Traffic-Based Adjustable Discontinuous Reception Mechanism with Bounded Delay

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***Abstract*—Long-Term Evolution (LTE) standard has been introduced to support high speed and reliable communication in mobile devices and wireless data terminals. High data rates are the main cause of the quick battery discharge in User Equipment (UE)s in 4G/LTE and beyond. To save the UEs battery power, LTE networks utilize the Discontinuous Reception (DRX) mechanism to enhance the energy efficiency of UEs. In the DRX mechanism, there is a tradeoff between the communication delay and power consumption of the device where DRX energy efficiency improves at the expense of higher latency and vice versa. This paper proposes a novel DRX technique for 4G and beyond, in which DRX long and short sleep cycles are adjusted adaptively based on the traffic condition and a threshold delay. Numerical analysis and system simulations show that this scheme is able to increase energy efficiency at UEs and maintains the wake-up delay around a threshold delay.**

***Index Terms*—DRX mechanism, 4G/LTE, Power Saving, Latency, 5G.**

I. INTRODUCTION

THE Long-Term Evolution (LTE) has been introduced as a standard for the fourth generation (4G) of mobile communication systems [1]. 4G/LTE offers a higher data rate and low latency for end-users [2] compared to the previous mobile network technologies. The computational power needed to support these technologies is inherently hight and it may cause a faster depletion of UE's battery power in comparison with previously adopted technologies.

In the LTE, Discontinuous Reception (DRX) has been introduced to save UEs battery power at mobile terminals. In DRX, the UE turns off its RF circuitry when there is no downlink data packets [3]. During this time, the UE stays in sleep mode and wakes up only at a periodic wake period to monitor Physical Downlink Control Channel (PDCCH) for data transfer [3]. DRX mechanism makes UE listen to the downlink channel less frequently, thus reducing the power consumption [3]. DRX power saving is achieved at the expense of higher latency because all data packets received in DRX sleep mode are buffered at the evolved Node B (eNodeB) until the UE listens to the PDCCH [4].

In the DRX mechanism, if there is no data activity, the UEs switch to sleep mode to save power [3]. In [5], the authors introduced a four-state semi-Markov process in order to get an expression for energy-saving and latency for the DRX mechanism. In [6], the authors propose a DRX mechanism to increase energy efficiency in the UEs when using video streaming applications. This paper uses the packet buffering technique at the eNodeB. The evaluation of the DRX mechanism in Machine-type Communications (MTC) is investigated in [7], [8] and [9]. DRX cycle adjustment scheme based on traffic is proposed in [10] to adjust the DRX parameters to improve the user experience at the UEs.

In [11], the authors introduce an adjustable DRX mechanism that utilizes the quick sleeping indication (QSI) for MTC UEs. An adjustable DRX mechanism is proposed in [12]. The proposed algorithm expands the DRX sleep cycles in the DRX mechanism. In [13], the authors examine the impact of different lengths of the DRX sleep cycles on the Quality of Service (QoS) and Quality of Experience (QoE) at the UEs. The DRX mechanism for IoT devices in which, the short DRX cycles are optimized based on the power consumption is proposed in [14] and [15].

In [16], the authors introduced an adaptive DRX scheme to reduce energy consumption at UE's while maintaining the average packet delay around the delay threshold. The algorithm adaptively modified the DRX inactivity-timer according to the traffic rate and queue threshold. The proposed algorithm features two delay thresholds for time-sensitive and non-time-sensitive applications and accordingly used two adaptive optimal parameters to save power and shorten the delay [16].

The proposed algorithm in this paper is different from the other works on DRX mechanisms. Our proposed algorithm utilizes traffic rate and average packet delay and dynamically adjusts DRX sleep cycles to enhance energy-saving performance in the UE. To prevent the excessive increase in average packet delay, a threshold delay is defined in the case when average packet delay exceeds the threshold delay, algorithm dynamically decreases DRX sleep cycles, so the average packet delay is always under control. In the present paper, the analytical and simulations results show that the proposed algorithm maximizes the power saving, adaptively modifies the DRX sleep cycles in terms of traffic rate and threshold delay and exhibits high performance in different traffic scenarios compared to other DRX schemes.

The main novelties and advantages of our proposed methods can be summarized as follows:

- We introduce an adaptive DRX algorithm to improve the energy efficiency of the UEs and maintain a wake-up

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delay under a threshold delay.

- We adjust the DRX sleep cycle based on the average packet delay and incoming traffic and utilize the application sensitivity to delay that runs on the UE.
- DRX long sleep cycle and DRX short sleep cycle are adjusted by two factors α and β.
- We evaluate the proposed algorithm in terms of energy consumption and the wake-up in the UE.

II. THE DRX MECHANISM IN 4G LTE

To obtain a model to evaluate the 4G DRX mechanism we use four states semi-Markov process [17]. The four states semi-Markov process for 4G DRX is depicted in Fig. 1. In active state (S_1), the UE listens to channel, if there are no downlink data packets, it stays awake for a period of t_I. During the t_I period if any packet received the timer will be reset to zero. When this timer expires, the UE goes to ON state (S_2). In this state in order to detect any data activities, the UE monitors PDCCH in t_{ON} period. Power consumption in this state is less than state S_1 but is more than state S_3 and state S_4. If there are no data packets during t_{ON}, the UE goes to state S_3 or S_4. The UE stays in S_3 for t_N times. After t_N expires, the UE moves to S_4. Power consumption in S_3 and S_4 is close to zero because the UE turns off its receiver. The DRX parameters are illustrated in Fig. 2.

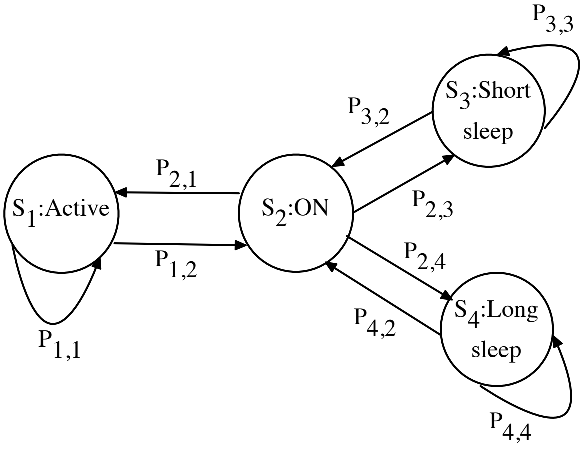

Fig. 1. Four-State Semi-Markov Process for DRX Mechanism.

The configuration of the DRX timers can maximize power saving or minimize wake-up delay in the UE. A configuration of the DRX parameters to achieve the best tradeoff between power saving and delay is critical at the UEs.

III. THE PROPOSED DRX MECHANISM

To enhance energy saving performance in the UE, Our proposed algorithm dynamically adjusts DRX short sleep cycle and DRX long sleep cycle based on traffic rate and average packet delay. We define DRX short sleep cycle (t_{SS}) and DRX long sleep cycle (t_{LS}) as follows:

$$\begin{cases} t_{SS} = \alpha 2^n \leq 2^9, & n \in \{1,2,3,...9\},\ 0 < \alpha \leq \alpha_{max} \\ t_{LS} = \beta 2^n \leq 2^{11}, & n \in \{1,2,3,...11\},\ 0 < \beta \leq \beta_{max} \end{cases} \tag{1}$$

where $\alpha_{max} = 2^{9-n}$ and $\beta_{max} = 2^{11-n}$. In low traffic rate for more power saving α and β should be increased dynamically in order to increase DRX sleep cycles, but only if the wake-up delay does not exceed from the threshold delay. In order to decrease the wake-up delay in high traffic rate, these factors should be dynamically decreased.

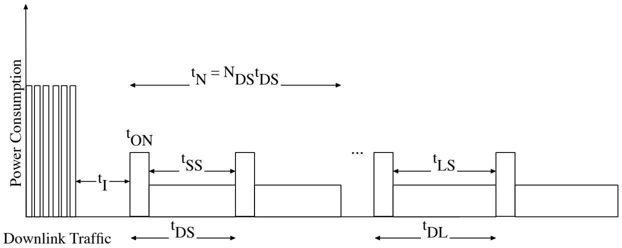

Fig. 2. DRX timers in 4G LTE .

Intuitively, the tuning of α and β for adjusting DRX sleep cycles should be based on the wake-up delay and the traffic conditions. Therefore, for configuring DRX short and long sleep cycles, an algorithm is presented to dynamically adjust α and β factors based on the traffic rate and the packet delay. In this algorithm, the packet delay $D[i]$ for each UE compares with the threshold delay D_{th}. If $D[i] > D_{th}$, α and β should be reduced to decrease packet delay and if $D[i] < D_{th}$ the average packet delay is low, so, α and β can be increased to save more power.

This algorithm assures us that to increase power saving, the average packet delay will not exceed from the threshold delay. According to sensitivity of application to the delay, different D_{th} can be considered.

Algorithm 1 : Tuning α based on Delay and Traffic rate

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Procedure Tuning $\alpha$
Executed procedure at the end of each cycle
for each user j estimates the average delay
($D[i]$) and the traffic rate ($\lambda$)
$\alpha[i+1] = \alpha[i] + 3/2\lambda(D_{th} - D[i])$
  if ($\alpha[i+1] \leq 0$) Then
    $\alpha[i+1] = 1$
  else if ($\alpha[i+1] > \alpha_{max}$) Then
    $\alpha[i+1] = \alpha_{max}$
  end if
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In Algorithm 1, the amount of increase in α depends on the difference between $D[i]$ and threshold delay (D_{th}), also we consider $\beta = 2\alpha$.

A. Wake-up delay and power saving factor analysis

In order to compute the wake-up delay and power saving factor European Telecommunication Standards Institute (ETSI) traffic model, [18] [19] is used. Statistical distribution was used as summarized in Table I. According to ETSI model, the inter-arrival time between two consecutive packet calls may be the interpacket call idle time (t_{ipc}) with probability $P_{pc} = 1 - 1/\mu_{pc}$ or the intersession idle time (t_{is}) with probability $P_s = 1/\mu_{pc}$.

TABLE I
ETSI TRAFFIC MODEL

Parameter	Distribution	Mean value
Intersession idle time (t_{is})	Exponential	$1/\lambda_{is}$
Number of packet calls per session (N_{pc})	Geometric	μ_{pc}
Inter-packet call idle time (t_{ipc})	Exponential	$1/\lambda_{ipc}$
Number of packet calls per packet call (N_p)	Geometric	μ_p
Inter-packet arrival time (t_{ip})	Exponential	$1/\lambda_{ip}$

In state S_1, the UE is waiting to receive a new packet, if a new packet arrives, the UE restarts t_I and remains in S_1. Otherwise, at the end of t_I period, the UE transmits to S_2. The probability that the UE remains in S_1 $(P_{1,1})$ or moves to S_2 $(P_{1,2})$ is:

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

$$P_{1,2} = P_{pc}\left(1 - q_1\right) + P_s\left(1 - q_2\right) \tag{3}$$

where q_1 and q_2 are the probability that a new packet call arrives in the current session or in the new session, respectively. Therefore, q_1 and q_2 can be computed as follows:

$$q_1 = Pr[t_{ipc} < t_I] = \int_0^{t_I} \lambda_{ipc} e^{-\lambda_{ipc} t} dt = 1 - e^{-\lambda_{ipc} t_I} \tag{4}$$

$$q_2 = Pr[t_{is} < t_I] = \int_0^{t_I} \lambda_{is} e^{-\lambda_{is} t} dt = 1 - e^{-\lambda_{is} t_I} \tag{5}$$

In state S_2 the probability that the UE returns to state S_1 to receive data packets is $P_{2,1}$. If there is no any packets for the UE during t_{ON}, it transits to state S_3 with probability $P_{2,3}$ or if t_N expires, it goes to state S_4 with probability $P_{2,4}$:

$$P_{2,1} = P_{pc}q_3 + P_s q_4 \tag{6}$$

$$P_{2,3} = P_{pc}(1 - q_3)q_5 + P_s(1 - q_4)q_6 \tag{7}$$

$$P_{2,4} = P_{pc}(1 - q_3)(1 - q_5) + P_s(1 - q_4)(1 - q_6) \tag{8}$$

where q_3, q_4, q_5 and q_6 can be computed as follows:

$$q_3 = Pr[t_{ipc} < t_{ON}] = \int_0^{t_{ON}} \lambda_{ipc} e^{-\lambda_{ipc} t} dt = 1 - e^{-\lambda_{ipc} t_{ON}} \tag{9}$$

$$q_4 = Pr[t_{is} < t_{ON}] = \int_0^{t_{ON}} \lambda_{is} e^{-\lambda_{is} t} dt = 1 - e^{-\lambda_{is} t_{ON}} \tag{10}$$

$$q_5 = Pr[t_{ipc} < t_N] = \int_0^{t_N} \lambda_{ipc} e^{-\lambda_{ipc} t} dt = 1 - e^{-\lambda_{ipc} t_N} \tag{11}$$

$$q_6 = Pr[t_{is} < t_N] = \int_0^{t_N} \lambda_{is} e^{-\lambda_{is} t} dt = 1 - e^{-\lambda_{is} t_N} \tag{12}$$

The UE remains in state S_3 and S_4 despite the arrival of the new packet at eNodeB. So, the probability that the UE transmits to S_2 from S_3 is $P_{3,2}$ and the probability the UE remains in state S_3 is $P_{3,3}$:

$$P_{3,2} = P_{pc}q_7 + P_s q_8 \tag{13}$$

$$P_{3,3} = P_{pc}(1 - q_7) + P_s(1 - q_8) \tag{14}$$

where q_7 and q_8 can be computed as follows:

$$q_7 = Pr[t_{ipc} > t_{SS} = \alpha 2^n] = \int_{\alpha 2^n}^{\infty} \lambda_{ipc} e^{-\lambda_{ipc} t} dt = e^{-\lambda_{ipc} \alpha 2^n} \tag{15}$$

$$q_8 = Pr[t_{is} > t_{SS} = \alpha 2^n] = \int_{\alpha 2^n}^{\infty} \lambda_{is} e^{-\lambda_{is} t} dt = e^{-\lambda_{is} \alpha 2^n} \tag{16}$$

After expiry of t_N, the UE transmits to state S_4. the probability that the UE transmits to S_2 from S_4 is $P_{4,2}$ and the probability the UE remains in state S_4 is $P_{4,4}$:

$$P_{4,2} = P_{pc}q_9 + P_s q_{10} \tag{17}$$

$$P_{4,4} = P_{pc}(1 - q_9) + P_s(1 - q_{10}) \tag{18}$$

where q_9 and q_{10} can be computed as follows:

$$\begin{aligned} q_9 &= Pr[t_{ipc} > t_{LS} = (2\alpha)2^n] = \int_{(2\alpha)2^n}^{\infty} \lambda_{ipc} e^{-\lambda_{ipc} t} dt \\ &= e^{-\lambda_{ipc} (2\alpha) 2^n} \end{aligned} \tag{19}$$

$$\begin{aligned} q_{10} &= Pr[t_{is} > t_{LS} = (2\alpha)2^n] = \int_{(2\alpha)2^n}^{\infty} \lambda_{is} e^{-\lambda_{is} t} dt \\ &= e^{-\lambda_{is} (2\alpha) 2^n} \end{aligned} \tag{20}$$

To compute the steady state probabilities $\delta_i (i \in \{1, 2, 3, 4\})$, we can use the following equations:

$$\sum_{i=1}^{4} \delta_i = 1, \quad \delta_i = \sum_{j=1}^{4} \delta_j P_{j,i} \tag{21}$$

Therefore it is:

$$\Delta = \begin{cases} \delta_1 = \frac{P_{2,1}(1-P_{3,3})(1-P_{4,4})}{M} \\ \delta_2 = \frac{(1-P_{1,1})(1-P_{3,3})(1-P_{4,4})}{M} \\ \delta_3 = \frac{P_{2,3}(1-P_{3,3})(1-P_{4,4})}{M} \\ \delta_4 = \frac{P_{2,4}(1-P_{3,3})(1-P_{4,4})}{M} \end{cases} \tag{22}$$

where:

$$\begin{aligned} M = {} & P_{2,1}(1 - P_{3,3})(1 - P_{4,4}) + P_{2,3}(1 - P_{1,1})(1 - P_{4,4}) \\ & + (1 - P_{1,1})(1 - P_{3,3})(1 - P_{4,4}) \\ & + P_{2,4}(1 - P_{3,3})(1 - P_{1,1}) \end{aligned} \tag{23}$$

After computing steady-state probabilities, in order to get power saving factor, there is a need to calculate the average amount of time that the UE spends in S_1, S_2, S_3, and S_4. Let $D_i (i \in \{1, 2, 3, 4\})$ represent the spending time at state $S_i (i \in \{1, 2, 3, 4\})$.

1) $E[D_1]$: In state S_1, we assume the UE handles N_p packets and after that, it has an idle time $\bar{t}_{t_I}$ within a packet call [20]. So, $E[D_1]$ can be calculated as:

$$E[D_1] = E[T_{service}] + E[\bar{t}_{t_I}] \tag{24}$$

where $T_{service}$ is service time for N_p packets:

$$E[T_{service}] = E[N_p]E[t_{service}] = \frac{\mu_p}{\lambda_s} \tag{25}$$

where μ_p is the mean of packet calls and $\frac{1}{\lambda_s}$ is the mean of service time. $E[\bar{t}_{t_I}]$ can be calculated as [3]:

$$E[\bar{t}_{t_I}] = P_{pc}E[min(t_{ipc}, t_I)] + P_s E[min(t_{is}, t_I)] \tag{26}$$

where:

$$\begin{aligned} E[min(t_{ipc}, t_I)] &= \int_{x=0}^{\infty} Pr[min(t_{ipc}, t_I) > x]dx \\ &= \int_{x=0}^{t_I} Pr[t_{ipc} > x]dx \\ &= \int_{x=0}^{t_I} e^{-\lambda_{ipc}x}dx \\ &= \frac{1}{\lambda_{ipc}}[1 - e^{-\lambda_{ipc}t_I}] \end{aligned} \tag{27}$$

Similarly:

$$\begin{aligned} E[min(t_{is}, t_I)] &= \int_{x=0}^{\infty} Pr[min(t_{is}, t_I) > x]dx \\ &= \int_{x=0}^{t_I} Pr[t_{is} > x]dx \\ &= \int_{x=0}^{t_I} e^{-\lambda_{is}x}dx \\ &= \frac{1}{\lambda_{is}}[1 - e^{-\lambda_{is}t_I}] \end{aligned} \tag{28}$$

Substitute (27) and (28) into (26):

$$E[\bar{t}_{t_I}] = \frac{P_{pc}}{\lambda_{ipc}}[1 - e^{-\lambda_{ipc}t_I}] + \frac{P_s}{\lambda_{is}}[1 - e^{-\lambda_{is}t_I}] \tag{29}$$

And finally:

$$E[D_1] = \frac{\mu_p}{\lambda_s} + \frac{P_{pc}}{\lambda_{ipc}}[1 - e^{-\lambda_{ipc}t_I}] + \frac{P_s}{\lambda_{is}}[1 - e^{-\lambda_{is}t_I}] \tag{30}$$

2) $E[D_2]$: The UE in this state goes to S_1 only when a packet arrives before the expiry of (t_{ON}), otherwise, it goes to DRX sleep mode. So, $E[D_2]$ can be derived as follows:

$$\begin{aligned} &E[D_2] = \\ &\quad P_{pc}(\int_0^{t_{ON}} tPr[t_{ipc} = t]dt + \int_{t_{ON}}^{\infty} t_{ON}Pr[t_{ipc} = t]dt) \\ &\quad + P_s(\int_0^{t_{ON}} tPr[t_{is} = t]dt + \int_{t_{ON}}^{\infty} t_{ON}Pr[t_{is} = t]dt) \\ &\quad = P_{pc}(\frac{1 - e^{-\lambda_{ipc}t_{ON}}}{\lambda_{ipc}}) + P_s(\frac{1 - e^{-\lambda_{is}t_{ON}}}{\lambda_{is}}) \end{aligned} \tag{31}$$

3) $E[D_3]$: Since any packet arrived during DRX sleep period will be buffered until the next t_{ON}, $E[D_3]$ can be computed as:

$$E[D_3] = \alpha 2^n = t_{SS} = t_{DS} - t_{ON} \tag{32}$$

4)$E[D_4]$: And also any packet in this state will be buffered until the next t_{ON}, so, $E[D_4]$ can be computed as:

$$E[D_4] = (2\alpha)2^n = t_{LS} = t_{DL} - t_{ON} \tag{33}$$

After computing the mean spending time and steady-state probabilities, the expression for the power saving factor that is achieved by the DRX mechanism can now be gotten which can be obtained as follows:

$$\begin{aligned} PS &= \frac{\delta_3 E[D_3] + \delta_4 E[D_4]}{\sum_{i=1}^{4} \delta_i E[D_i]} \\ &= \frac{\delta_3 \alpha 2^n + \delta_4 (2\alpha)2^n}{\sum_{i=1}^{4} \delta_i E[D_i]} \end{aligned} \tag{34}$$

DRX improves energy efficiency at the expense of packet delay. The wake-up delay can be calculated as follows:

$$D_{wakeup} = P_3 E[W_3] + P_4 E[W_4] \tag{35}$$

where P_3 and P_4 are the probability that a new packet call arrives during DRX sleep mode (S_3 or S_4) and $E[W_3]$ and $E[W_4]$ are the average wake-up delay during state S_3 and S_4. $E[W_3]$ can be computed as follows:

$$\begin{aligned} E[W_3] = P_{pc} &\int_0^{\alpha 2^n} (\alpha 2^n - t)Pr[t_{ipc} = t]dt \\ + P_s &\int_0^{\alpha 2^n} (\alpha 2^n - t)Pr[t_{is} = t]dt \\ &= \alpha 2^n - P_{pc}(\frac{1 - e^{-\lambda_{ipc}\alpha 2^n}}{\lambda_{ipc}}) \\ &- P_s(\frac{1 - e^{-\lambda_{is}\alpha 2^n}}{\lambda_{is}}) \end{aligned} \tag{36}$$

and for $E[W_4]$:

$$\begin{aligned} E[W_4] = P_{pc} &\int_0^{(2\alpha)2^n} ((2\alpha)2^n - t)Pr[t_{ipc} = t]dt \\ + P_s &\int_0^{(2\alpha)2^n} ((2\alpha)2^n - t)Pr[t_{is} = t]dt \\ &= (2\alpha)2^n - P_{pc}(\frac{1 - e^{-\lambda_{ipc}(2\alpha)2^n}}{\lambda_{ipc}}) \\ &- P_s(\frac{1 - e^{-\lambda_{is}(2\alpha)2^n}}{\lambda_{is}}) \end{aligned} \tag{37}$$

P_3 can be computed as:

$$P_3 = \alpha_{ipc}\sum_{i=1}^{N_{DS}} e^{-i\lambda_{ipc}t_{DS}} + \alpha_{is}\sum_{i=1}^{N_{DS}} e^{-i\lambda_{is}t_{DS}} \tag{38}$$

where $\alpha_{ipc} = P_{pc}e^{-\lambda_{ipc}(t_I - t_{DS} + t_{ON})}(1 - e^{-\lambda_{ipc}t_{SS}})$ and $\alpha_{is} = P_s e^{-\lambda_{is}(t_I - t_{DS} + t_{ON})}(1 - e^{-\lambda_{is}t_{SS}})$.

P_4 can be computed as:

$$P_4 = \beta_{ipc}\sum_{i=1}^{\infty} e^{-i\lambda_{ipc}t_{DL}} + \beta_{is}\sum_{i=1}^{\infty} e^{-i\lambda_{is}t_{DL}} \tag{39}$$

where $\beta_{ipc} = P_{pc}e^{-\lambda_{ipc}(t_I + t_N - t_{DL} + t_{ON})}(1 - e^{-\lambda_{ipc}t_{LS}})$ and $\beta_{is} = P_s e^{-\lambda_{is}(t_I + t_N - t_{DL} + t_{ON})}(1 - e^{-\lambda_{is}t_{LS}})$.

IV. PERFORMANCE EVALUATION

In the Analytical study, the impact of various values of α and β on power saving factor (PS) and the wake-up delay is shown, while in the system level simulation α and β dynamically change. Details of performance evaluation parameters are provided in Table II.

TABLE II
PERFORMANCE EVALUATION PARAMETERS

Parameter	**Value**
$[\lambda_{ip}, \lambda_{ipc}, \lambda_{is}, \lambda_s]$	[10, $\frac{1}{10}$, $\frac{1}{2000}$, 10]
$[\mu_{pc}, \mu_p]$	[5, 5]
$[PSF, t_{ON}, t_I, N_{DS}]$	[1ms, 100ms, 10ms, 10]

A. Analytical Results

The impact of α and β on power saving factor and wake-up delay is illustrated in Fig. 3 and Fig. 4. With increasing α and β the UE will be in sleep mode for a longer time. Therefore, it is expected that the power saving factor increases. The power-saving factor and the wake-up delay are computed for four different values of α and β. The maximum amount of power saving is achieved in the case of $\alpha = 4$ and $\beta = 8$. With increasing α and β the wake-up delay will increase. For $\alpha = 4$ and $\beta = 8$ the wake-up delay is more than the other cases. According to Fig.4, the use of an adaptive algorithm (Algorithm 1) is essential in order to be able to adjust α and β based on incoming packets with the aim of limiting the average packet delay under a threshold delay.

B. Simulation Results

According to the proposed algorithm, two different threshold delays are considered. If the application runs in the UE is delay-sensitive, the threshold delay is considered D_{th}= 64ms, and if the application is delay tolerant, D_{th}= 512ms is chosen. To evaluate the proposed algorithm in different traffic conditions, two traffic models, Poisson, and Pareto traffic are used.

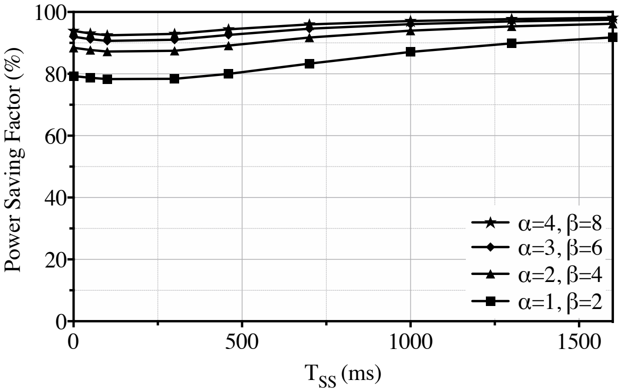

Fig. 3. Impact of α and β on Power Saving factor.

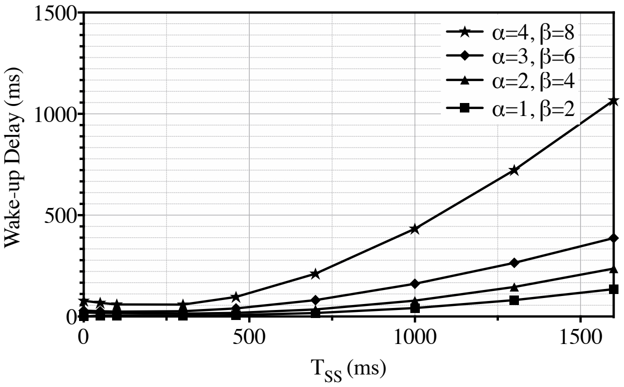

Fig. 4. Impact of α and β on Wake-up Delay.

Fig. 5 shows the percentage of time that the UE spends in the low power mode for the proposed algorithm (proposed-DRX) and the conventional DRX (DRX). As expected, the proposed algorithm can adjust the long sleep cycle and a short sleep cycle based on incoming traffic and average packet delay. The dynamic adjustment of sleep cycles has led to saving significant energy rather than conventional DRX. The reason for that is when average packet delay is less than D_{th}, α and β increase consequently, therefore, both long sleep cycle and short sleep cycle also increase to increase power saving in the UE and when average packet delay is higher than D_{th}, α and β decrease which leads to both long sleep cycle and short sleep cycle decrease to reduce the average packet delay. For example in the case of $D_{th} = 512ms$ in traffic rate 0.35 packet per PSF, the power efficiency has increased by about 43 percentage points compared to conventional DRX.

Fig. 6 shows the wake-up delay incurred by the DRX mechanism. In conventional DRX maximum delay is 13ms and by increasing traffic rate the amount of delay decreases. The algorithm in low traffic rate maintains the delay around the threshold delay in order to save more energy and by increasing

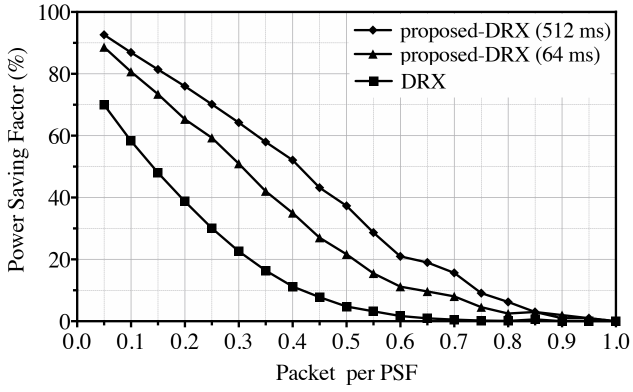

Fig. 5. Energy Saving in two different DRX models.

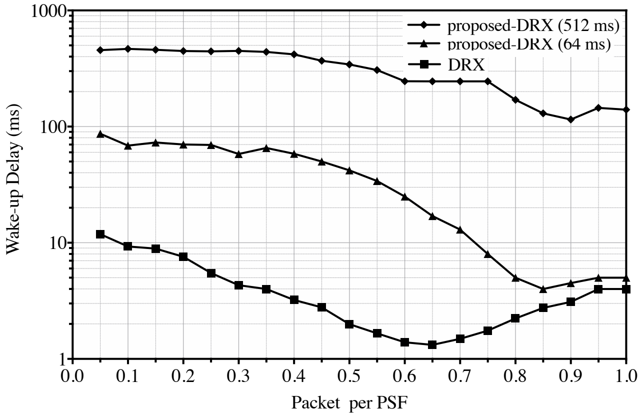

Fig. 6. Wake-up delay in two different DRX models.

traffic rate, it decreases the average packet delay. With the higher D_{th}, the greater energy saving will be obtained, while the packet delay also increases.

V. CONCLUSION

In this paper, a scheme was introduced to optimize the DRX mechanism in 4G LTE systems to reduce the energy consumption in the mobile device which will consequently increase battery power life. The algorithm adaptively modifies the DRX short and long sleep cycles in terms of the traffic rate and average packet delay. Also, we adjusted the DRX sleep cycle based on the average packet delay and incoming traffic and utilized the application sensitivity to delay that runs on the UE. The numerical analysis and simulation results have shown that the proposed scheme can achieve significant power saving compared to the conventional DRX mechanisms.

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