LTE/LTE-A Discontinuous Reception Modeling for Machine Type Communications

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***Abstract*—Machine type communications (MTC) are considered as key applications in LTE/LTE-A networks, for which lowering power consumption is among the primary requirements. In this paper, we model the LTE/LTE-A discontinuous reception (DRX) mechanism for MTC applications based on a Semi-Markov chain model. With our model the power saving factor and wake up latency can be accurately estimated for a given choice of DRX parameters, thus allowing to select the ones presenting the best tradeoff. The proposed model is validated through simulations. We also investigate the effect of different DRX parameters on performance.**

***Index Terms*—LTE, DRX, MTC, Semi-Markov model**

I. Introduction

MTC such as metering, remote monitoring/control, etc. are playing an increasingly important role in cellular networks. For these types of applications, most MTC devices are powered by battery. Therefore, lowering the power consumption is among the primary requirements. To achieve this, DRX is employed in LTE/LTE-A networks. With DRX, a user equipment (UE) only turns on the receiver at some pre-defined time points while sleeps at others. It can be seen that the DRX mechanism attains power savings at the expense of an extra delay. Therefore it is preferred that the DRX parameters are selected such that the power saving is maximized while the application delay constraint is satisfied. However, the optimal trade-off between the power saving factor and wakeup delay is unknown.

[1], [2] present analytical methods to model the DRX mechanism in UMTS. However, LTE introduces two types of DRX cycles which is different form the single DRX cycle in UMTS. Hence, the models used in UMTS are not applicable to the LTE case. [3], [4] provide methods to model the LTE DRX mechanism in the presence of bursty and Poisson traffic, respectively. However, they do not take into account the "ON" duration, which is part of every short and long DRX cycle. They assume that a packet (always) arrives during the sleep period and has to be delayed and buffered. In practice, a packet may arrive during the ON part of a cycle and be sent by the eNB (base station) right away. This is not accounted for in the aforementioned models, leading to inaccurate estimates for the power-saving factor and average latency.

In this paper, we present a semi-Markov chain model to analyze the detailed DRX mechanism in LTE/LTE-A with MTC traffic. We do model the On duration parameter, which in LTE/LTE-A takes values between 1 and 200ms [6], by using two type of states to differentiate the On duration from the sleep period of short or long DRX cycle and show that it has a significant impact on the DRX performance. We use simulation to validate our results.

II. DRX mechanism in LTE

The mechanism of DRX is shown in Fig. 1. When enabled, the UE wakes up and checks for the downlink scheduling information during the subframes referred to as the *On Duration* (the period of *On Duration* is denoted as T_{ON}), which is located at the beginning of short/long DRX cycles. If not scheduled, the UE goes back to sleep for the purpose of power saving, otherwise it starts an *Inactivity Timer* T_0 and enters the continuous reception mode to check the scheduling information at every subframe. The *Inactivity Timer* will be restarted if the UE is rescheduled before the expiry of the timer. Otherwise, the UE starts a *Short DRX Cycle* T_S. If the UE is not scheduled after several short DRX, which is specified by the *DRX Short Cycle Timer* N, the UE starts the *Long DRX Cycle* T_L to increase the power saving factor (T_L is a multiple of T_S as specified in [6]).

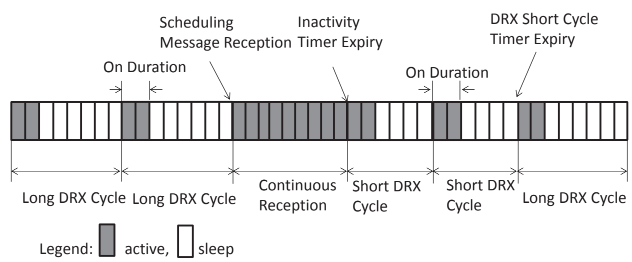
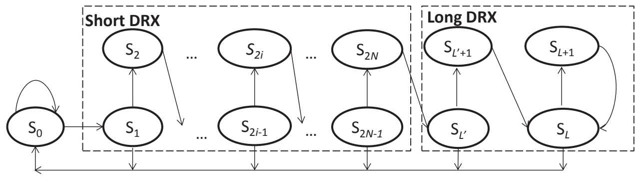


Fig. 1. DRX procedure in LTE

Here we assume that the traffic is Poisson distributed. The DRX mechanism can be regarded as a Semi-Markov chain model as shown in Fig. 2. The transitions between states are:

1) When the UE is at state S_0, if it is not scheduled before the expiry of the *Inactivity Timer*, the UE transfers to state S_1; otherwise it restarts the *Inactivity Timer* and remains at state S_0.
2) When the UE is at state S_{2i-1}, $i \in [1, N]$, if it is not scheduled before the expiry of the *On Duration*, the UE transfers to state S_{2i} and starts sleep; otherwise, the UE transfers to S_0.
3) When the UE is at state S_{2i}, $i \in [1, N-1]$, after sleeping for a period of $T_S - T_{ON}$ it wakes up and transfers to state S_{2i+1}.
4) When the UE is at state S_{2N}, after sleeping for a period of $T_S - T_{ON}$ it transfers to state $S_{L'}$ to start the first long DRX cycle.
5) When the UE is at state $S_{L'}$ if it is not scheduled before the expiry of the *On Duration*, it transfers to state $S_{L'+1}$ and starts sleep; otherwise, the UE transfers to S_0.



State	Description
S_0	Continuous reception mode
S_{2i-1}	Active period of the ith short DRX $i \in [1, N]$
S_{2i}	Sleep period of the ith short DRX $i \in [1, N]$
$S_{L'}$	Active period of the first long DRX
$S_{L'+1}$	Sleep period of the first long DRX
S_L	Active period of other long DRX
S_{L+1}	Sleep period of other long DRX

Fig. 2. Semi-Markov Chain model for DRX

6) When the UE is at state $S_{L'+1}$, after sleeping period of $T_L - T_{ON}$ it wakes up and transfers to state S_L.
7) When the UE is at state S_L if it is not scheduled before the expiry of the On *Duration*, it transfers to state S_{L+1} and starts sleep; otherwise, the UE transfers to S_0.
8) When the UE is at state S_{L+1}, after sleeping period of $T_L - T_{ON}$ it wakes up and transfers to state S_L.

The sleeping period is $T_S - T_{ON}$ before entering into state $S_{L'}$ while it is $T_L - T_{ON}$ when entering into state S_L, which is the reason why we use two states ($S_{L'}$ and S_L) to differentiate the first long DRX cycle from other DRX cycles.

For this Semi-Markov chain model, we start with the calculation for the stationary probability for each state and then derive the states' holding times. Denoting $p_{i,j}$ as the transition probability from state S_i to state S_j, the stationary probability of state i, π_i can be calculated as:

$$\pi_i = \pi_{i-1} \cdot p_{i-1,i}, \ i \in [1, 2N], \tag{1}$$

$$\pi_{L'} = \pi_{2N} \cdot p_{2N,L'}, \tag{2}$$

$$\pi_{L'+1} = \pi_{L'} \cdot p_{L',L'+1}, \tag{3}$$

$$\pi_L = \pi_{L'+1} \cdot p_{L'+1,L} + \pi_{L+1} \cdot p_{L+1,L}, \tag{4}$$

$$\pi_{L+1} = \pi_L \cdot p_{L,L+1} \tag{5}$$

With the above equations, we can get:

$$\pi_i = \pi_0 \cdot \prod_{j=1}^{i} p_{j-1,j}, i \in [1, 2N], \tag{6}$$

$$\pi_{L'} = \pi_0 \cdot p_{2N,L'} \prod_{j=1}^{2N} p_{j-1,j} \tag{7}$$

$$\pi_{L'+1} = \pi_0 \cdot p_{L',L'+1} \cdot p_{2N,L'} \prod_{j=1}^{2N} p_{j-1,j}, \tag{8}$$

$$\pi_L = \pi_0 \cdot \frac{p_{L'+1,L} \cdot p_{L',L'+1} \cdot p_{2N,L'}}{1 - p_{L,L+1} \cdot p_{L+1,L}} \prod_{j=1}^{2N} p_{j-1,j}, \tag{9}$$

$$\pi_{L+1} = \pi_0 \cdot \frac{p_{L,L+1} \cdot p_{L'+1,L} \cdot p_{L',L'+1} \cdot p_{2N,L'}}{1 - p_{L,L+1} \cdot p_{L+1,L}} \prod_{j=1}^{2N} p_{j-1,j}. \tag{10}$$

The state transition probability for this model is calculated as following. Here we assume that packet arrival rate of the Poisson distributed traffic is λ, therefore the packet interval time T' follows an exponential distribution with expected value $1/\lambda$. Moreover, we assume that at the eNB side there is at most one packet arriving in the short or long DRX cycle for a UE. This assumption is realistic and comes from the observation that most MTC traffic is *uplink dominated* and the average downlink packet interval per UE is much larger than the short or long DRX cycle. In [7]- [9] the proposed packet interval time for MTC traffic is 30 or 300s, while the maximum short and long DRX cycle is 640ms and 2.56s respectively. Assuming the packet arrival interval is 30s and the long DRX cycle is 2.56s (maximum value), the probability that more than one packets arrive in a long DRX is 0.003. Moreover for delay sensitive MTC applications the long DRX cycle is usually set to be in the order of several hundred milliseconds to comply with latency requirements, where the probability that more than one packets arriving in a long DRX is even smaller (it equals 0.0002 when the long DRX cycle is 640ms). Though we take the assumption here to be an accurate approximation for existing applications, we will test the model against simulations with higher traffic rates.

There are eight types of state transitions. We start with the calculation for the first case. Recall that from the Markov chain model described above we can see that, after receiving a packet, the UE is at state S_0 for a period of T_0 at most. As we assume that there is at most one packet arrived in a short/long DRX cycle, the transition from state S_0 to S_1 is only triggered by the event that another packet arrives after the expiry of the *Inactivity Timer*. Hence the state transition probability $p_{0,1} = p(T' > T_0) = e^{-\lambda T_0}$. Similarly, $p_{1,2} = e^{-\lambda T_{ON}}$.

When the UE is at state S_{2i}, $i \in [1, N-1]$, it transfers to state S_{2i+1} with probability 1, i.e. $p_{2i,2i+1} = 1$. Similarly, $p_{2N,L'} = 1$, $p_{L'+1,L} = 1$, and $p_{L+1,L} = 1$.

When the UE is at state S_{2i+1}, $i \in [1, N-1]$, if it receives a packet which arrived at eNB during the state S_{2i} and *On Duration*, it transfers to state S_0; otherwise it transfers to states S_{2i+2}. Therefore, $p_{2i+1,2i+2} = p(T' > T_S) = e^{-\lambda T_S}, i \in [1, N-1]$. Similarly, $p_{L',L'+1} = e^{-\lambda T_S}$, and $p_{L,L+1} = e^{-\lambda T_L}$.

Now let us calculate the holding time H_i for state S_i ($i = 0, 1, ..., 2N, L', L'+1, L, L+1$).

H_0. When UE is at state S_0, the packet arrives after the expiry of the *Inactivity Timer* with probability $p_{0,1}$ or it arrives at the ith subframe of the *Inactivity Timer* with probability p_i. Therefore, $H_0 = p_{0,1} \cdot T_0 + \sum_{i=1}^{T_0} T_i p_i$, where T_i is the state holding time (in the unit of subframe) when the packet arrives at the ith subframe and $p_i = p(i-1 < T' < i) = e^{-(i-1)\lambda} - e^{-i\lambda}, i \in [1, T_0]$. If a packet arrives at the ith subframe of the *Inactivity Timer*, a new continuous reception is started. Hence, $T_i = i + H_0$. With these results, we can get

$$H_0 = T_0 + \sum_{i=1}^{T_0} i p_i / p_{0,1} = \frac{1 - e^{-\lambda T_0}}{(1 - e^{-\lambda}) e^{-\lambda T_0}}. \tag{11}$$

H_{2i-1}, $i \in [2, N]$. When UE is at state S_{2i-1}, there are three cases for packet arrivals: (i) the packet arrives after the expiry of the *On Duration* with probability $p_{2i-1,2i}$, (ii) the packet arrives at the jth subframe of the *On Duration* with probability p_j^{ON}, (iii) the packet arrived during the last sleep period (sleep period of the $(i-1)$th short DRX cycle) with probability p_s. Hence, $H_{2i-1} = p_{2i-1,2i} \cdot T_{ON} + \sum_{j=1}^{T_{ON}} T_j^{ON} p_j^{ON} + T_{sh} p_s$.

where T_j^{ON} is the state holding time if the packet arrives at the jth subframe of the *On Duration* and T_{sh} is the state holding time if the packet arrived during the last sleep period.

When the UE is at state S_{2i-1}, the probability that the packet arrived during the sleep period of the $(i-1)$th short DRX cycle is $p_s = p(T' < T_S - T_{ON}) = 1 - e^{-(T_S - T_{ON})\lambda}$ and the probability that the packet arrives at the jth subframe of the *On Duration* is $p_j^{ON} = p(T_S - T_{ON} + j - 1 < T' < T_S - T_{ON} + j) = e^{-(T_S - T_{ON} + j - 1)\lambda} - e^{-(T_S - T_{ON} + j)\lambda}, j \in [1, T_{ON}]$.

If a packet arrived during the sleeping period of the $(i-1)$th short DRX, it is delivered at the first subframe of the next *On Duration*. Hence, the state holding time T_{sh} is 1. Moreover, when a packet arrives at jth subframe of the *On Duration* the state holding time is $T_j^{ON} = j, j \in [1, T_{ON}]$.

With the above results, we can get

$$H_{2i-1} = \frac{e^{-\lambda(T_S - T_{ON})} - e^{-\lambda T_S}}{1 - e^{-\lambda}} + 1 - e^{-\lambda(T_S - T_{ON})}. \quad (12)$$

H_1. When the UE is at state S_1, there are two cases for packet arrival: (i) the packet arrives after the expiry of the *On Duration* with probability $p_{1,2}$, (ii) the packet arrives at the jth subframe of the *On Duration* with probability p_j^1. Therefore $H_1 = p_{1,2} \cdot T_{ON} + \sum_{j=1}^{T_{ON}} T_j^1 p_j^1$, where $T_j^1 = j$ is the state holding time when the packet arrives at the jth subframe of the *On Duration*.

When the UE is at state S_1, the probability that the packet arrives at the ith subframe of the *On Duration* is $p_j^1 = p(i-1 < T' < i) = e^{-(i-1)\lambda} - e^{-i\lambda}, i \in [1, T_{ON}]$. Hence, we have

$$H_1 = \frac{1 - e^{-\lambda T_{ON}}}{1 - e^{-\lambda}}. \quad (13)$$

$H_{L'}$. When the UE is state S_L', the packet arrival process is same as that of the state S_{2i-1}, $i \in [2, N]$. Therefore

$$H_{L'} = \frac{e^{-\lambda(T_S - T_{ON})} - e^{-\lambda T_S}}{1 - e^{-\lambda}} + 1 - e^{-\lambda(T_S - T_{ON})}. \quad (14)$$

H_L. When UE is at state S_L, there are also three cases for packet arrival: (i) the packet arrives after the expiry of *On Duration* with probability $p_{L,L+1}$; (ii) the packet arrives at the jth subframe of *On Duration* with probability $p_j^{L\_ON}$; (iii) the packet arrived during the last sleep period with probability p_{L_S}. Hence, $H_L = p_{L,L+1} \cdot T_{ON} + \sum_{j=1}^{T_{ON}} T_j^{L\_ON} p_j^{L\_ON} + T_{L\_S} p_{L\_S}$, where $T_j^{L\_ON}$ is the state holding time when the packet arrives at the jth subframe of the *On Duration* and T_{L_S} is the state holding time when the packet arrived at the ith subframe of the last sleep period.

When UE is at state H_L, the probability that the packet arrived during sleep period of the last long DRX cycle $p_{L\_S} = p(T' < T_L - T_{ON}) = 1 - e^{-(T_L - T_{ON})\lambda}$ and the probability that the packet arrives at the jth subframe of the *On Duration* is $p_j^{L\_ON} = p(T_L - T_{ON} + j - 1 < T' < T_L - T_{ON} + j) = e^{-(T_L - T_{ON} + j - 1)\lambda} - e^{-(T_L - T_{ON} + j)\lambda}, j \in [1, T_{ON}]$. Similar to the case of $E(H_{2i-1})$, $T_j^{L\_S} = 1$ and $T_j^{L\_ON} = j$. With these results we have

$$H_L = \frac{e^{-\lambda(T_L - T_{ON})} - e^{-\lambda T_L}}{1 - e^{-\lambda}} + 1 - e^{-\lambda(T_L - T_{ON})}. \quad (15)$$

The state holding time for other states is obvious: $H_{2i} = T_S - T_{ON}, i \in [1, N]$, $H_{L'+1} = T_L - T_{ON}$, and $H_{L+1} = T_L - T_{ON}$.

III. Power saving factor and wake up delay

With the results derived in the last section the proportion of time that the UE is in the sleep period of short DRX, p_{sd}, is

$$\begin{aligned} p_{sd} &= \frac{\sum_{i=1}^{N} \pi_{2i} H_{2i}}{\sum_{i=0}^{2N} \pi_i H_i + \sum_{i=0}^{1} \pi_{L'+i} H_{L'+i} + \sum_{i=0}^{1} \pi_{L+i} H_{L+i}} \quad (16) \\ &= \frac{e^{-\lambda(T_0 + T_{ON})} \frac{1 - e^{-\lambda N T_S}}{1 - e^{-\lambda T_S}} (T_S - T_{ON})}{T} \end{aligned}$$

where T is calculated by equation (20).

Similarly, the proportion of time that the UE is in the sleep period of long DRX, p_{ld}, is

$$\begin{aligned} p_{ld} &= \frac{\pi_{L'+1} H_{L'+1} + \pi_{L+1} H_{L+1}}{\sum_{i=0}^{2N} \pi_i H_i + \sum_{i=0}^{1} \pi_{L'+i} H_{L'+i} + \sum_{i=0}^{1} \pi_{L+i} H_{L+i}} \quad (17) \\ &= \frac{(e^{-\lambda(T_0 + T_{ON} + N T_S)} + \frac{e^{-\lambda(T_0 + T_{ON} + N T_S + T_L)}}{1 - e^{-\lambda T_L}})(T_L - T_{ON})}{T}. \end{aligned}$$

Therefore the power saving factor α, which is defined as the percentage of time the UE is at the power saving states is

$$\alpha = p_{sd} + p_{ld}. \quad (18)$$

Since packet arrivals are Poisson, the packet arrival time over short or long DRX follows a uniform distribution. Hence, the wake up delay, which is the interval between the time when a packet arrived at the eNB and the time when the packet is delivered by eNB, caused by short DRX and long DRX is $d_S = (T_S - T_{ON})/2$ and $d_L = (T_L - T_{ON})/2$, respectively. Finally, the overall wake up latency is

$$d = p_{sd} d_S + p_{ld} d_L. \quad (19)$$

As $d_S \le d_L$, therefore $\alpha d_S \le d \le \alpha d_L$, i.e. the wake up latency d is upper bounded by αd_L and lower bounded by αd_S. Moreover, from (18) and (19) we can see that the power saving factor and wake up latency tradeoff is affected by T_{ON}, which is different from the results in [3], [4].

IV. Simulation Validation

To validate the proposed method, simulations are carried out with a Matlab based simulator to compare the numerical results with analytical results under different packet arrival rates λ. The simulation parameters are chosen to represent a set of realistic and valid set of DRX parameters as specified in [6] and to also satisfy the constraints that $T_{ON} < T_S$, $T_{ON} < T_L$, and T_L to be a multiple of T_S. From Fig. 3, we can see that the analytical results are very close to the simulated ones, which verifies our method. Even when the packet arrival rate is 1 packet/s, our model still accurately estimates the power saving factor and wake up latency since in this scenario the probability that two packets arriving in the long DRX cycle is 0.03. We also compare the simulated and analytical results under different varied DRX parameters as shown in Fig. 4- 8. We observe that the *On Duration*, *Short DRX Cycle*, and *Long DRX Cycle* has stronger effect on the DRX performance than that of *Inactivity Timer* and *DRX Short Cycle Timer*.

$$T = \frac{1-e^{-\lambda T_0}}{(1-e^{-\lambda})e^{-\lambda T_0}} + e^{-\lambda T_0}\frac{1-e^{-\lambda T_{ON}}}{1-e^{-\lambda}} + e^{-\lambda(T_0+T_{ON})}\frac{1-e^{-\lambda N T_S}}{1-e^{-\lambda T_S}}(T_S - T_{ON}) \tag{20}$$
$$+ (e^{-\lambda(T_0+T_{ON})}\frac{1-e^{-\lambda(N-1)T_S}}{1-e^{-\lambda T_S}} + e^{-\lambda(T_0+T_{ON}+(N-1)T_S)})(\frac{e^{-\lambda(T_S-T_{ON})}-e^{-\lambda T_S}}{1-e^{-\lambda}} + 1 - e^{-\lambda(T_S-T_{ON})})$$
$$+ (e^{-\lambda(T_0+T_{ON}+NT_S)} + \frac{e^{-\lambda(T_0+T_{ON}+NT_S+T_L)}}{1-e^{-\lambda T_L}})(T_L - T_{ON}) + \frac{e^{-\lambda(T_0+T_{ON}+NT_S)}}{1-e^{-\lambda T_L}}(\frac{e^{-\lambda(T_L-T_{ON})}-e^{-\lambda T_L}}{1-e^{-\lambda}} + 1 - e^{-\lambda(T_L-T_{ON})}).$$

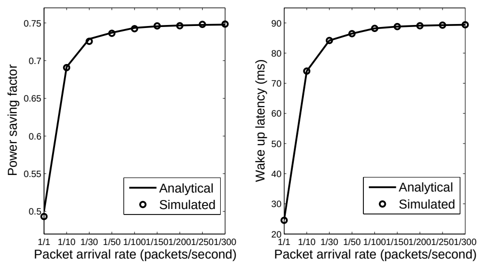


Fig. 3. DRX performance under different packet arrival rates, and $T_0 = 20ms$, $T_{ON} = 80ms$, $T_S = 160ms$, $N = 16$, $T_L = 320ms$

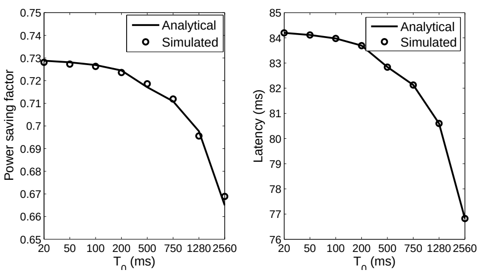


Fig. 4. DRX performance under different inactivity timers, and $T_{ON} = 80ms, T_S = 160ms, N = 16, T_L = 320ms$, $\lambda = 1/30$ packets/s.

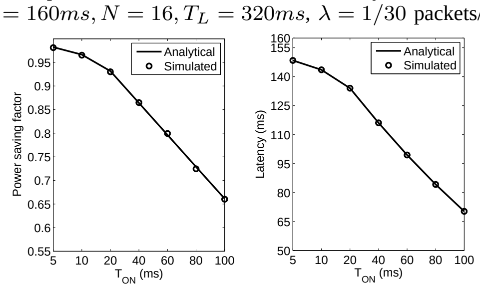


Fig. 5. DRX performance under different On durations, and $T_0 = 20ms, T_S = 160ms, N = 16, T_L = 320ms$, $\lambda = 1/30$ packets/s.

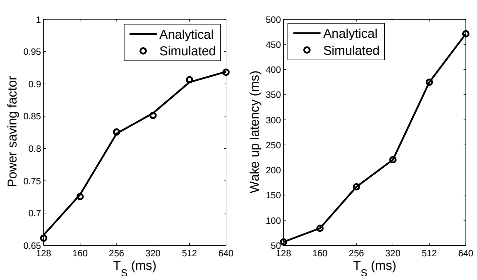


Fig. 6. DRX performance under different short DRX cycle, and $T_0 = 20ms, T_{ON} = 80ms, N = 16, T_L = 2 \cdot T_S ms$, $\lambda = 1/30$ packets/s.

V. Conclusion

We propose a Semi-Markov chain model to analyze the DRX mechanism for MTC over LTE/LTE-A. The model accurately derives the wake up latency and power saving factor by calculating the stationary probabilities and holding times for the active and sleeping states. The accuracy of the proposed model is validated through simulations. We also find out that the *On Duration*, *Short DRX Cycle* and *Long DRX Cycle* have a stronger impact on the DRX performance than *Inactivity Timer* and *DRX Short Cycle Timer*.

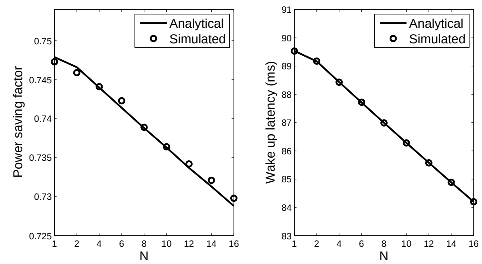


Fig. 7. DRX performance under different DRX short cycle timer, and $T_0 = 20ms, T_{ON} = 80ms, T_S = 160ms, T_L = 320ms$, $\lambda = 1/30$ packets/s.

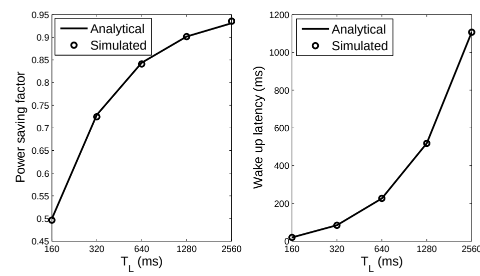


Fig. 8. DRX performance under different long DRX cycle, and $T_0 = 20ms, T_{ON} = 80ms, T_S = 160ms, N = 16$, $\lambda = 1/30$ packets/s.

VI. Acknowledgments

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