Optimization of Discontinuous Reception (DRX) for Mobile Internet Applications Over LTE

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***Abstract*—Discontinuous reception (DRX) brings power saving at user equipment (UE) at the cost of increased delay in 3GPP long term evolution (LTE) network. While configuring DRX parameters, a tradeoff between power saving and delay is inevitable in practice. For example, delay is crucial factor for delay sensitive applications such as online gaming, while power saving becomes the main concern for social networking applications. In this paper, we propose an algorithm to efficiently select DRX parameters to ensure a balanced tradeoff between these two conflicting performance parameters depending on application's delay requirement and UE power constraint. The proposed scheme is capable of optimizing one of these performance parameters while satisfying a specified level of guarantee for the other. Simulation results show that proposed algorithm is able to increase the power saving significantly by efficiently selecting the DRX parameters. For example, smart selection of DRX cycle for given inactivity timer increases the power saving by more than 40% depending on the delay requirement. Simulation results further show that proposed algorithm provides higher flexibility in DRX parameter selection by allowing a DRX parameter to be relaxed with the adjustment in other DRX parameter without any performance degradation.**

I. Introduction

The evolving 4G wireless communication technology called long term evolution (LTE) has shown promise to offer higher data transfer rate over radio access part of the network by using higher order modulation, advanced coding and advanced antenna system [1][2]. However, the computationally complex circuitry used in user equipment (UE) has also increased battery energy consumption at UE and hence limit the potential use of 4G services.

The potential capability of LTE network to provide high speed internet connection combined with recent development of smart phones, tablets and e-readers has changed the internet usage paradigm drastically. Numerous diverse data applications have been developed for these devices, which attract users to access internet more frequently over the LTE network [3]. It has been found that the traffic generated by these applications has quite different pattern than that of the traditional wireless applications [4]. These recent applications generate random and short bursts of packet activities even when user is not actively using these applications. As a result, UE keeps connecting (entering RRC_CONNECTED) and disconnecting (moving to RRC_IDLE) from the network more frequently which causes continuous battery power consumption. In order to avoid frequent state changes, UE can stay in the connected (RRC_CONNECTED) state with an effective DRX parameter setting which can give the same level of power saving compared to idle (RRC_IDLE) state.

Discontinuous reception (DRX) is adopted as one of the efficient UE power saving mechanisms for LTE networks in the recent 3GPP releases [5] [6]. LTE supports always connected experience by forcing the UE to continuously monitor the control signals on the channel called Physical Downlink Control Channel (PDCCH) to be able to send and receive actual data. In DRX, UE saves power by monitoring PDCCH less frequently whenever there is no uplink (UL) and downlink (DL) data transmission related to it [5].

In DRX mechanism, UE remains asleep and wakes up only for a short period called DRX ON period in order to monitor PDCCH for each DRX cycle. Each DRX cycle consists of DRX ON and DRX OFF/sleep periods. Note that we use DRX OFF and DRX sleep interchangeably throughout this paper. The amount of power saving largely depends on DRX parameters setting. For example, longer and frequent DRX cycle for a predefined DRX ON duration improves UE power saving at the expense of data packet delay. In practice, a trade off between power saving and delay seems to be inevitable and hence an efficient DRX scheme which can adopt its parameters based on applications and instantaneous UE conditions are required.

Since adaptive DRX mechanism in LTE is relatively a new research area, only a few work has been reported in literature. A tradeoff relationship between power saving and packet waiting delay has been investigated for LTE DRX mechanism with adjustable DRX cycles in [7]. The work in [7] has also shown that LTE DRX achieves better power saving than that of Universal Mobile Telecommunications System (UMTS) DRX at the cost of longer packet waiting delay in the former. Authors in [8] have pointed out the fact that power saving by DRX comes at the cost of degraded system utility. The authors proposed an adaptive DRX inactivity timer based on the channel condition between UE and enhanced nodeB (eNB), so that UE with bad channel quality will go to sleep for lesser time. In this way UE with bad channel condition can increase its transmission opportunity to increase average throughput at the cost of reduced power saving. Note that inactivity timer defines the period during which UE must monitor PDCCH after the previous successful decoding of PDCCH message. Ref [9] presents the effect of DRX functionality on the traditional LTE scheduling. It proposes a DRX-aware scheduling scheme to reduce the packet loss

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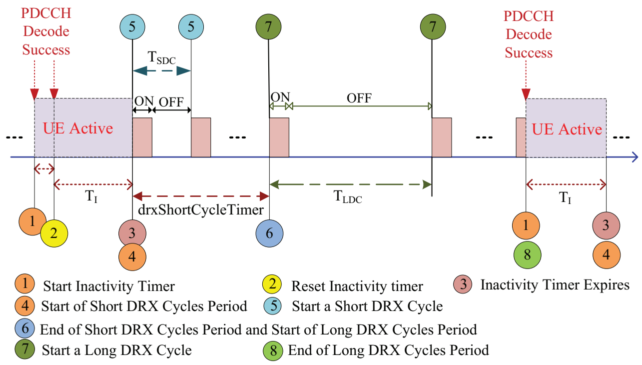

Fig. 1. A typical scenario of DRX mechanism in LTE.

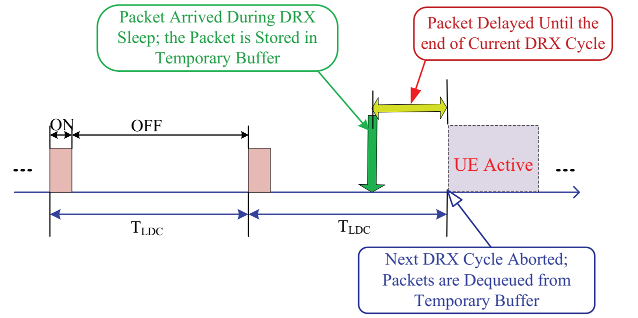

Fig. 2. Buffering functionality in the proposed DRX model. Buffering is performed at eNB for DL packets and at UE for UL packets

rate due to DRX sleep. However, in most of the existing work in literature, effect of buffering delay during DRX sleep have not received much attention.

In this paper, we investigate the effect of packet buffering on application delay performance. We also propose an efficient algorithm to select DRX parameters based on delay requirement of the application and power saving constraint of UE. The proposed algorithm is able to provide a balanced tradeoff between power consumption and delay over air interface due to buffering. It optimizes one of these performance parameters while satisfying a predefined performance guarantee to other. Moreover, the proposed algorithm provides a flexible approach in which one of the DRX parameters can be relaxed with adjustment in other DRX parameters.

The rest of this paper is organized as follows. Section II presents overview of DRX mechanism in LTE. Design of DRX mechanism and proposed DRX parameters selection algorithm are presented in Section III. Then, in Section IV we present simulation setup and provide selected simulation results to evaluate the proposed DRX scheme. Finally, the paper is concluded in Section V.

II. Overview of DRX Mechanism in LTE

UE may be configured by the radio resource control (RRC) with a DRX mechanism which controls the UE's PDCCH monitoring activity in the LTE system [5]. In LTE there are two different UE States: RRC_IDLE and RRC_CONNECTED. UE is actively connected with eNB in RRC_CONNECTED, while UE enters low power state called RRC_IDLE when it is no longer actively connected with eNB. UE in RRC_IDLE state can be traced by network using a mechanism called paging. DRX functionality can be configured for both of these states. Since data transmission sessions take place in RRC_CONNECTED state, in this paper, we focus on DRX functionality only in RRC_CONNECTED state.

Fig. 1 depicts the DRX functionality in RRC_CONNECTED state. For simplicity, RRC_IDLE state is not shown in 1. RRC controls the DRX mechanism on per UE basis by configuring the timers: $on\ Duration\ Timer$ (T_{ON}), $DRX\ Inactivity\ Timer$ (T_I), $Long\ DRX\ Cycle$ (T_{LDC}), $drxStartOffset$, and optionally the $drxShortCycleTimer$ and $short\ DRX\ Cycle$ (T_{SDC}) [5]. These timers are referred to as DRX parameters throughout this paper. When T_I is running, UE continuously monitors PDCCH for possible DL transmission scheduled for the UE. After getting indication of DL transmission, the T_I is reset. Upon expiration of T_I, UE enters DRX cycles by starting T_{SDC} and $drxShortCycleTimer$ if short cycle is configured. Short cycle T_{SDC} repeats until $drxShortCycleTimer$ expires which finally triggers long DRX cycle T_{LDC}. If short cycle is not configured T_{LDC} starts right after expiration of T_I. After expiration of T_I, DRX cycle (short or long) may not start immediately. $drxStartOffset$ determines the next subframe where DRX cycle shall start after the expiration of T_I as described in [5]. During each DRX cycle (short or long) UE monitors PDCCH for a period T_{ON} and stays asleep for rest of the cycle. Note that on duration is of same length T_{ON} for short and long DRX cycles. Indication of DL transmission during T_{ON} terminates the DRX operation and starts T_I. Similarly, arrival of higher layer data packets for uplink transmission during T_{ON} terminates the DRX cycle and starts T_I.

III. Design of DRX Mechanism and Choices

Fig. 2 illustrates an arbitrary scenario of temporary packet buffering during the DRX OFF period. In the proposed DRX model, if a DL packet for a UE in DRX sleep arrives at eNB, the packet is buffered in a temporary DRX buffer. At the end of DRX OFF period which is also the end of DRX cycle, eNB dequeues all these buffered packets. Similarly, UE buffers UL data packets which arrive during the DRX OFF period and dequeues them at the end of DRX OFF period. Arrival of any data packet (UL or DL) during a DRX OFF period aborts DRX operation at the end of the current DRX cycle and makes UE active.

Due to unpredictable user activity, data packet arrival during sleep period and hence the temporary buffering of these packets cannot be avoided. As a result, delay performance over air can be degraded with DRX mechanism in operation. Fig. 3 depicts simulation result showing effect of DRX buffering on the delay performance for each packet. The results are collected for a typical LTE network scenario where users UE_S_1 and UE_S_2 are running same application (voice over internet

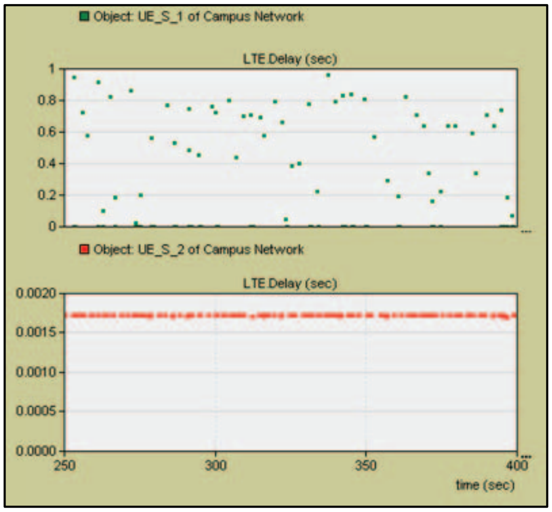

Fig. 3. Effect of DRX buffering on delay over LTE air interface. UE_S_1 with DRX ($T_{ON} = 10ms$, $T_I = 300ms$ and $T_{LDC} = 1024ms$) and UE_S_2 with no DRX.

protocol (VoIP) with the setting as described in Section IV-A later). From Fig. 3, it is obvious that power saving achieved by DRX functionality adds buffering delay in the overall delay over LTE air interface and hence may increase end-to-end packet delay. It can be seen that buffering delay in Fig. 3 is always less than $1000ms$. Note that maximum possible buffering delay for given setting is $T_{LDC} - T_{ON} = 1014ms$.

In the following section, we present an algorithm to optimize a balance between power saving and delay performance degradation.

A. Proposed DRX Parameters Selection Algorithm

In this section we discuss a DRX parameters selection algorithm which considers maximum delay t_{max} constraint of the application and minimum power saving $P_{s,min}$ imposed by the UE in order to decide a balanced tradeoff between power saving and delay. We also introduce two parameters γ_{delay} and γ_{PS} which indicates priority levels assigned to delay constraint and power saving respectively. γ_{delay}, γ_{PS}, t_{max} and $P_{s,max}$ may be adjustable based on the instantaneous UE conditions such as remaining battery power, type of application running and so on.

We now first define two scenarios which provide different levels of performance in terms of power saving and delay.

- *Configuration 1: Power saving maximization with predefined delay constraint ($\gamma_{delay} >= \gamma_{PS}$).* In this case, first we find feasible ranges for values of DRX parameters which can guarantee the specified delay constraint t_{max}. The parameters are then adjusted to maximize the power saving within the calculated feasible ranges. This scenario is more suitable for delay sensitive applications such as online gaming.
- *Configuration 2: Delay minimization with predefined power saving constraint ($\gamma_{PS} > \gamma_{delay}$).* In this case, feasible ranges of values for DRX parameters satisfying specified UE power saving constraint $P_{s,max}$ are identified. The parameters are then tuned to minimize the delay within the calculated feasible ranges. This scenario is more suitable for UE with stringent battery power constraint or for the application with flexible delay requirement such as social networking applications.

For a fixed T_{ON}, power saving and delay performance are greatly dependent on values of T_I and T_{LDC}. Longer T_I forces UE to be active for longer time and reduces number of DRX cycle entry. Therefore, increase in T_I decreases average buffering delay at the cost of keeping UE in highest power consuming state (i.e. active state) for longer time. On the other hand, larger T_{LDC} for a fixed T_{ON}, increases DRX OFF duration for each DRX cycle. Increase in least power consuming state (i.e. DRX OFF) increases power saving. However, due to packet buffering during DRX OFF state, increase in DRX OFF period adds buffering delay. Therefore, power saving can be increased by making DRX cycle longer and more frequent (i.e. shorter T_I), while delay performance can be improved by using shorter DRX cycle and longer T_I.

Let $\mathcal{I}$ and $\mathcal{D}$ represent the sets of all possible values under consideration for T_I and T_{LDC} respectively. 3GPP Standard values for T_I and T_{LDC} can be found in [6]. Selection of DRX parameters in proposed algorithm is then carried out at UE as described in Algorithm 1 where calculation of $average\ delay$ and $power\ saving$ are needed. In practice, UE and/or eNB can estimate $average\ delay$ and $power\ saving$ from statistics of previous communication. For example, initially $average\ delay$ can be approximated as $(T_{LDC} - T_{ON})/2$ for the purpose of DRX parameters selection assuming random packet arrival distribution. Once transmission of packets starts between UE and eNB, they can calculate actual $average\ delay$ over a time window and use it later to modify the DRX parameters by recalling Algorithm 1. Fraction of time UE is in DRX OFF state should be a reasonable $power\ saving$ metric. For the purpose of Algorithm 1, initially we may choose $power\ saving \approx (T_{LDC} - T_{ON})/(T_{LDC} + T_I)$. After application has started to send the packets, UE or eNB can calculate the actual fraction of time UE spends in DRX OFF in average over a time window to estimate the $power\ saving$ more precisely. Algorithm 1, can then use this value to tune DRX parameters. We will describe DRX parameters selection process by providing examples in Section IV-C.

IV. Performance Evaluation

A. Traffic Models and Simulation Setup under Consideration

We have used OPNET Modeler 16.1.A [10] as our simulation platform. We added DRX functionality into OPNET's default LTE Module. In our simulation scenario, two UEs are connected to an eNB and the eNB is connected to application server via EPC. The users UE_S_1 and UE_S_2 are running similar voice over internet protocol (VoIP) applications simultaneously in a LTE network with single cell site. Unless otherwise specified, we use VoIP application with following settings: incoming/outgoing silence length $= 0.5s$, incom-

Algorithm 1 DRX Parameters Selection

Update γ_{delay}, γ_{PS}, $\mathcal{I}$ and $\mathcal{D}$
if $\gamma_{delay} >= \gamma_{PS}$ **then**
  Read/Update t_{max}
  Select Configuration 1- Configure DRX parameters as follows:
  Calculate optimal T_{LDC}:
  $T_{LDC,Opt} \leftarrow \max_{T_{LDC} \in \mathcal{D}} T_{LDC}$
  such that $average\ delay \leq t_{max} \quad \forall T_I \in \mathcal{I}$
  Calculate optimal T_I given that $T_{LDC} = T_{LDC,Opt}$:
  $T_{I,Opt} \leftarrow \arg\max_{T_I \in \mathcal{I}} \ Power\ Saving$
else
  Read/Update $P_{s,min}$
  Select Configuration 2- Configure DRX parameters as follows:
  Calculate optimal T_I:
  $T_{I,Opt} \leftarrow \max_{T_I \in \mathcal{I}} T_I$
  such that $power\ saving \geq P_{s,min} \quad \forall T_{LDC} \in \mathcal{D}$
  Calculate optimal T_{LDC} given that $T_I = T_{I,Opt}$:
  $T_{LDC,Opt} \leftarrow \arg\min_{T_{LDC} \in \mathcal{D}} \ average\ delay$
end if
return $T_{LDC,Opt}$ and $T_{I,Opt}$

ing/outgoing talk spurt length $= 0.5s$, incoming/outgoing encoder $G.726\ 40K$ (silence), session duration $= 1s$, and session repetition with time offset uniformly distributed between $0.1s$ and $2s$. UE_S_1 uses DRX functionality, while UE_S_2 uses no DRX and is always active. For each set of DRX parameter, simulation results are collected for a simulation duration of $4000s$ and a constant DRX ON duration $T_{ON} = 10ms$ is used for each simulation run. The values of DRX timers such as T_I, T_{LDC} and T_{ON} used in the simulation are aligned with the 3GPP Standard [6] values. Note that only long DRX cycle has been configured to obtain the results in this paper. Therefore, DRX cycle refers to long DRX cycle in rest of the paper.

B. Performance parameters

We have selected delay and power saving as two major performance parameters to evaluate the DRX parameters selection. We have calculated packet delay over the LTE air interface in order to evaluate the delay performance for various DRX parameter sets. Lower LTE delay means better delay performance. To quantify the power saving performance, we have measured the time periods UE has spent in various states such as DRX OFF, DRX ON and Active. DRX OFF state consumes minimal UE battery power, while Active state consumes the highest amount of UE power. Power consumption in DRX ON state is in between those of DRX OFF and Active states. Since DRX OFF is the minimal power consuming state, higher value of DRX OFF state represents higher power saving.

C. Selected Simulation Results and Discussion

In this section, we will discuss the tradeoff between power consumption and delay for different DRX parameter sets with

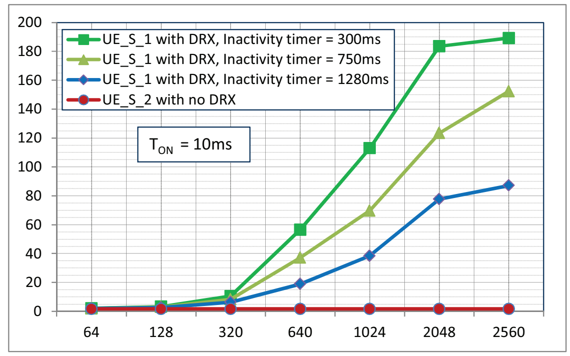

Fig. 4. Variation of average delay over LTE air interface versus DRX long cycle (T_{LDC}) for various inactivity timers (T_I).

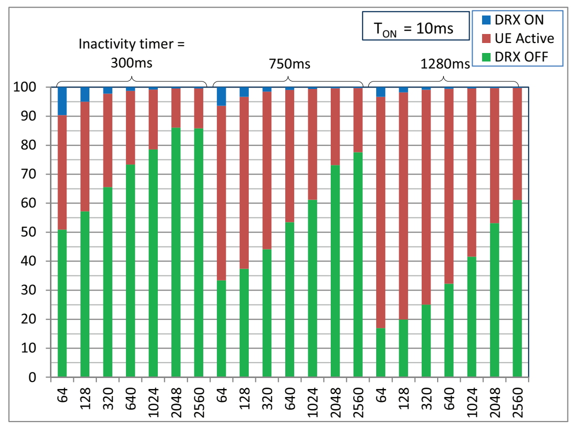

Fig. 5. Variation of UE states versus DRX cycle (T_{LDC}) for various inactivity timers (T_I).

the help of selected simulation results. In Fig. 4, we compare average delay performance for various T_{LDC} changing from 64ms to 2560ms. Average delay increases with increasing T_{LDC} for a given value of T_I. The reason is longer T_{LDC} increases DRX OFF duration in each cycle for a constant T_{ON}. Increase in DRX OFF duration causes more packets being buffered and delayed. For the similar reason time spent by UE in DRX OFF state increases with increase in T_{LDC} as can be seen in Fig. 5. Note that proposed algorithm is able to increase the power saving (i.e. DRX OFF state time) approximately by 35% and 44% respectively for $T_I = 300ms$ and $750ms$ by choosing proper T_{LDC}. The average delay for a UE with no DRX is found to be approximately constant around 1.72ms. However UE with no DRX always stays in UE Active mode and consumes more power compared to that in DRX mode.

In Fig. 6, we show variation of average delay with T_I. It is observed that for a given DRX cycle, average delay decreases with the increase in T_I. Increase in T_I decreases number of DRX entry and therefore probability of going into DRX OFF state also decreases. As a result, lesser packets get buffered resulting in lower average delay. As expected, if we increase T_I to highest possible value of 2.56s, with the simulated traffic UE rarely enters the DRX mode and therefore the average delay is close to that in case of no DRX. However, longer T_I means UE is active for longer time and hence power consumption is increased as shown in Fig. 7. In the following we discuss DRX parameters selection with the help of these results.

1) Maximize Power Saving with Predefined Delay Constraint: In this case each application has a delay bound (i.e. maximum acceptable delay). Given a delay bound, using Figs. 4–7, we will try to come up with a DRX setting which should satisfy this delay bound and maximize power saving by selecting the best DRX parameters. For example, let us choose a delay bound of 120ms. Then, from Fig. 4, we can see that $T_{LDC} \leq 1024ms$ satisfies 120ms delay for all three different T_I values considered in the same figure. After picking the range of T_{LDC}, using Fig. 5 we can pick the best T_I depending on the power saving needs. For example for 1024ms cycle length , if we want to save power more than 70% of the time, we must choose T_I of 300ms. More concisely, any value of T_I less than 300ms can save power more than 70% time and keep average delay below 120ms as can be figured out from Figs. 6 and 7. By the statement 'saving power for more than 70% time' we mean keeping UE in minimal power state called DRX OFF state for more than 70% of time in rest of the paper.

2) Minimize Delay with Predefined Power Saving Constraint: As an LTE operator, we can design our system to have a predefined minimum power saving requirement at UE with DRX in operation. In this case, DRX parameters must be configured to achieve the minimum power saving first. Using Figs. 6 and 7, we will try to come up with a DRX parameter setting which will satisfy power saving need of the operator first and then try to minimize the delay. For example if we want to save power more than 40% of time, using Fig. 7, it is clear that T_I must be 750ms or smaller so that power saving of 40% of time can be achieved for all three values of DRX cycles considered in the same figure. Let us say we select T_I as 750ms. After choosing the T_I, using Fig. 6, we now try to minimize the delay by picking $T_{LDC} = 320ms$. Note that average delay cannot be further decreased by selecting T_{LDC} of lower values, otherwise power saving constraint (40% or more) will not be satisfied as depicted in Fig. 5.

V. Conclusion

In this paper, we explored the tradeoff between power saving and delay for discontinuous reception (DRX) functionality in LTE network. We showed that these two performance parameters are conflicting to each other and a tradeoff between them is essential during the DRX parameters selection. We proposed an algorithm to select DRX parameters depending on the delay and power saving constrains. The proposed algorithm optimizes one of these two performance parameters while satisfying a predefined level of performance guarantee to other. We focus on the DRX inactivity timer and DRX cycle length in this paper with fixed DRX ON duration. Consideration of

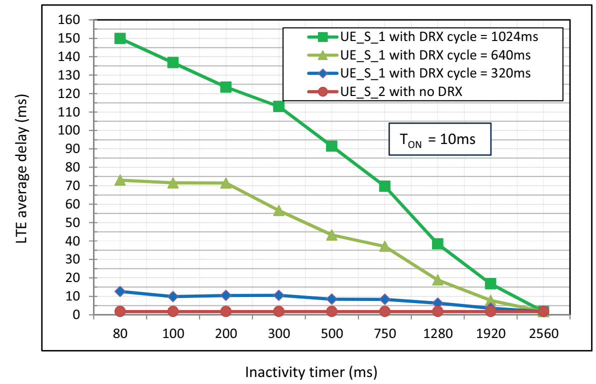

Fig. 6. Variation of delay over LTE air interface versus DRX inactivity timer (T_I) for various DRX cycles (T_{LDC}).

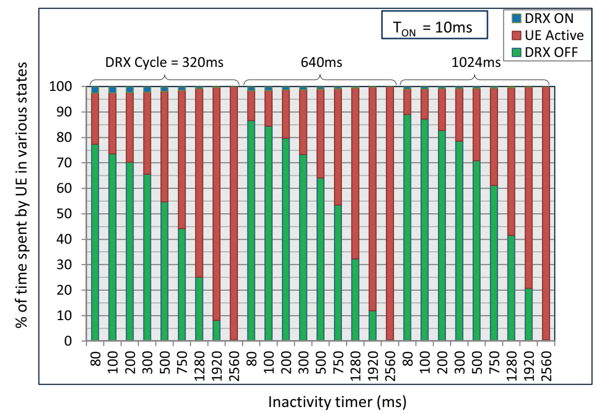

Fig. 7. Variation of UE states versus DRX inactivity timer (T_I) for various DRX cycles (T_{LDC}).

variable DRX ON duration may further enhance the system performance and is a topic for future research.

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