Analysis of Adjustable and Fixed DRX Mechanism for Power Saving in LTE/LTE-Advanced

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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, consequently, a better experience for the end user. 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). However, there is a need to optimize the DRX parameters, so as to maximize power saving without incurring network re-entry and packet delays. In this paper, we take an overview of the fixed frame DRX cycle and compare it against an adjustable DRX cycle of the LTE/LTE-Advanced power saving mechanism, 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.**

***Index Terms*—Broad band networks, quality of service, WDM.**

I. Introduction

Today, we are starting to see a variety of powerful smart mobile devises (e.g. iPhone, iPad, Android) handling a wide range of traffic including multimedia. However, the current 3G (third generation) wireless cellular technology has been unsuccessful in delivering multimedia with an acceptable level of quality due to the low transmission rate and high service costs. Thus, a 4G (fourth generation) standard, LTE/LTE-Advanced has been developed that is intended for larger capacity and higher speed of mobile networks.

While 4G LTE/LTE-Advanced increases data rates by a factor of 50 over 3G networks, the battery, the power source of mobile devices, have not seen any sizeable advancement and still possess the same energy density characteristics. Thus substantial improvements in energy-efficient operation mechanisms are necessary for accommodating these very high data rates in 4G LTE/LTE-Advanced (henceforth referred to as LTE) [5].

Through monitoring the activities of the User Equipment (UE), Discontinuous Reception (DRX) is able to lengthen the battery life. The objective of such mechanisms is to turn off the radio signal (or sleep) for the maximum length of time, while staying connected to the network, thus reducing energy consumption when there is no data transmission. Hence, the receiver should be operated discontinuously for downlink (DL) services. In fact, DRX is not a novel idea in LTE [2] since it has been applied in the 2^{nd} generation system, e.g. the Global System for Mobile Communications (GSM). In [7] models the LTE DRX and proves that the LTE DRX achieves a more power saving gain over Universal Mobile Telecommunications System (UMTS) DRX [1] at the cost of prolonged wake up delay (The same can be said about GSM).

The main difference between LTE and previous DRX is whether the UE is allowed to enter a sleep state when the traffic buffer is not empty. The change of states in LTE DRX relies heavily on scheduling since it will lengthen the active time of an UE by restarting the Inactivity Timer. Meanwhile, due to the sleep duration, the scheduling in LTE DRX is affected by the DRX accordingly. The theoretical basis of traditional scheduling mechanisms becomes invalid when DRX is adopted. The present LTE DRX is based on static sleep mode, consequently performance degradation is inevitable. 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 investigate the use of adjustable and non-adjustable DRX cycle frame duration in LTE.

II. LTE and the DRX Concept

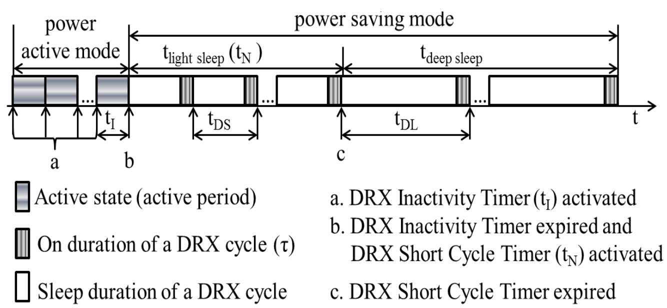

Figure 1: *LTE DRX timing for UE receiver operations.*

It is particularly important for mobile communications to have efficient power saving mechanisms as the energy source for wireless devises is limited. Therefore, LTEs proposed method for energy efficient operation is to utilize sleep (OFF)/wake (ON) scheduling.

LTEs energy efficient strategy exploits the concepts of DRX and Discontinuous Transmission (DTX) [3]. By using DRX/DTX, the terminal can turn the radio frequency modem into sleep mode for prolonged period either in RRC_IDLE or RRC_CONNECTED state.

In the LTE DRX mechanism, the sleep/wake scheduling of each UE is determined by the following four parameters [3]: DRX Short Cycle (t_{DS}), DRX 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 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 receiver works during the Inactivity period, Light Sleep period, and Deep Sleep period [2].

DRX Inactivity period: When the DRX Inactivity Timer[1] is ON and the UE receiver is monitoring the PDCCH, at the same time ready to receive packets through the evolved node-B (eNB) from Evolved Packet Core (EPC). The DRX Inactivity Timer, (when not time out) the PDCCH indicated a Downlink transmission or Uplink transmission. Should the DRX Inactivity Timer expire, then the DRX Short Cycle Timer is activated and the Light Sleep period begins.

DRX Light Sleep period: The period is the DRX Short Cycle (t_{DS}). During each of the DRX Short Cycle the UE wakes up to monitor the PDCCH (Active state (active period) or also know as Listen Interval in Figure 1). If the PDCCH indicates a downlink transmission, the UE change from Light Sleep period to an activity period and starts the DRX Inactivity Timer. Otherwise the UE will return to Light Sleep period. The UE will keep entering Light Sleep period until the DRX Short Cycle Timer[2] expires. While in DRX Light Sleep period the eNB will not transmit any packets to the UE.

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 period. While in DRX Deep Sleep period the eNB will not transmit any packets to the UE.

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 [13] rather than the traditional queuing that is contingent on the data traffic to be Poisson. In the traditional Poisson Traffic model, it usually has a very limited range of time scales, making it short range dependent. With self-similar traffic, it displays burstiness and interacts over an immensely wide range of time scales, making it long range dependent. In addition, it has been shown to be heavy tailed such as Pareto and Weibull distributions are more applicable when modeling data network traffic [9]. For this paper, we used the European Telecommunication Standards Institute (ETSI) traffic model [4], where the packets size and the packet transmission timer are assumed to follow the truncated Pareto distribution. The [4] is a widely used in various analytical and simulation studies of 3GPP networks, such as [7], [10], [12], [16], [17].

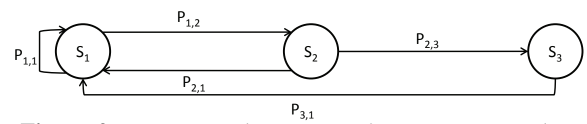

Figure 2: *A semi-Markov process for LTE DRX analysis.*

The LTE DRX mechanism is a semi-Markov process [11] and is illustrated in Figure 2. The state transition diagram consists of three states, which are relevant to the three periods show in Figure 1.

- *State* S_1 comprises a sequence of adjacent active time intervals corresponding to the entire duration of a single packet call transmission, i.e. the UE is in *power active mode*.
- *State* S_2 comprises a *Light Sleep period* ($t_{light\ sleep}(t_N)$) which is entered from S_1, i.e. the UE follows DRX Short Cycles.
- *State* S_3 comprises a *Deep Sleep period* ($t_{deep\ sleep}$) which is entered from S_2, i.e. the UE follows DRX Long Cycles.

A new packet call can be viewed as continuation of the current session (*Condition 1*) or as the onset of a new session (*Condition 2*) 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 P_{pc} = 1 - $1/\mu_{pc}$ or the inter-session idle time (t_{is}) with probability P_s = $1/\mu_{pc}$. 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 $i, j \in \{1, 2, 3\}$. Next, we derive these state transition probabilities.

B. State 1 to State 1 and State 1 to State 2

State S_1 contains N_p inactivity periods[3]. During the last inactivity period, if the PDCCH indicates the next packet call delivery happened before DRX Inactivity Timer expires, the DRX Inactivity Timer is cancelled, another inactivity period is started and state S_1 is re-entered (t_I has not expired); otherwise, state S_2 is entered when DRX Inactivity Timer expires. The probability that a new packet call begins before

[1]Inactivity 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.

[2]DRX 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.

[3]N_p: Number of packets per packet call.

the expiration of t_I is q_1 = Pr[$t_{ipc} < t_I$] = 1 - e$^{-\lambda_{ipc} t_I}$ in *Condition 1* and q_2 = Pr[$t_{is} < t_I$] = 1 - e$^{-\lambda_{is} t_I}$ in *Condition 2*, respectively. Then we have:

$$P_{1,1} = P_{pc} q_1 + P_s q_2 \tag{1}$$

$$P_{1,2} = P_{pc}(1 - q_1) + P_s(1 - q_2) \tag{2}$$

C. Adjustable DRX Timer State for Light Sleep

Short DRX Cycle is the first DRX cycle to be followed after enabling DRX. The probable short DRX cycles are 2^n, where $n = 1, 2, ...9$ and 5×2^m, where $m = 1, 2, ...6$ in terms of subframes or time. The duration of the n^{th} sleep interval is obtained by:

$$T(n) = \begin{cases} \kappa 2^n & 1 \leq \text{n} < \text{M} \\ T_{max} & \text{M} \geq \text{n} \end{cases}$$

where *M* is the value that *T(n)* = T_{max} and κ is a rescaling factor, which is used to control the total Light Sleep cycle duration. The duration of the k^{th} sleep cycle, which consists of a sleep interval and a listening, is given by:

$$C_{DS}^n = T_n + L \tag{3}$$

where *L* is the duration of listen interval.

The probability that there is no initiation of awakening during C_{DS}^n*(P_n)* is obtained by:

$$P_n = e^{-\lambda C_{DS}^n}, 1 \leq \text{n} < \text{M} \tag{4}$$

According to the Figure 1, the transition from Light Sleep to Deep Sleep consist of:

$$t_{CS} = t_N = \kappa \sum_{1}^{n} C_{DS}^n \tag{5}$$

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

According to adjustable DRX Light Sleep cycle, the probability that there is at least one initiation of awakening during C_{DS} is 1–e$^{-\lambda C_{DS}}$. In state S_2 the UE follows DRX Short Cycles. If the PDCCH indicates that a new packet call starts before the adjustable DRX Short Cycle Timer expires (means new packet call occurs before t_N has expired), the timer is cancelled, and state S_1 is entered; otherwise state S_3 is entered. The probability that there is at least one initiation of awakening in the n^{th} sleep cycle during a sleep-mode operation is achieved by:

$$P_{2,1} = P_{pc} \cdot \sum_{\alpha}^{n} (1 - P_\alpha) + P_s \cdot \sum_{\alpha}^{n} (1 - P_\alpha) \tag{6}$$

$$= P_{pc} \left(1 - \prod_{\alpha}^{n} e^{-\kappa \lambda_{ipc} C_{DS}^\alpha} \right) + P_s \left(1 - \prod_{\alpha}^{n} e^{-\kappa \lambda_{is} C_{DS}^\alpha} \right)$$

and

$$\begin{aligned} P_{2,3} &= P_{pc} \cdot \sum_{\alpha}^{n} P_\alpha + P_s \cdot \sum_{\alpha}^{n} P_\alpha \\ &= P_{pc} e^{-\lambda_{ipc} \kappa \sum_{\alpha}^{n} C_{DS}^\alpha} + P_s e^{-\lambda_{is} \kappa \sum_{\alpha}^{n} C_{DS}^\alpha} \\ &= P_{pc} \prod_{\alpha}^{n} e^{-\kappa \lambda_{ipc} C_{DS}^\alpha} + P_s \prod_{\alpha}^{n} e^{-\kappa \lambda_{is} C_{DS}^\alpha} \end{aligned} \tag{7}$$

E. State 3 to State 1

There is only one transition out of state S_3 to the state S_1, thus, we have $P_{3,1}$ =1.

F. Transition Probability Matrix

The transition probability matrix $\mathbf{P} = (P_{i,j})$ of the embedded Markov chain can, hence, be given as (8):

$$\mathbf{P} = \begin{bmatrix} P_{1,1} & P_{1,2} & 0 \\ P_{2,1} & 0 & P_{2,3} \\ 1 & 0 & 0 \end{bmatrix} \tag{8}$$

Let $\pi_i (i \in \{1, 2, 3\})$ denote the probability that the embedded Markov chain is in state $S_i (i \in \{1, 2, 3\})$. By using $\sum_{j=1}^{3} \pi_i = 1$ and the balance equation $\pi_i = \sum_{j=1}^{3} \pi_j P_{j,i}$, we can solve the stationary distribution and obtain (9)

$$\prod = \begin{cases} \pi_1 &= \frac{1}{1+P_{1,2}+P_{1,2}P_{2,3}} \\ \pi_2 &= \frac{P_{1,2}}{1+P_{1,2}+P_{1,2}P_{2,3}} \\ \pi_3 &= \frac{P_{1,2}P_{2,3}}{1+P_{1,2}+P_{1,2}P_{2,3}} \end{cases} \tag{9}$$

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

E[H_i]: In state S_1, mobile device experiences a busy period t_B[4] and then an interpacket call inactivity period t_I. In LTE 8-process Stop-And-Wait Hybrid Automatic Request (SAW-HARQ) flow-control algorithm is implemented in packet transmission, which can be modelled as an M/M/8 queuing model. According to [6] we have:

$$E[H_1] = E[t_B] + E[t_I] \tag{10}$$

Since a busy period is identical to the duration of a packets call delivery, a t_B consists of N_p packets service times t_x[5]. From Wald's Theorem 5.18 [8], we have

$$E[t_B] = E[N_p] E[t_x] = \frac{\mu_p}{\lambda_x} \tag{11}$$

where μ_p is the number of packets calls within a packet service session and λ_x is the Inter-packet arrive time.

If a packets arrives before the Inactivity Timer expires ($t_{ipc} < t_I$), then the Inactivity period equals the inter-packet call idle time, $t_I = t_{ipc}$; Otherwise the next packet arrives after the DRX Inactivity Timer has expired ($t_I \geq t_{ipc}$). Therefore, we have $t_I = min(t_{ipc}, t_I)$. Similarly, in Inter-session idle time (t_{is}), we have $t_I = min(t_{is}, t_I)$.

Therefore, we have for t_I for t_{ipc} and t_{is} yields:

$$E[t_I] = P_{pc} E[min(t_{ipc}, t_I)] + P_s E[min(t_{is}, t_I)] \tag{12}$$

We obtain that:

[4] t_B: consists of the number of packet within a per packet call (N_p).

[5] t_x: The time interval between when the packet is transmitted by the LTE RNC processor and when the corresponding positive ACK is received by the LTE RNC processor.

$$E\left[min(t_{ipc},t_I)\right] = \int_{x=0}^{\infty} Pr\left[min(t_{ipc},t_I) > x\right]dx \quad (13)$$
$$= \int_{x=0}^{t_I} Pr\left[t_{ipc} > x\right]dx$$
$$= \int_{x=0}^{t_I} e^{-\lambda_{ipc}x}dx = (\frac{1}{\lambda_{ipc}})\left[1-e^{-\lambda_{ipc}t_I}\right]$$

where $f(t_{ipc})$ = $\lambda_{ipc}e^{-\lambda_{ipc}t_{ipc}}$ is the *PDF* of the inter-packet call idle time t_{ipc}. Likewise:

$$E\left[min(t_{is},t_I)\right] = (\frac{1}{\lambda_{is}})\left[1-e^{-\lambda_{is}t_I}\right] \quad (14)$$

Substitute equation (13) and (14) into (12)

$$E\left[t_I\right] = (\frac{P_{pc}}{\lambda_{ipc}})\left[1-e^{-\lambda_{ipc}t_I}\right] + (\frac{P_s}{\lambda_{is}})\left[1-e^{-\lambda_{is}t_I}\right] \quad (15)$$

Substitute equation (11) and (15) into (10)

$$E\left[H_1\right] = (\frac{\mu_p}{\lambda_x}) + (\frac{1}{\lambda_{ipc}})\left[1-e^{-\lambda_{ipc}t_I}\right] + (\frac{1}{\lambda_{is}})\left[1-e^{-\lambda_{is}t_I}\right] \quad (16)$$

IV. Adjustable DRX Cycles in 3GPP LTE

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 a packet call delivery starts during the i^{th} DRX Cycle is in a fixed DRX Cycles:

$$p_i = \begin{cases} \underbrace{\begin{array}{l} P_{pc}e^{-\lambda_{ipc}t_I}e^{-\lambda_{ipc}(i-1)t_{DS}}(1-e^{-\lambda_{ipc}t_{DS}}) \\ +P_s e^{-\lambda_{is}t_I}e^{-\lambda_{is}(i-1)t_{DS}}(1-e^{-\lambda_{is}t_{DS}}), \end{array}}_{1\le i\le N_{DS}} \\ \\ \underbrace{\begin{array}{l} P_{pc}e^{-\lambda_{ipc}[(t_I+N_{DS}t_{DS}+(i-N_{DS}-1)t_{DL}]}(1-e^{-\lambda_{ipc}t_{DL}}) \\ +P_s e^{-\lambda_{is}[(t_I+N_{DS}t_{DS}+(i-N_{DS}-1)t_{DL}]}(1-e^{-\lambda_{is}t_{DL}}), \end{array}}_{i\ge N_{DS}} \end{cases} \quad (17)$$

However, by having adjustable DRX Sleep cycle in t_{DS}, equation (17), the probability a packet call delivery starts during the ith DRX Cycle is now:

$$p_i = \begin{cases} \underbrace{\begin{array}{l} P_{pc}e^{-\lambda_{ipc}t_I}\prod_{j=1}^{i}e^{-\kappa\lambda_{ipc}C_{DS}^j}(1-e^{-\kappa\lambda_{ipc}C_{DS}^j}) \\ +P_s e^{-\lambda_{is}t_I}\prod_{j=1}^{i}e^{-\kappa\lambda_{is}C_{DS}^j}(1-e^{-\kappa\lambda_{is}C_{DS}^j}), \end{array}}_{1\le i\le N_{DS}} \\ \\ \underbrace{\begin{array}{l} P_{pc}e^{-\lambda_{ipc}[(t_I+t_N+(i-N_{DS}-1)t_{DL}]}(1-e^{-\lambda_{ipc}t_{DL}}) \\ +P_s e^{-\lambda_{is}[(t_I+t_N+(i-N_{DS}-1)t_{DL}]}(1-e^{-\lambda_{is}t_{DL}}), \end{array}}_{i\ge N_{DS}} \end{cases} \quad (18)$$

V. Sleep States H_2 and H_3

State S_2 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 state S_3 is entered. 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_2 is:

$$E\left[H_2\right] = E\left[N_{DS}\right]\langle t_{CS}\rangle = (P_{23}N_{DS} + P_{21}E\left[N_{DS}^*\right])\,\kappa\sum_{i=1}^{n}\frac{C_{DS}^i}{n} \quad (19)$$

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:

$$E\left[N_{DS}^*\right] = \frac{P_{pc}}{Pr\left[t_{ipc} < C_{DS}\right]} + \frac{P_s}{Pr\left[t_{is} < C_{DS}\right]} = \frac{P_{pc}}{1-\prod_{i=1}^{n}e^{-\kappa\lambda_{ipc}C_{DS}^i}} + \frac{P_s}{1-\prod_{i=1}^{n}e^{-\kappa\lambda_{is}C_{DS}^i}} \quad (20)$$

Then we substitute equations (6), (7) and (20) into (19):

$$\begin{aligned} E\left[H_2\right] = & \Bigg(\left[P_{pc}\prod_{\alpha}^{n}e^{-\kappa\lambda_{ipc}C_{DS}^{\alpha}} + P_s\prod_{\alpha}^{n}e^{-\kappa\lambda_{is}C_{DS}^{\alpha}}\right]N_{DS} \\ + & \left[P_{pc}\left(1-\prod_{\alpha}^{n}e^{-\kappa\lambda_{ipc}C_{DS}^{\alpha}}\right) + P_s\left(1-\prod_{\alpha}^{n}e^{-\kappa\lambda_{is}C_{DS}^{\alpha}}\right)\right] \\ \cdot & \left[\frac{P_{pc}}{1-\prod_{\alpha=1}^{n}e^{-\kappa\lambda_{ipc}C_{DS}^{\alpha}}} + \frac{P_s}{1-\prod_{\alpha=1}^{n}e^{-\kappa\lambda_{is}C_{DS}^{\alpha}}}\right]\Bigg)\kappa\sum_{\alpha=1}^{n}\frac{C_{DS}^{\alpha}}{n} \end{aligned} \quad (21)$$

State S_3 contains of Deep Sleep period consisting of State n_{DL} Long DRX Cycles. Therefore:

$$E\left[H_3\right] = \left(\frac{P_{pc}}{1-e^{-\lambda_{ipc}t_{DL}}} + \frac{P_s}{1-e^{-\lambda_{is}t_{DL}}}\right)t_{DL} \quad (22)$$

VI. Power Saving Factor (PS)

The power saving factor (PS) is equal to the probability that the semi-Markov process is at S_2 and S_3 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 C_{DS} - τ or t_{DL} - τ. Hence, the effective sleep time in both states S_2 and S_3 are derived as the following:

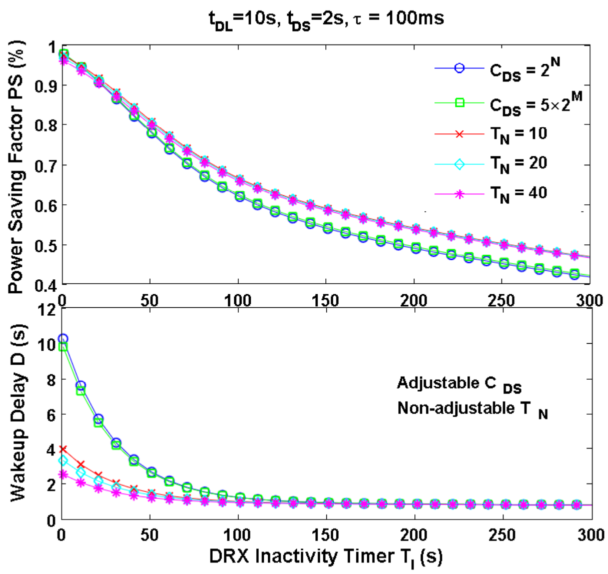

Figure 3: *(Top) LTE DRX Inactivity Timer on T_I for Power. (Bottom) LTE DRX Inactivity Timer on T_I for Delay.*

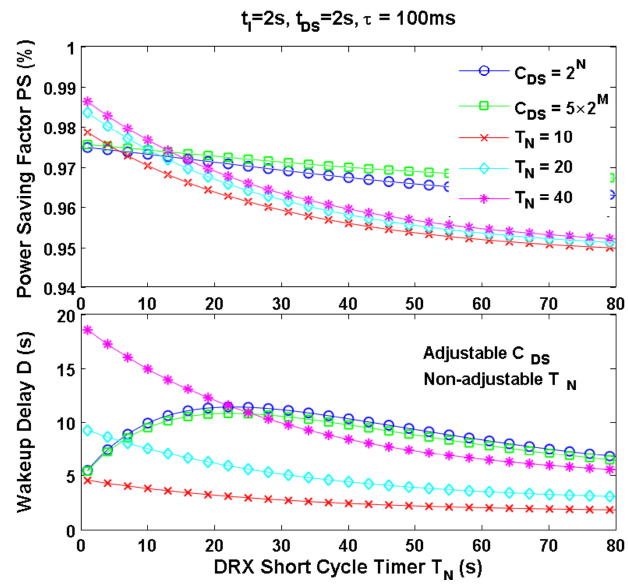

Figure 4: *(Top) LTE DRX Short Cycles on T_N for Power. (Bottom) LTE DRX Short Cycles on T_N for Delay.*

$$E\left[H_2^{'}\right] = \left(P_{23}N_{DS} + P_{21}E[N_{DS}^{*}]\right)\left(\kappa\sum_{i=1}^{n}\frac{C_{DS}^{i}}{n} - \tau\right) \tag{23}$$

and

$$E\left[H_3^{'}\right] = \left(\frac{P_{pc}}{1-e^{-\lambda_{ipc}t_{DL}}} + \frac{P_s}{1-e^{-\lambda_{is}t_{DL}}}\right)(t_{DL} - \tau) \tag{24}$$

From Theorem 4.8.3 [11], we obtain *PS* = $\lim_{t\to\infty}$ *Pr*[UE receiver is turned off at time *t*] for *PS* to be obtain by:

$$PS = \frac{\pi_2 E\left[H_2^{'}\right] + \pi_3 E\left[H_3^{'}\right]}{\sum_{i=1}^{3}\pi_i E\left[H_i\right]} \tag{25}$$

Substituting Equations (18), (16), (21), (22), (23), (24) into Equation (25), we derive the closed-form equation for the power saving factor PS.

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 [14], [15], [18]. Therefore we have:

$$E\left[D\right] = \sum_{i=1}^{N_{DS}} p_i\frac{C_{DS}^{i}}{2i} + \sum_{i=N+1}^{\infty} p_i\frac{t_{DL}}{2} \tag{26}$$

Substituting Equation (18) into Equation (26), we derive the closed-form equation for the mean of wake-up delay $E\left[D\right]$.

VII. Numerical Results

The effects of the DRX Inactivity Timer T_I and the DRX Short Cycle Timer T_N are described in Figures 3 - 4. Both *PS* and *D* decrease as T_I and T_N increase with the non-adjustable approach, but this is not always true for the adjustable case. When T_I becomes larger, in the case of the non-adjustable cycle, it is more probable that a packet call delivery occurs before the DRX Inactivity Timer expires, resulting in fewer transition to the power saving mode. Since the number of transitions to the power saving mode are more infrequent, the impact, of the amount of packet call deliveries delayed, will be minor, consequential both power saving and delay are smaller.

At lower values of T_I for the adjustable DRX cycle, the UE resides in the power saving mode longer, however, as T_I becomes larger the *PS* decreases for adjustable DRX while the non-adjustable *PS* is higher. This is due to less time spent in *PS* mode, since C_{DS} is smaller with an adjustable DRX at the beginning, but then becomes larger, resulting in fewer transition to the power saving mode.

In Figure 4 the adjustable DRX has a lower power saving value when T_N is between 8 - 18, but has a greater power saving factor as T_N increases. The power saving still decreases, due to the fact that the UE is less likely to enter the Deep Sleep period. Since the adjustable DRX cycle preforms better power saving function at small values of T_N, the corresponding delay is greater when compared to the non-adjustable case. But as T_N increases in size, the delay peaks at around 25 and then decreases, as shown in Figure 4. This behaviour is due to the exponential distribution of the frames within the Light Sleep period and the statistical nature of the packets, which begin to arrive in the more densely packed region of the cycle (.i.e. towards the beginning).

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 Figure 5 are increasing for both T_{DS} and T_{DL} for the non-adjustable method, which is due to the Sleep Cycles are longer and the “ON Duration is fixed”. The longer DRX Cycles translate into more

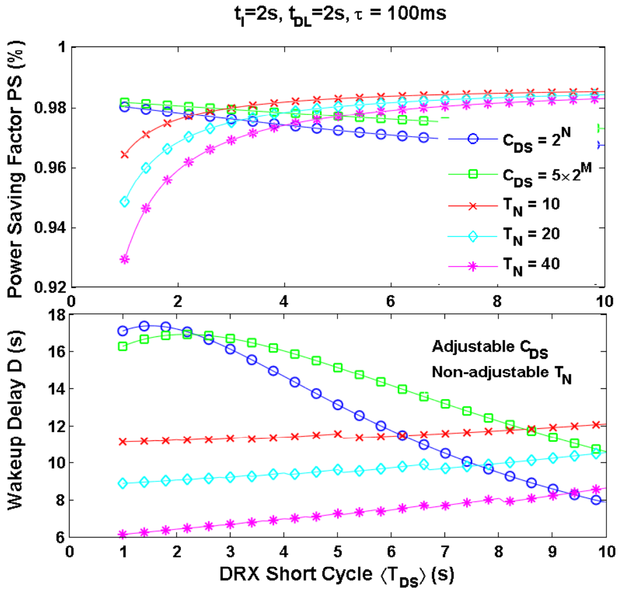

Figure 5: *(Top) LTE DRX Short Cycles on T_{DS} for Power. (Bottom) LTE DRX Short Cycles on T_{DS} for Delay.*

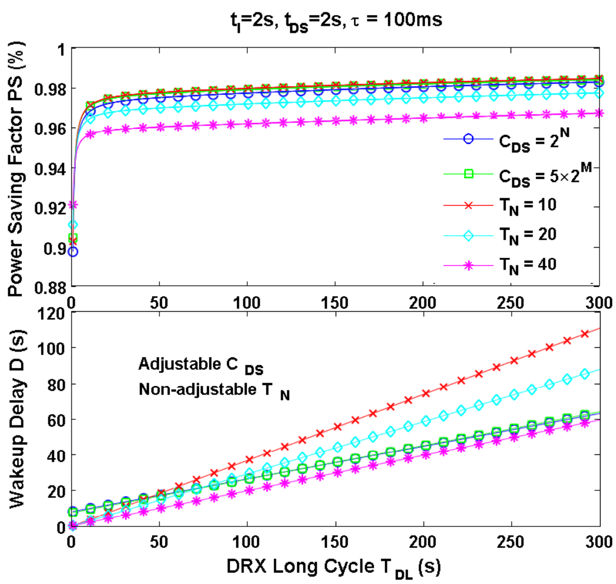

Figure 6: *(Top) LTE DRX Long Cycles on T_{DL} for Power. (Bottom) LTE DRX Short Cycles on T_{DL} for Delay.*

effective sleep time per cycle, resulting in better power saving and a decrease in performance of the wake-up delay.

The power saving factor in Figure 5 is decreasing for the adjustable case. As the Sleep Cycles are increasing in size and the "ON Duration is adjusting", the longer DRX Cycles translate into less effective sleep time per cycle, resulting in a decrease in performance for power saving. The T_{DS} in Figure 5 has a longer wake-up delay at around 1.5, but then begins to improve, which is due to the correlation between the exponential distributions of the frames within the adjustable DRX cycle and the statistical nature of the packets.

The adjustable DRX cycle is able to adapt to the scheduling behaviour of the system in order to enhancing the power saving gain mechanism for T_{DL}. However, having increased the power saving factor, it inevitably effects the performance of the wake-up delay, as in the situation when T_N is in the region below and around 30, as shown in Figure 6. Although, at larger values of around 40 and above for both $C_{DS} = 2^N$ and $C_{DS} = 5 \times 2^M$ the adjustable DRX cycle has a smaller delay.

VIII. Conclusion

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

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