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The Tradeoff between Mean Delay and Energy Saving Factor under DRX Scheme

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ABSTRACT

Recently power saving is a vital issue for wireless devices of 4G and 5G networks. A device enters in sleeping mode (short and long sleep cycle) when there is no arrival of traffic but wakeup once the arrival of traffic. Before wakeup, the UE user equipment (UE) spends the rest of the sleeping cycle which incurs a delay of service. There is a tradeoff between the length of a sleep cycle (power saving factor ids higher for longer sleep cycle) and mean delay of service. In this paper, a Markov chain is designed including timer inactivity, short sleep, and long sleep and active service states. The closed-form solution of the chain is performed using node equations hence comparison of performance is made with previous work in the context of power-saving factor and mean delay. Both the power saving factor and mean delay of this paper are found marginally better than the previous work at lower packet arrival rate but at higher arrival rate performance are almost the same but claims some explanations.

General Terms

Energy savings, wireless communication, Long Term Evaluation.

Keywords

LTE, DRX, long sleep, short sleep, QoS, Markov Chain.

1. INTRODUCTION

The data rate of the Long Term Evaluation (LTE) network has increased tremendously compared to the previous 3G network. LTE provides many services like mobile TV, real-time gaming, HD video streaming and so on. However, these services consume the battery life of the devices very rapidly. The size of the battery is not increased to cope with the data rate. For this reason, several methods have been implemented to reduce the energy consumption of UE in wireless networks including idle/sleep modes in WiMAX and discontinuous reception (DRX) in LTE summarized in [1].

The DRX mechanism of LTE is a power-saving mechanism that saves the UE's battery. When there is no data to receive by the UE from the evolved Node-B (eNB), UE will go for short sleep mode, then wake up periodically at pre-determined times to check whether there is any data to receive or not. After a certain period of short sleep, UE will go for a long sleep. In these sleeping modes, UE will turn off its circuitry related to the transmission-reception to save the battery life found in [2]. However, there is a tradeoff between this power saving mechanism and user-end delay. For example, eNB has some data to transmit to the UE, but the UE is in sleeping mode, therefore it will wake up after its pre-determined schedule. In this case, the eNB has to wait until the UE wakes up, hence the communication system will experience a delay. This delay will hamper the applications which are delay-sensitive [3]. Intense research work is going on regarding the delay or latency of the wireless network. In [4], the authors have proposed a fuzzy-based power-saving scheduling scheme for IoT over the LTE/LTE-A networks. They have focused on three individual metrics: radio resource management, power consumption and the unexpected delay caused by the DRX mechanism from the scheduling and resource allocation perspective. The authors made a tradeoff among three individual metrics.

The authors in [5], showed the trade-off between the power-saving and wake-up delay performance based on the analytical model. The paper provides an overview of adjustable and non-adjustable DRX cycles of the LTE/LTE- A power-saving mechanism. They have modeled the system with bursty packet data traffic using a semi-Markov process. Ali et al., in [6] have developed an analytical model to estimate power saving achieved and latency incurred by DRX operation. They have formulated a tradeoff scheme to maintain a balance between these two parameters based on the operator's preference for power saving. They showed that their proposed scheme can achieve a significant delay improvement with a small decrease in power saving. Their results have indicated that the short DRX cycles are very effective in reducing latency for active traffic. They have pointed out the necessity of optimizing DRX configuration in order to maintain a tradeoff between power saving and buffering delay. Their conclusion is that a higher number of short DRX cycles is preferable for active traffic. The impact of latency on the power saving factor is also shown in [7-12].

In the previous work of the authors of this paper in [13], the sleep mode of the LTE network has been analyzed based on two statistical models: Poisson's probability density function (pdf) and Engset pdf with the help of Markov chain. In [14], the state transition chain contains three states: serving the state, state of timer inactivity and silent state, where a simplified statistical model using traffic parameters of arrival rate, pdf of interarrival time and its threshold value have been considered. In [15], a new simplified model of two states was developed. The model is helpful to measure the inclination of sleep and active state of a UE on the LTE network using the entropy of binary state. In [16] the concept of DRX is explained in a different way called optimistic DRX (ODRX), which is modeled by the finite state machine. The profiles of a power-saving factor against wakeup latency, data arrival rate and length of the cycle are shown with a comparison of DRX. A similar concept is available in [17], where the state transition chain is developed using a semi-Markov model and the results deal with the same parameters. Five steps Markov chain of the energy-saving model is found in [18] for 5G user equipment (UE). This paper mainly deals with analytical results on a state transition chain of ten states for the DRX scheme. The relation between traffic parameters, latency, and power-saving factors are shown graphically with some comparison of previous work.

This paper is organized as section 2 deals with the DRX scheme of UE using Markov chain with provides a complete solution of the chain and derivation of all parameters of DRX, section 3 provides the discussions of the results obtained based on a statistical analysis of section 2 and section 4 concludes the entire analysis.

2. SYSTEM MODEL

A UE under DRX enters a sleeping state when there is no downlink traffic for it for some duration above the threshold time. The UE wakes up from the sleeping state periodically to check whether it has any downlink packet from eNB. The time duration for which the UE remains in 'on state' for such checking is indicated as T_{ON}. The length of T_{ON} is about the duration of a few sub-frame. If there is no incoming packet for the UE within this T_{ON} period, then the UE will go to sleep mode again. When there is any packet destined for UE, then it starts the 'inactivity time' and goes to the continuous reception mode and on an average, it stays on that state for duration of T_0.

Figure. 1 shows the state transition chain of UE under DRX scheme, consists of 10 states. The state 0 is continuous reception state and states 1 to 9 are sleeping states. The sleep states are divided into two categories: states 1 to 6 are considered as short sleep states and that of 7 to 9 are long sleep states.

Table 1 shows the parameters used in designing the state transition chain are.

Let us apply node equations of [19-21] on node S_1,

$$S_1\left(e^{-\lambda T_{ON}}+\alpha\right)=S_0 e^{-\lambda T_0}$$

Table 1: Description of the notations used in the equations.

Symbol	Meaning
S_0	probability of staying in continuous reception mode
S_i: i=1 to 6	probability of staying in short sleep mode
S_i: i=7 to 10	the probability of staying in long sleep mode
α	probability of transition from short DRX to continuous reception mode
α'	probability of transition from long DRX to continuous reception mode
T_0	period of staying in continuous reception mode
T_S	short DRX cycle
T_L	long DRX cycle
T_{ON}	when a UE is enabled, it wakes up and stay in on mode for the duration T_{ON} to check whether any traffic is available for it or not
λ	mean packet arrival rate
λ_{pc}	mean packet arrival rate per session
μ_{pc}	mean packet call length per session
t_N	short sleep period (when terminates from short DRX)

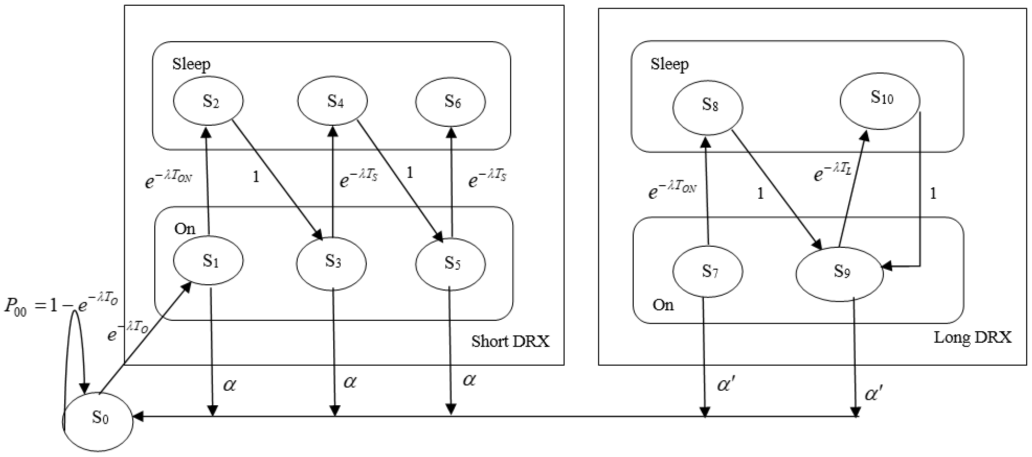


Figure. 1 State Transition between ON mode to short sleep and long sleep mode

$$\Rightarrow S_1=S_0\frac{e^{-\lambda T_0}}{\left(e^{-\lambda T_{ON}}+\alpha\right)}. \tag{1}$$

Node equation on state S_2,

$$S_2.1=S_1 e^{-\lambda T_{ON}}=S_0\frac{e^{-\lambda\left(T_0+T_{ON}\right)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)}. \tag{2}$$

At S_3,

$$S_3\left(\alpha+e^{-\lambda T_S}\right)=S_2.1$$

$$\Rightarrow S_3=\frac{S_2}{\left(\alpha+e^{-\lambda T_S}\right)}=S_0\frac{e^{-\lambda\left(T_O+T_{ON}\right)}}{\left(e^{-\lambda T_S}+\alpha\right)\left(e^{-\lambda T_{ON}}+\alpha\right)}. \tag{3}$$

At S_4,

$$S_4(1) = S_3 e^{-\lambda T_S}$$

$$\Rightarrow S_4 = S_0 \frac{e^{-\lambda(T_O+T_{ON}+T_S)}}{\left(e^{-\lambda T_S}+\alpha\right)\left(e^{-\lambda T_{ON}}+\alpha\right)}. \quad (4)$$

At S_5,

$$S_5\left(\alpha + e^{-\lambda T_S}\right) = S_4 \quad \Rightarrow S_5 = S_0 \frac{e^{-\lambda(T_O+T_{ON}+T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2} . \quad (5)$$

At S_6,

$$S_6 \times 1 = S_5 e^{-\lambda T_S}$$

$$\Rightarrow S_6 = S_0 \frac{e^{-\lambda(T_O+T_{ON}+2T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2} . \quad (6)$$

At S_7,

$$S_7\left(\alpha' + e^{-\lambda T_S}\right) = S_6$$

$$\Rightarrow S_7 = S_0 \frac{e^{-\lambda(T_O+T_{ON}+2T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2\left(e^{-\lambda T_S}+\alpha'\right)}. \quad (7)$$

At S_8,

$$S_8 \times 1 = S_7 e^{-\lambda T_S}$$

$$\Rightarrow S_8 = S_0 \frac{e^{-\lambda(T_O+T_{ON}+3T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2\left(e^{-\lambda T_S}+\alpha'\right)} . \quad (8)$$

At S_9,

$$S_9\left(\alpha' + e^{-\lambda T_L}\right) = S_8 \times 1 + S_{10} \times 1$$

$$\Rightarrow S_9 = \frac{S_8}{\left(\alpha' + e^{-\lambda T_L}\right)} + \frac{S_{10}}{\left(\alpha' + e^{-\lambda T_L}\right)} . \quad (9)$$

At S_{10},

$$S_{10} \times 1 = S_9 . e^{-\lambda T_L}$$

$$\Rightarrow S_{10} = S_9 . e^{-\lambda T_L} . \quad (10)$$

From (9) and (10),

$$S_9 = \frac{S_8}{\left(\alpha' + e^{-\lambda T_L}\right)} + \frac{S_9 e^{-\lambda T_L}}{\left(\alpha' + e^{-\lambda T_L}\right)}$$

$$\Rightarrow S_9\left(1 - \frac{e^{-\lambda T_L}}{\left(\alpha' + e^{-\lambda T_L}\right)}\right) = \frac{S_8}{\left(\alpha' + e^{-\lambda T_L}\right)}$$

$$\Rightarrow S_9 \times \frac{\alpha'}{\left(\alpha' + e^{-\lambda T_L}\right)} = \frac{S_8}{\left(\alpha' + e^{-\lambda T_L}\right)}$$

$$\Rightarrow S_9 = \frac{S_8}{\alpha'} \quad (11)$$

$$\therefore S_{10} = \frac{S_8}{\alpha'} . e^{-\lambda T_L} . \quad (12)$$

In this paper, 10 probability states of Markov chain are considered. To get the normalized probability states, the sum of probability of entire sampling space is needed as,

$$\sum_{i=1}^{10} S_i = 1 \quad (13)$$

From (13), the normalized probability of staying at state 0 will be,

$S_0 = 1/(A+B+C+D+E+F+G+H+I+J)$ (14)

, where

$$A = \frac{e^{-\lambda T_0}}{\left(e^{-\lambda T_{ON}}+\alpha\right)}, \qquad B = \frac{e^{-\lambda(T_0+T_{ON})}}{\left(e^{-\lambda T_{ON}}+\alpha\right)},$$

$$C = \frac{e^{-\lambda(T_O+T_{ON})}}{\left(e^{-\lambda T_S}+\alpha\right)\left(e^{-\lambda T_{ON}}+\alpha\right)},$$

$$D = \frac{e^{-\lambda(T_O+T_{ON}+T_S)}}{\left(e^{-\lambda T_S}+\alpha\right)\left(e^{-\lambda T_{ON}}+\alpha\right)},$$

$$E = \frac{e^{-\lambda(T_O+T_{ON}+T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2},$$

$$F = \frac{e^{-\lambda(T_O+T_{ON}+2T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2},$$

$$G = \frac{e^{-\lambda(T_O+T_{ON}+2T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2\left(e^{-\lambda T_S}+\alpha'\right)},$$

$$H = \frac{e^{-\lambda(T_O+T_{ON}+3T_S)}}{\left(e^{-\lambda T_{ON}}+\alpha\right)\left(e^{-\lambda T_S}+\alpha\right)^2\left(e^{-\lambda T_S}+\alpha'\right)}, \qquad I = \frac{H}{\alpha'}$$

$$J = \frac{H}{\alpha'} . e^{-\lambda T_L}$$

The other probability states can be determined from eq. (1)-(12).

Two important traffic parameters α and α' used in the Markov chain of Figure.1 are expressed like [22] as,

$$\alpha = \left(1 - \frac{1}{\mu_{pc}}\right)\left(1 - e^{-\lambda_{pc} t_N}\right) + \frac{1}{\mu_{pc}}\left(1 - e^{-\lambda_s t_N}\right) \quad (15)$$

and

$$\alpha' = \left(1 - \frac{1}{\mu_{pc}}\right)\left(1 - e^{-\lambda_{pc} t_{deep}}\right) + \frac{1}{\mu_{pc}}\left(1 - e^{-\lambda_s t_{deep}}\right) \quad (16)$$

Now the probability of staying in data reception mode is S_0.

The probability of staying in short DRX cycle is,

$P_{SS} = S_1+S_2+S_3+S_4+S_5+S_6$ (17)

The probability of staying in long DRX cycle is,

$P_{LS} = S_7+S_8+S_9+S_{10}$. (18)

The power saving factor,

$$P_{sf} = (P_{Ss}\times T_S+P_{LS}\times T_L)/(S_0\times T_0+ P_{SS}\times T_S+P_{LS}\times T_L) \qquad (19)$$

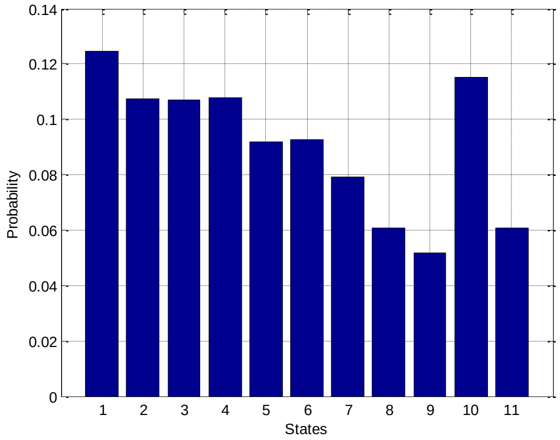
Mean Delay in ms

$$D = (P_{SS}\times TS+P_{LS}\times T_L)\times 1000 \qquad (20)$$

The next section will deal with numerical results using eq. (1)-(20) of this section.

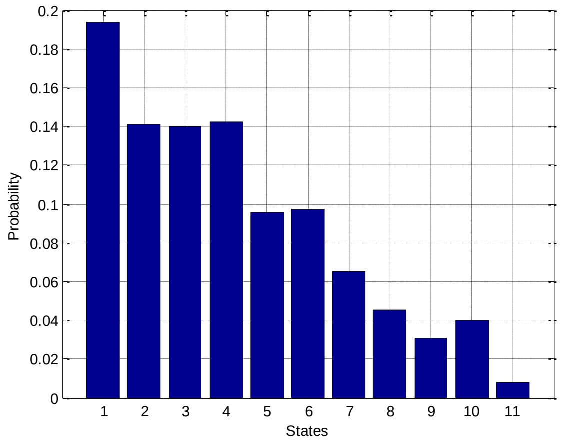
3. RESULTS AND DISCUSSIONS

Taking the usually used value of traffic parameters like [1]: on duration, T_{ON} = 2ms, duration of continuous reception, T_0 = 10 ms, length of short DRX cycle, T_S = 80ms and length of long DRX cycle, T_L = 320 ms; the following six-bar graph of Figure.2 (a)-(f) of 11 probability states have been obtained. In bar graph state 1 correspond to S_0, state 2 corresponds to S_1 and so on. Here mean packet arrival rate is taken as, λ = 2, 5, 10, 15, 20 and 25 packets/ms for six different bar graph. The numerical value of the probability of entering short sleep state P_{SS}, long sleep state P_{LS}, power-saving factor P_{sf} and mean delay D_{mean} in ms are shown with the heading of the corresponding bar graph. Comparing six bar graphs, it is found that all the 4 above parameters decrease with an increase in packet arrival rate which is also visualized from Figure.3. At a very low packet arrival rate, the UE will mostly stay in a long sleep state hence probability of entering at short sleep state is very low again when the arrival rate starts to grow then UE will move toward a short sleep state from the long sleep state. The phenomenon is visualized from Figure.3 for λ = 1 to 5 packets/ms. Further increase in λ, the UE will have the trend to move to a busy state hence probability of entering short sleep state decreases beyond the value of λ = 5 packets/ms also found from the same figure.



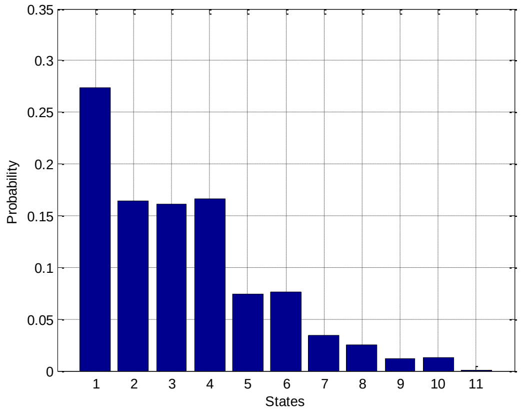
(a) Probability states for λ = 2 packets/ms,

P_{SS} = 0.5867, P_{LS} = 0.2885, P_{sf} = 0.9911 and D_{Mean}= 139.2503 ms

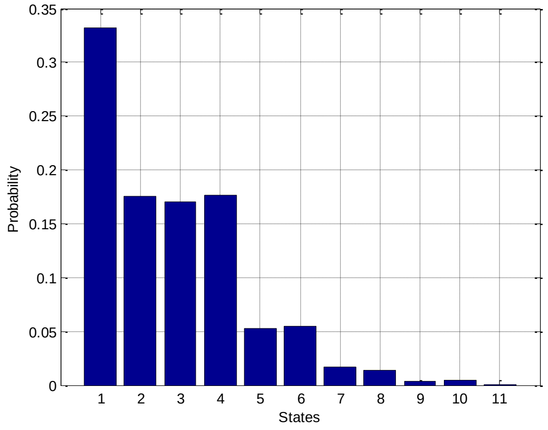


(b) Probability states for λ = 5 packets/ms,

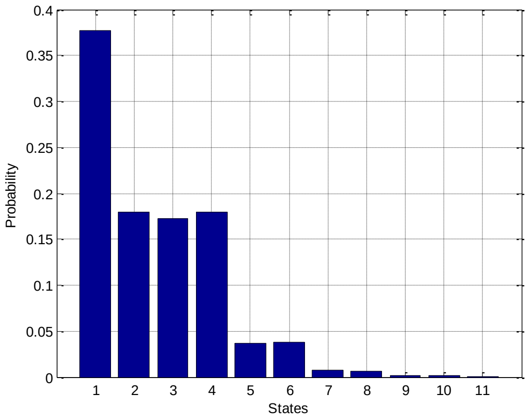
P_{SS} = 0.6816, P_{LS} = 0.1245, P_{sf} = 0.9799 and D_{Mean}= 94.3691 ms



(c) Probability states for λ = 10 packets/ms, P_{SS} = 0.6771, P_{LS} = 0.0496, P_{sf} = 0.9625 and D_{Mean}= 70.0522ms

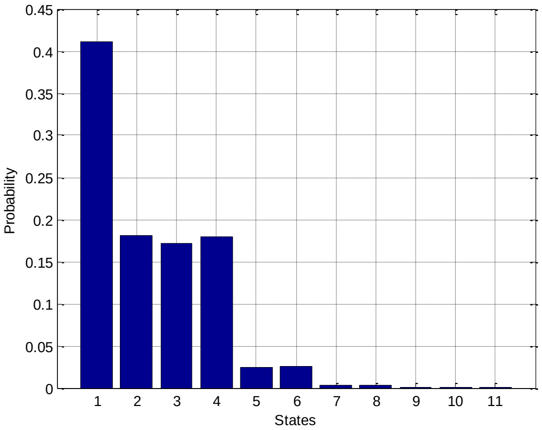


(d) Probability states for λ = 15 packets/ms, P_{SS} = 0.6458, P_{LS} = 0.0216, P_{sf} = 0.9463 and D_{Mean}= 58.58 ms



(e) Probability states for λ = 20 packets/ms,

P_{SS} = 0.6136, P_{LS} = 0.0094, P_{sf} = 0.9325 and D_{Mean}= 52.0882 ms



(f) Probability states for λ = 25 packets/ms, P_{SS} = 0.5850, P_{LS} = 0.0040, P_{sf} = 0.9213 and D_{Mean}= 48.0923 ms

Figure.2 Probability of 11 states of the state transition chain of Figure.1

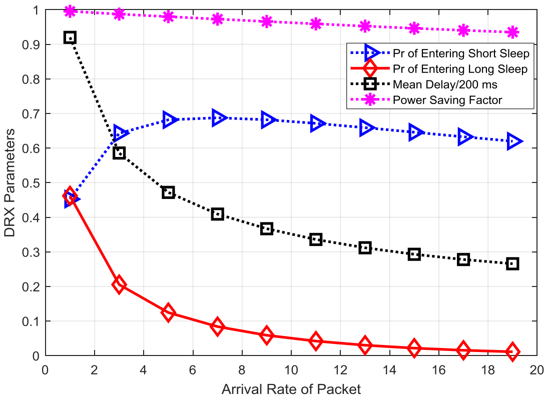


Figure.3 Variation of DRX parameters against the packet arrival rate

Figure.4 shows the variation of a power-saving factor against packet arrival rate in a session taking T_S as a parameter. The power-saving factor decreases exponentially with an increase in packet arrival rate since a higher packet arrival rate will keep the UE busier. With an increase in T_S the UE will stay longer duration at short sleep state also visualized from Figure.4. Al low arrival rate the UE will almost stay in long sleeping hence the impact of T_S will be less prominent compared to a moderate or higher value of packet arrival rate found from Figure.4. The impact of T_L will be very little on the power saving factor as shown in Figure.5 since the probability of entering al long sleep is very low.

Next, the variation of mean delay in ms is plotted against the packet arrival rate taking T_S as a parameter, where mean delay decreases with an increase in λ but increases with an increase in T_S shown in Figure.6. For a fixed probability of entering short sleep, the mean waiting time at short sleep will be higher for a larger value of T_S. The impact of T_L is less prominent on mean delay as shown in Figure.7 since the probability of entering at long sleep is low as found in Figure.5. The DRX algorithm saves energy of battery (indicated by a power-saving factor) at the expends of mean delay of buffer since when a new session arrives with several numbers of packets in the midst of sleep state then the packets will be buffered till the start of next DRX cycle. This phenomenon is found in Figure.6. When a UE stays in sleep for long then the energy of its battery is saved found from Figure.4. A 3D plot of arrival rate, mean delay and power-saving factor is shown in Figure.8, which reveals the tradeoff among the three parameters.

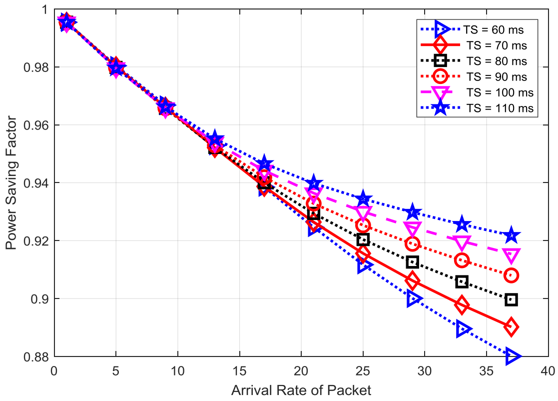


Figure.4 Variation of power-saving factor taking T_S as a parameter

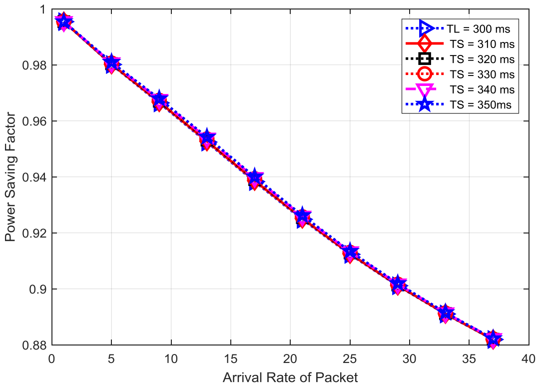


Figure.5 Variation of power-saving factor taking T_L as a parameter

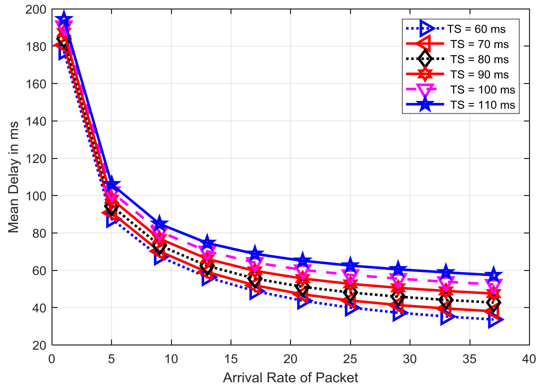


Figure.6 Variation of mean delay factor taking T_S as a parameter

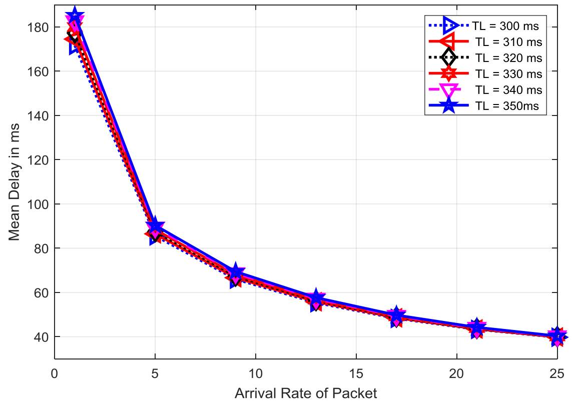


Figure.7 Variation of mean delay factor taking T_L as a parameter

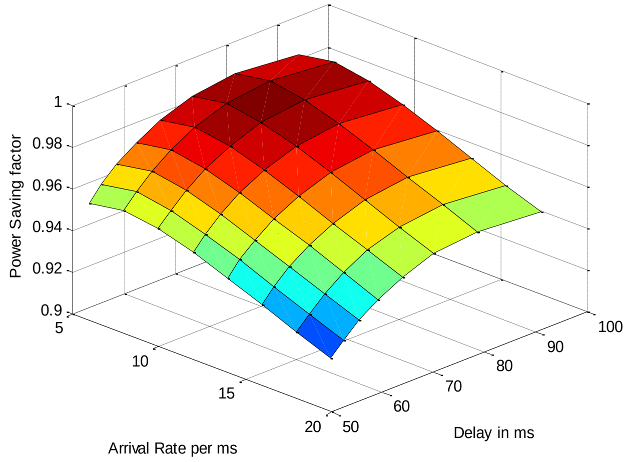


Figure.8 Tradeoff between mean delay and power-saving factor

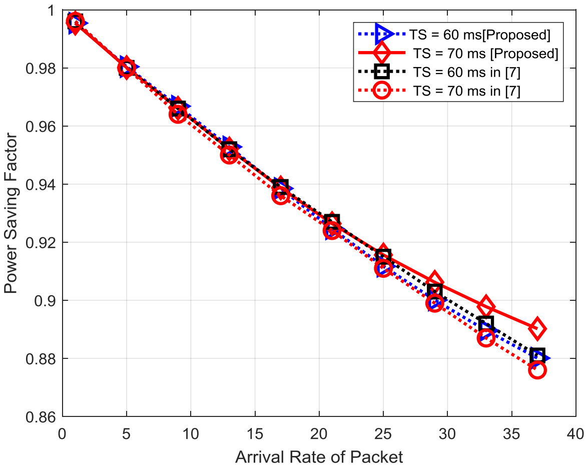


Figure.9 Comparison of the power-saving factor with [7]

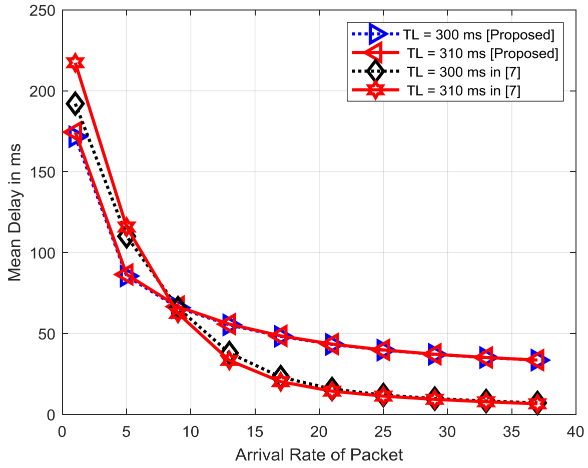


Figure.10 Comparison of mean delay with [7]

Finally, this paper is compared for the power saving factor with [7] for T_S = 60 ms and 70 ms as shown in Figure. 9. At lower arrival rate $\lambda < 25$ packets/ms, the four P_{sf} of the graph are very closed and all are above 92%. For higher arrival rate $\lambda > 25$ packets/ms, the traffic model used in this paper shows little improvement for T_S = 70 ms but for T_S = 60 ms the previous work reveals the better result. Our proposed model is superior to [7] at higher T_S. Again, the mean delay for the traffic model of the paper shows better results at low packet arrival rate $\lambda < 8$ packets/ms but at higher arrival rate, the traffic model of [7] shows much better results as shown in Figure.10. The main reason for such improvement is: the service time of the packet of [7] follows general distribution instead of exponential service time of this paper. The proposed model of the paper is suitable for an asynchronous connectionless link (ACL) where data integrity is more important than avoiding latency; provided the model of [7] is suitable for synchronous connection-oriented (SCO) link, where avoiding latency is more important than integrity (error-free delivery).

4. CONCLUSION

In this paper, the tradeoff between mean delay and power-saving factor are analyzed and the profile of both parameters are shown against the arrival rate of a packet. A comparison is made with previous work and found a better result on mean delay and power-saving factor at lower and higher offered traffic respectively. Still, there are the scopes to analyze the

DRX (discontinuous reception) for $M/G/1/m$, $M/D/1/m$ and $G/G/1$ traffic model to observe the relative power saving factor and mean delay of TCP/IP, ATM and mixed traffic of the wireless network. Two-dimensional Markov chain can be designed for traffic of dissimilar BW to observe the parameters of DRX under a complete sharing scheme of traffic. In the future, a phase-type Markov renewal process will be designed with active state, short DRX state and long DRX state considering the active state as the absorbing state.

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