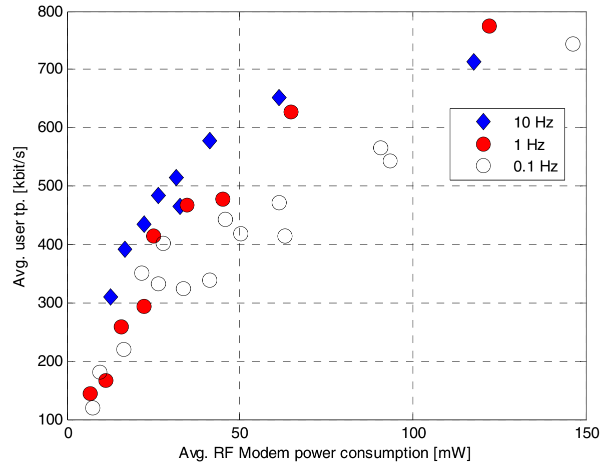

Fig. 5. Average user session throughput vs. average model power consumption for DRX with optimal DRX period and different maximum RRC reconfiguration rates (0 ms delay).

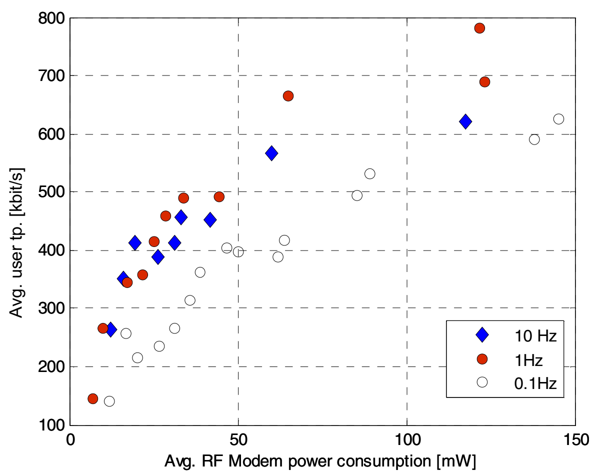

Fig. 6. Average user session throughput vs. average model power consumption for DRX with optimal DRX period and different maximum RRC reconfiguration rates (40 ms delay).

In Figure 7 we show the user throughput versus power consumption for the case where the on-duration equals 1 TTI and the inactivity timer is used. The different points in the figure represent different inactivity timers (from 1 to 50 ms). It can be seen that the use of the inactivity timer easily outperforms the semi static DRX with more than 30% gain at 10 mW. The inactivity based scheme has the extra advantage that no extra overhead is caused by RRC signaling.

Figure 8 shows the average user throughput and average power consumption as function of the inactivity timer. In this case where the DRX user has highest scheduling priority, the throughput per power consumption ratio is best for lowest setting of the inactivity timer.

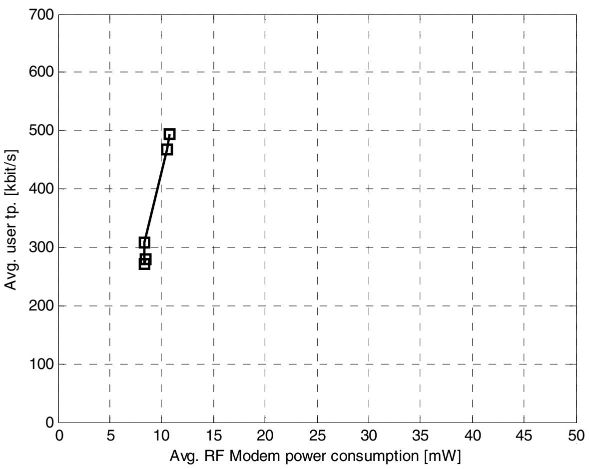

Fig. 7. Average user session throughput vs. average model power consumption for DRX with inactivity timer.

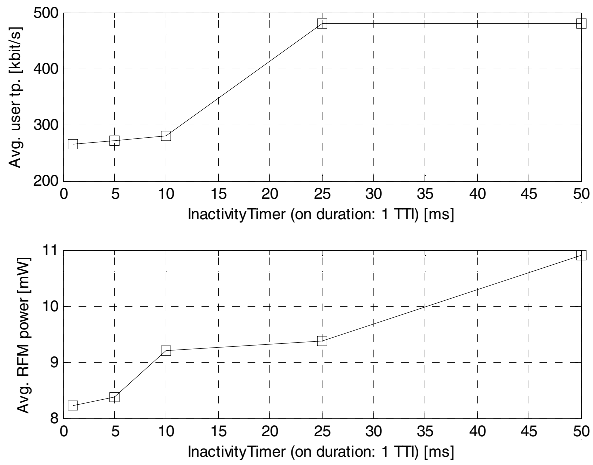

Fig. 8. Average user throughput and power usage as function of the inactivity timer with 1 user in the system.

Figure 9 shows the average user throughput and average power consumption for a user at the cell border in the case of K=10 and P_{ps}=0.5. Hence, the user has limited scheduling priority. As can be seen the user throughput is lower compared to having one user in the system, while both user throughput and power consumption are rather insensitive to the setting of the inactivity timer. The power consumption is much higher than with just one user, since users are active longer. This indicates that from a single-user power consumption perspective it is important to give high priority to DRX users or to use efficient time-multiplexing in the system of such users.

VII. CONCLUSIONS

In this paper we have illustrated the power of having a flexible and efficient DRX frame-work. In the LTE system we can achieve near optimum performance (e.g. 90%) at a small fraction (e.g. 5-10%) of UE power consumption if optimizing the scheduler for DRX users and setting DRX parameters correctly.

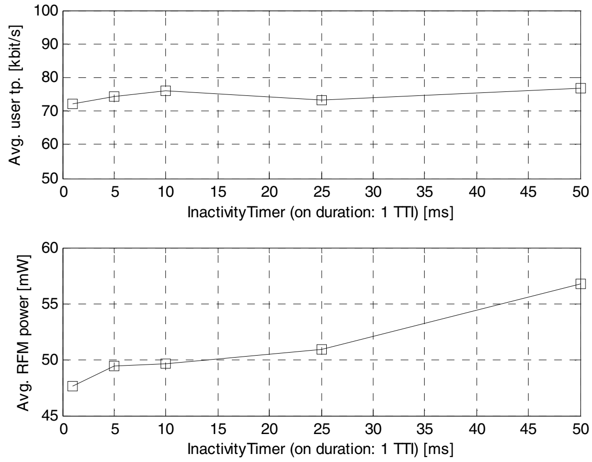

Fig. 9. Average user throughput and power usage vs. the inactivity timer with 10 users and 50% scheduling probability.

We have shown the importance of adapting DRX parameters in order to track the dynamic traffic characteristics for best QoS at UE side. We have shown two practical schemes based on adaptation either through slowly changing the DRX parameters (using RRC signaling) or using the Inactivity timer for more aggressive DRX user handling. Both ways have their pros and cons seen from a network perspective considering control channel aspects etc. Best scheme for saving power is using the Inactivity timer, which provides a significant gain over semi static DRX. However, even with the semi-static scheme we achieve 30-40% gain for same power consumption compared to a statically configured DRX user. When multiple users are considered in a simple model we find that the system is rather insensitive to the setting of the inactivity timer. Hence, proper prioritization of DRX users is more important to provide the maximum benefit from the DRX feature. Note that the model assumed in this paper only considers the power consumption related to the RF modem. An alternative to putting users to sleep during reading times is to move users to IDLE mode. Including this is for further study as well as further optimization of the DRX settings, considering control channels, short DRX, CQI reporting, etc.

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