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Analytic Analysis of LTE/LTE-Advanced Power Saving and Delay with Bursty Traffic

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Abstract

The 4G standard Long Term Evolution (LTE) has been developed for high-bandwidth mobile access for today’s data-heavy applications. However, these data-heavy applications require lots of battery power on the user equipment. To extend the user equipment battery lifetime, plus further support various services and large amount of data transmissions, the 3GPP standards for LTE/LTE-Advanced has adopted discontinuous reception (DRX). In this paper, we take an overview of various static/fixed DRX cycles of the LTE/LTE-Advanced power saving mechanisms, by modelling the system with bursty packet data traffic using a semi-Markov process. Based on the analytical model, we will show the trade-off relationship between the power saving and wake-up delay performance. This work will help to select the best parameters when LTE/LTE-Advanced DRX is implemented depending on the protocols and desired outcome of the traffic.

I. INTRODUCTION

The advancement of mobile technologies has profoundly affected our lives. It is a rapidly growing trend that more users are becoming dependent on the mobile tools as their primary computing devices and replacing the traditional stationary hardware. We see a variety of powerful smart mobile devices (e.g. iPhone, iPad, Tablets) handling a wide range of traffic including multimedia. Thus, a 4G (fourth generation) standard, LTE/LTE-Advanced (henceforth referred to as LTE) has been developed that is intended for larger capacity and higher speed of mobile networks. Even though mobile hardware keeps evolving, they will always be resource-poor relative to stationary hardware. The reason is that, first, battery technologies for mobile devices only allow limited computing power on a portable-lightweight package, and second, the processing power and the memory of mobile hardware are much smaller than those of traditional desktops and laptops. This presents a challenge for a mobile device to execute resource-hungry user applications.

To extend the user equipment battery lifetime, plus further support various services and large amount of data transmissions, the 3GPP standards for LTE has adopted DRX and Discontinuous Transmission (DTX) power-saving mechanisms protocols, thereby providing energy-efficient-Green Network. The theoretical basis of traditional scheduling mechanisms becomes invalid when DRX is adopted. To address this problem there is a need to optimize the DRX parameters, so as to maximize power saving without incurring network re-entry and packet delays. In particular, care should be exercised for real-time services.

In this paper, we take an overview of the fixed/static DRX cycles with a semi-Markov process in order to evaluate the power saving and wake-up delay performance of LTE DRX mechanisms. The results show that there is a trade-off relationship between the power saving and wake-up delay performance for various fixed/static DRX parameters. This work will help to select the best parameters when LTE DRX is implemented.

II. LTE AND THE DRX CONCEPT

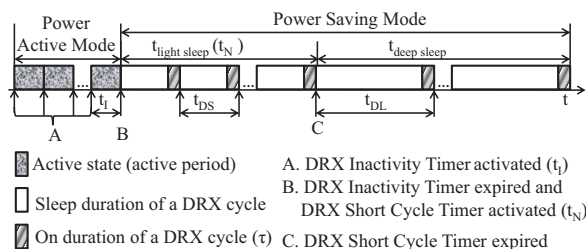


Fig. 1: LTE DRX timing for UE receiver operations.

LTE’s energy efficient strategy exploits the concepts of DRX and DTX [2], [4]. In the LTE DRX mechanism, the sleep/wake scheduling of each User Equipment (UE) is determined by the following four parameters [10]¹DRX Short Cycle (t_{DS}), DRX

¹previous work focused on a 3-state adjustable cycles, while this work focuses on 4-state fixed cycles

Long Cycle (t_{DL}), DRX Inactivity Timer (t_I) and DRX Short Cycle Timer (t_N) as shown in Figure 1. The t_{DS} and t_{DL} define duration of OFF and ON period, which is a fixed/static value applied to both long and short cycles. UE monitors the physical downlink control channel (PDCCH) to determine if there is any transmission over the shared data channel allocated to the UE during ON duration. The t_I specify the period where UE should stay awake and monitor PDCCH after the last successful decoding of PDCCH. The t_N specifies the period where UE should follow t_{DS} after the t_I has expired.

In LTE DRX, the sleep/wake-up mode consists of the three different states, namely, Inactivity period, Light Sleep period, and Deep Sleep period. The Inactivity period is the power active mode, whereas the Light Sleep period and the Deep Sleep period are the power saving mode. The transition from the Inactivity period to the Light Sleep period is controlled by t_I , while the transition from the Light Sleep period to the Deep Sleep period within the power saving mode is controlled by t_N .

The following describes how the UE works during the Inactivity, Light Sleep, and Deep Sleep periods [1].

DRX Inactivity period: Is when the DRX Inactivity Timer² is ON, and the UE receiver is monitoring the PDCCH, while being ready to receive packets through the evolved node-B (eNB) from Evolved Packet Core (EPC). Should the DRX Inactivity Timer expire, then the DRX Short Cycle Timer is activated and the Light Sleep period begins.

DRX Light Sleep period: Consists of the DRX Short Cycles (t_{DS}). During each of the DRX Short Cycle the UE wakes up to monitor the PDCCH (also know as Listen Interval). If the PDCCH indicates a downlink transmission, the UE changes to an activity period and starts the t_I . Otherwise the UE will return to Light Sleep period. The UE will keep entering Light Sleep period until the DRX Short Cycle Timer³ expires.

DRX Deep Sleep period: During each of the DRX Deep Long Cycle the UE wakes up to monitor the PDCCH. If the PDCCH indicates a downlink transmission, the UE changes from Deep Sleep period to activity period and starts the DRX Inactivity Timer. Otherwise, the UE will return to Deep Sleep.

III. AN ANALYTICAL MODEL FOR LTE POWER SAVING

A. Bursty Packet Traffic Model

Studies have shown that for some environments, the traffic data are self-similar [12] rather than the traditional queuing that is contingent on the data traffic to be Poisson as mentioned in [10]. In the traditional Poisson Traffic model, it usually has a very limited range of time scales and making it short range dependent. Self-similar traffic displays burstiness and interacts over an immensely wide range of time scales and making it long range dependent. In addition, it has been shown that heavy tailed such as Pareto and Weibull distributions are more applicable when modelling data network traffic [7]. For this paper, we used the European Telecommunication Standards Institute (ETSI) traffic model [3], where the packets size and the packet transmission timer are assumed to follow the truncated Pareto distribution. The ETSI model is a widely used in various analytical and simulation studies of 3GPP networks, such as [5], [8], [11], [15], [16]. [7] shows that the $M/G/\infty$ model with infinite-variance Pareto distributions can be used to generate self-similar traffic.

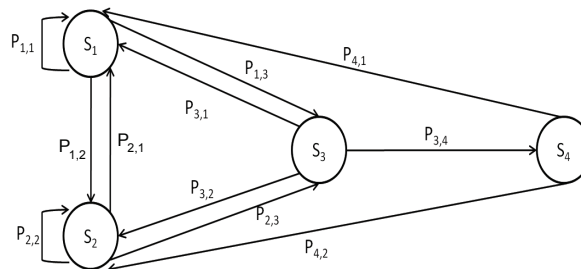


Fig. 2: 4-State semi-Markov process for LTE DRX.

The LTE DRX mechanism is a semi-Markov process [9] and is illustrated in Figure 2. The state transition diagram consists of four states⁴, which are relevant to the three periods shown in Figure 1.

- State S_1 comprise a busy/active period t_B^* (*Power Active Mode*) and inter-packet call inactivity period t_{I1}^* .
- State S_2 comprise a busy/active period t_B^* (*Power Active Mode*) and inter-session inactivity period t_{I2}^* .
- State S_3 comprises a *Light Sleep period* ($t_{light\ sleep}$) which is entered from S_1 or S_2 .
- State S_4 comprises a *Deep Sleep period* ($t_{deep\ sleep}$) which is entered from S_3 .

²Inactivity Timer: Specifies the number of consecutive TTIs during which UE shall monitor PDCCH after successfully decoding a PDCCH indicating a UL or DL data transfer for this UE.

³DRX Short Cycle Timer (t_N): Indicates the number of initial DRX cycles to follow the short DRX cycle before transitioning to the long DRX cycle.

⁴Even combining S_1 and S_2 , we had the same results. However, by separating the “Powering Active Mode” (S_1 and S_2), it will provide future research on the behaviour of energy saving when t_I is small.

A new packet call can be viewed as continuation of the current session or as the onset of a new session depending on the time interval-arrive between two consecutive packet calls. The packet calls may be the inter-packet call idle time (t_{ipc}) with probability $1 - 1/\mu_{pc}$ or the inter-session idle time (t_{is}) with probability $1/\mu_{pc}$. The probabilities take into account the memoryless property of a geometric distributions. If we view this semi-Markov process only at the times of state transitions, we obtain an embedded Markov chain with state transition probabilities $P_{i,j}$, where $i, j \in \{1, 2, 3, 4\}$.

B. State 1 to State 1, State 1 to State 2 and State 1 to State 3

In state S_1 , the RNC inactivity timer is activated at the end of the busy period t_B^* , and then the UE enters the DRX Inactivity period t_{I1} . When the first packet of the next call arrives at the RNC before the DRX Inactivity timer expires, with a probability of $q_1 = \Pr[t_{ipc} < t_I] = 1 - e^{-\lambda_{ipc} t_I}$, the timer is stopped, and another busy period begins. In this case, if the new arriving packet call is the last one of the ongoing session (with probability $1/\mu_{pc}$), then the UE enters state S_2 , otherwise with the probability $1 - 1/\mu_{pc}$ the ongoing session continues, and the UE enters state S_1 again. This gives us:

$$p_{1,1} = (1 - e^{-\lambda_{ipc} t_I}) \left(1 - \frac{1}{\mu_{pc}}\right) = q_1(1 - q_2) \quad (1)$$

$$p_{1,2} = (1 - e^{-\lambda_{ipc} t_I}) \left(\frac{1}{\mu_{pc}}\right) = q_1 q_2 \quad (2)$$

If no packets arrives before the inactivity timer expires, then the UE enter into light sleep:

$$p_{1,3} = (e^{-\lambda_{ipc} t_I}) = 1 - q_1 \quad (3)$$

C. State 2 to State 1, State 2 to State 2 and State 2 to State 3

The derivations of $p_{2,1}$ and $p_{2,2}$ are exactly the same as that of $p_{1,1}$ and $p_{1,2}$ except that the inter-packet call idle period t_{ipc} is replaced by the inter-session idle period t_{is} and q_1 is replaced by $q_3 = \Pr[t_{is} < t_I] = 1 - e^{-\lambda_{is} t_I}$. Therefore, we have:

$$p_{2,1} = (1 - e^{-\lambda_{is} t_I}) \left(1 - \frac{1}{\mu_{pc}}\right) = q_3(1 - q_2) \quad (4)$$

$$p_{2,2} = (1 - e^{-\lambda_{is} t_I}) \left(\frac{1}{\mu_{pc}}\right) = q_2 q_3 \quad (5)$$

Similarly, $p_{2,3}$ can be derived by substituting q_3 for q_1 in Equation (3), we have:

$$p_{2,3} = (e^{-\lambda_{is} t_I}) = 1 - q_3 \quad (6)$$

D. State 3 to State 1, State 3 to State 2 and State 3 to State 4

In state S_3 , the UE follows DRX Short Cycles with the probability that there is at least one initiation of awakening during Inter-packet call is $1 - e^{-\lambda_{ipc} t_N}$. If the PDCCH indicates that a new packet call starts before the DRX Short Cycle Timer expires (means new packet call occurs before t_N has expired), the timer is cancelled. If the next packet call terminates the ongoing session (with probability q_2), then the UE will move to S_2 in the next transition. Otherwise (with probability $1 - q_2$), the UE will change to S_1 . Thus

$$p_{3,1} = (1 - e^{-\lambda_{ipc} t_N}) \left(1 - \frac{1}{\mu_{pc}}\right) = q_4(1 - q_2) \quad (7)$$

$$p_{3,2} = (1 - e^{-\lambda_{ipc} t_N}) \left(\frac{1}{\mu_{pc}}\right) = q_2 q_5 \quad (8)$$

If the PDCCH indicates that there is no packet call delivery happening after the DRX Short Cycle Timer expires (meaning no new packet during the DRX Short Cycle times t_N), then S_4 is entered:

$$\begin{aligned} p_{3,4} &= (e^{-\lambda_{ipc} t_N}) \left(1 - \frac{1}{\mu_{pc}}\right) + (e^{-\lambda_{is} t_N}) \left(\frac{1}{\mu_{pc}}\right) \\ &= (1 - q_2)(1 - q_4) + q_2(1 - q_5) \end{aligned} \quad (9)$$

E. State 4 to State 1 and State 4 to State 2

In state S_4 , if the next packet call terminates the ongoing session (with probability q_2), then the UE will move to S_2 in the next state transition. Otherwise, (with probability $1 - q_2$), the UE will switch to state S_1 . This gives us:

$$p_{4,1} = \left(1 - \frac{1}{\mu_{pc}}\right) = 1 - q_2 \quad (10)$$

$$p_{4,2} = \left(\frac{1}{\mu_{pc}}\right) = q_2 \quad (11)$$

F. Transition Probability Matrix

The transition probability matrix $\mathbf{P} = (P_{i,j})$ of the embedded Markov chain can, hence, be given as (12):

$$\mathbf{P} = \begin{bmatrix} P_{1,1} & P_{1,2} & P_{1,3} & 0 \\ P_{2,1} & P_{2,2} & P_{2,3} & 0 \\ P_{3,1} & P_{3,2} & 0 & P_{3,4} \\ P_{4,1} & P_{4,2} & 0 & 0 \end{bmatrix} \quad (12)$$

Let $\pi_i (i \in \{1, 2, 3, 4\})$ denote the probability that the embedded Markov chain is in state $S_i (i \in \{1, 2, 3, 4\})$. By using $\sum_{j=1}^4 \pi_j = 1$ and the balance equation $\pi_i = \sum_{j=1}^4 \pi_j P_{j,i}$, we can solve the stationary distribution and obtain (13)

$$\Pi = \begin{cases} \pi_1 = \frac{(1-q_2)(1+q_2(1-q_3)(q_4-q_5))}{1+(1-q_2)(1-q_1)(2-q_4)+q_2(2-q_5)(1-q_3)} \\ \pi_2 = \frac{q_2(1-(1-q_1)(1-q_2)(q_4-q_5))}{1+(1-q_2)(1-q_1)(2-q_4)+q_2(2-q_5)(1-q_3)} \\ \pi_3 = \frac{(1-q_1)(1-q_2)+q_2(1-q_3)}{1+(1-q_2)(1-q_1)(2-q_4)+q_2(2-q_5)(1-q_3)} \\ \pi_4 = \frac{((1-q_1)(1-q_2)+q_2(1-q_3))((1-q_4)(1-q_2)+q_2(1-q_5))}{1+(1-q_2)(1-q_1)(2-q_4)+q_2(2-q_5)(1-q_3)} \end{cases} \quad (13)$$

Let $H_i (i \in \{1, 2, 3, 4\})$ be the holding time of semi-Markov process at state S_i . Now we proceed to derive $E[H_i]$:

$$E[H_1] = E[t_B^*] + E[t_{I1}^*] \quad (14)$$

From Wald's theorem [6]

$$E[t_B^*] = E[N_p] E\left[\frac{1}{\lambda_{ip}}\right] = \frac{\mu_p}{\lambda_x} \quad (15)$$

$t_{I1}^* = \min(t_{ipc}, t_I)$. If a packet arrives before the inactivity expire $t_{ipc} < t_I$, this means $t_{I1}^* = t_{ipc}$, otherwise $t_{I1}^* = t_I$ (next packet arrives after the inactivity has expired, $t_{ipc} \geq t_I$). Therefore,

$$E[t_{I1}^*] = P_{pc} E[\min(t_{ipc}, t_I)] \quad (16)$$

We have

$$\begin{aligned} E[\min(t_{ipc}, t_I)] &= \int_{x=0}^{\infty} Pr[\min(t_{ipc}, t_I) > x] dx \\ &= \int_{x=0}^{t_I} e^{-\lambda_{ipc}x} dx = \frac{1}{\lambda_{ipc}} [e^{-\lambda_{ipc}t_I}] \end{aligned} \quad (17)$$

Substitute (15) and (17) into (14)

$$E[H_1] = \frac{\mu_p}{\lambda_{ip}} + \frac{P_{pc}}{\lambda_{ipc}} [1 - e^{-\lambda_{ipc}t_I}] \quad (18)$$

$E[H_2]$. S_2 contains a busy period t_B^* and an intersession inactivity period t_{I2}^* . Therefore,

$$E[H_2] = E[t_B^*] + E[t_{I2}^*] \quad (19)$$

Similar to the derivation of $E[t_{I1}^*]$, $E[t_{I2}^*]$ is

$$\begin{aligned} E[\min(t_{is}, t_I)] &= \int_{x=0}^{\infty} Pr[\min(t_{is}, t_I) > x] dx \\ &= \int_{x=0}^{t_I} Pr[t_{is} > x] dx \\ &= \int_{x=0}^{t_I} e^{-\lambda_{is}x} dx = \frac{1}{\lambda_{is}} [e^{-\lambda_{is}t_I}] \end{aligned} \quad (20)$$

Substitute (15) and (20) into (19)

$$E[H_2] = \frac{\mu_p}{\lambda_{ip}} + \frac{P_s}{\lambda_{is}} [1 - e^{-\lambda_{is}t_I}] \quad (21)$$

IV. SLEEP STATES H_3 AND H_4

State S_3 comprises a Light Sleep period consisting of N_{DS} DRX Short Cycles. We denote N_{DS} as the total length of t_N expressed in terms of the number of DRX Short Cycles. In this case the DRX Short Cycle Timer has expired and the UE enters into state S_4 . The probability that a new packet call begins before t_N expires results in N_{DS}^* , meaning $N_{DS}^* < N_{DS}$. Therefore, the mean holding time in state S_3 is:

$$\begin{aligned} E[H_3] &= E[N_{DS}]t_{DS} \\ &= \left(P_{34}N_{DS} + P_{31}E[N_{DS}^{ipc}] + P_{32}E[N_{DS}^{is}] \right) t_{DS} \end{aligned} \quad (22)$$

Due to the memoryless property of the exponential t_{ipc} and t_{is} , N_{DS}^* has a geometric distribution with mean $1/P_{DS}$, where P_{DS} is the probability that packets arrive during a DRX cycle and is derived as follows:

$$E[N_{DS}^{ipc}] = \frac{P_{pc}}{Pr[t_{ipc} \leq t_{DS}]} = \frac{P_{pc}}{1 - e^{-\lambda_{ipc}t_{DS}}} \quad (23)$$

$$E[N_{DS}^{is}] = \frac{P_s}{Pr[t_{is} \leq t_{DS}]} = \frac{P_s}{1 - e^{-\lambda_{is}t_{DS}}} \quad (24)$$

Then we substitute equations (9), (7), (8), (23) and (24) into (22):

$$\begin{aligned} E[H_3] &= \left[(1 - q_2)(1 - q_4) + q_2(1 - q_5) \right] N t_{DS} \\ &\quad + \left(\frac{q_4(1 - q_2)P_{pc}}{1 - e^{-\lambda_{ipc}t_{DS}}} + \frac{q_2q_5P_s}{1 - e^{-\lambda_{is}t_{DS}}} \right) t_{DS} \end{aligned} \quad (25)$$

State S_4 contains of Deep Sleep period consisting of State n_{DL} Long DRX Cycles. Therefore $E[H_4] = E[n_{DL}]t_{DL}$:

$$E[H_4] = \left(\frac{P_{pc}}{1 - e^{-\lambda_{ipc}t_{DL}}} + \frac{P_s}{1 - e^{-\lambda_{is}t_{DL}}} \right) t_{DL} \quad (26)$$

V. POWER SAVING FACTOR (PS)

The power saving factor (PS) is equal to the probability that the semi-Markov process is at S_3 and S_4 in the steady state. Note that each DRX Short Cycle and each DRX Long Cycle contains a fixed On Duration τ so that it can listen to the paging information from the network. Therefore, the effective sleep duration is $t'_{DS} = t_{DS} - \tau$ or $t'_{DL} = t_{DL} - \tau$. Hence, the effective sleep time in both states S_3 and S_4 are derived as the following:

$$\begin{aligned} E[H'_3] &= \left(P_{34}N + P_{31}E[N_{DS}^{ipc}] + P_{32}E[N_{DS}^{is}] \right) t'_{DS} \\ &= \left[(1 - q_2)(1 - q_4) + q_2(1 - q_5) \right] N t'_{DS} \\ &\quad + \left(\frac{q_4(1 - q_2)P_{pc}}{1 - e^{-\lambda_{ipc}t_{DS}}} + \frac{q_2q_5P_s}{1 - e^{-\lambda_{is}t_{DS}}} \right) t'_{DS} \end{aligned} \quad (27)$$

$$E[H'_4] = \left(\frac{P_{pc}}{1 - e^{-\lambda_{ipc}t_{DL}}} + \frac{P_s}{1 - e^{-\lambda_{is}t_{DL}}} \right) t'_{DL} \quad (28)$$

From Theorem 4.8.3 [9], we obtain $PS = \lim_{t \rightarrow \infty} Pr[\text{UE receiver is turned off at time } t]$ for PS to be obtain by:

$$PS = \frac{\pi_3 E[H'_3] + \pi_4 E[H'_4]}{\sum_{i=1}^4 \pi_i E[H_i]} \quad (29)$$

Substituting Equations (13), (18), (22), (25), (26), (27) and (28) into Equation (29), we derive the closed-form equation for the power saving factor PS.

Next, we analyze the wake-up delay from the DRX. Whether we are in Deep Sleep or Light Sleep, a packet call transmission may begin in one of the sleep states. The probability that a packet call delivery starts during the i^{th} DRX Cycle is in a fixed DRX Cycles:

$$p_i = \begin{cases} \underbrace{P_{pc} e^{-\lambda_{ipc}t_{ipc}} e^{-\lambda_{ipc}(i-1)t_{DS}} (1 - e^{-\lambda_{ipc}t_{DS}})}_{1 \leq i \leq N_{DS}} \\ \underbrace{P_{pc} e^{-\lambda_{ipc}[t_{ipc} + t_N + (i - N_{DS} - 1)t_{DL}]} (1 - e^{-\lambda_{ipc}t_{DL}})}_{i \geq N_{DS}} \end{cases} \quad (30)$$

$$q_i = \begin{cases} P_s e^{-\lambda_{is} t_{I_{is}}} e^{-\lambda_{is} (i-1) t_{DS}} (1 - e^{-\lambda_{is} t_{DS}}) & 1 \leq i \leq N_{DS} \\ P_s e^{-\lambda_{is} [t_{I_{is}} + N_{DS} t_{DS} + (i - N_{DS} - 1) t_{DL}]} (1 - e^{-\lambda_{is} t_{DL}}) & i \geq N_{DS} \end{cases} \quad (31)$$

The packet call arrivals follow a Poisson distribution since the inter-packet call idle time and inter-session idle timer are random exponential distributed variables. Also, the arrival event are random observers to the sleep durations [13], [14], [17]. Therefore we have:

$$E[D] = \sum_{i=1}^{N_{DS}} p_i \frac{t_{DS}}{2} + \sum_{i=N+1}^{\infty} p_i \frac{t_{DL}}{2} + \sum_{i=1}^{N_{DS}} q_i \frac{t_{DS}}{2} + \sum_{i=N+1}^{\infty} q_i \frac{t_{DL}}{2} \quad (32)$$

Substituting Equation (30) into Equation (32), we derive the closed-form equation for the mean of wake-up delay $E[D]$.

VI. NUMERICAL RESULTS

The values of the parameters of the bursty packet data traffic model for the analytical model are as follows: $\lambda_{ip}=10$, $\lambda_{ipc}=1/30$, $\lambda_{is}=1/2000$, $\mu_{pc}=5$, and $\mu_p=25$. We first analyse the effects of DRX parameters on DRX performance on the DRX Inactivity Timer T_I in Figure 3. As T_I increases, it is more likely that the next packet call starts before its expiration, which means lower transition probability for entering light or deep sleep state, respectively. Therefore, we observe a decrease in PS and D if T_I increases. When T_N increases, both PS and D decrease as well (Figure 4). It is more likely that the subsequent packet call deliveries happen before DRX Short Cycle Timer expires, and UE has less chance to enter the deep sleep period, so power saving performance becomes worse and wake-up delay performance gets better. Here we see the trade-off relationship between power saving factor and wake-up delay.

Next we will look at Figures 5 - 6, by focusing on the effects of the DRX Short Cycle T_{DS} and the DRX Long Cycle T_{DL} . The power saving and delay shown in both Figures are increasing for both T_{DS} and T_{DL} , which is due to the Sleep Cycles are longer and the ‘‘On Duration is fixed’’. The longer DRX Cycles translate into more effective sleep time per cycle, resulting in better power saving and a decrease in performance of the wake-up delay power saving.

From the Figures 3 - 6 there is a trade-off relationship between power saving factor and wake-up delay performance. When power saving performance is improved, wake-up delay performance will become worse. Therefore, DRX parameters should be selected carefully according to the tradeoff power saving factor and wake-up delay performance.

VII. CONCLUSION

In this paper, we have taken an overview of LTE DRX mechanism with fixed/static DRX cycles and model it with bursty packet data traffic using a semi-Markov process. The analytical results show that LTE DRX will perform differently when adjusting the four DRX parameters. To verify the performance, four DRX parameters on output performance through the

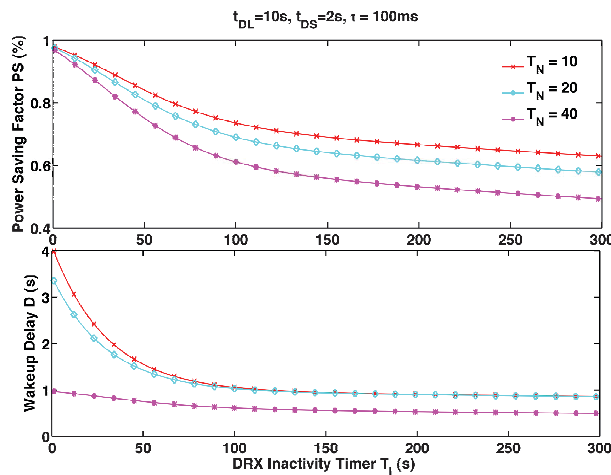


Fig. 3: (Top) LTE DRX Inactivity Timer on T_I for Power. (Bottom) LTE DRX Inactivity Timer on T_I for Delay.

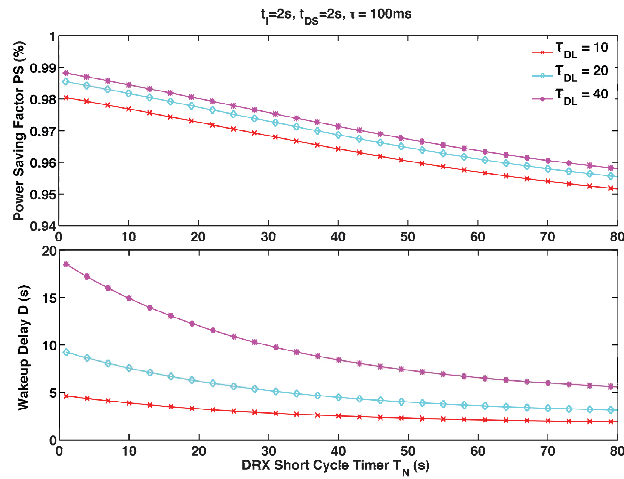


Fig. 4: (Top) LTE DRX Short Cycles on T_N for Power. (Bottom) LTE DRX Short Cycles on T_N for Delay.

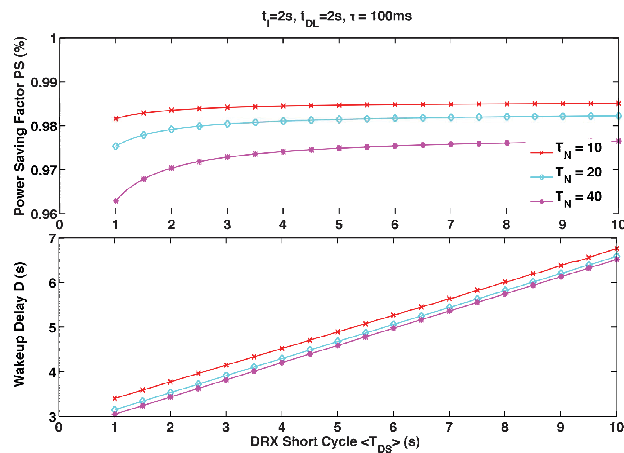


Fig. 5: (Top) LTE DRX Short Cycles on T_{DS} for Power. (Bottom) LTE DRX Short Cycles on T_{DS} for Delay.

analytical model in addition to a trade-off relationship between the power saving and wake-up delay performance was investigated. This work will help to select the best parameters when LTE DRX is implemented to achieve an efficient battery usage at a acceptable level of wake-up delay.

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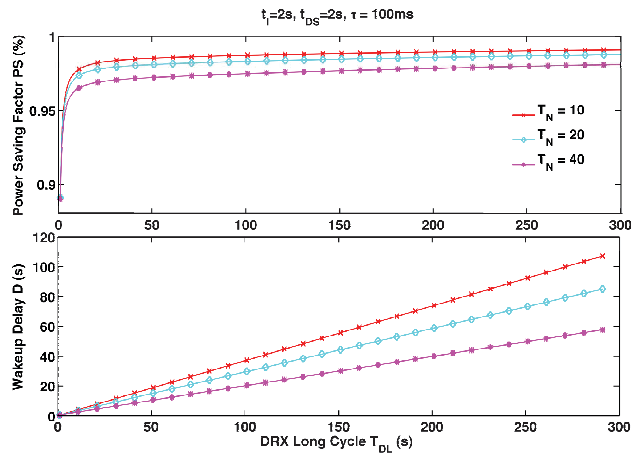


Fig. 6: (Top) LTE DRX Long Cycles on T_{DL} for Power. (Bottom) LTE DRX Short Cycles on T_{DL} for Delay.

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