Traffic-based DRX Cycles Adjustment Scheme for 3GPP LTE Systems

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***Abstract*—The 3GPP long term evolution (LTE) standard is developed to enhance mobile services from the former 3G systems. In order to prolong the battery life of mobile device, a novel discontinuous reception (DRX) scheme is specified in the standard to reduce the power consumption of a user equipment. In this paper, a traffic-based DRX cycles adjustment (TDCA) scheme is proposed to enhance the energy saving performance based on existing DRX operation. A partially observable Markov decision process (POMDP) is employed to conjecture the present traffic status. Optimal policy for the selection of DRX parameters can be obtained via the POMDP framework in the proposed TDCA scheme. Simulation results show that the TDCA scheme can enhance the energy saving efficiency while the quality-of-service constraint is still satisfied.**

I. Introduction

The long term evolution (LTE) systems is developed by the 3rd generation partnership project (3GPP) as a mobile communication standard from the former 3G systems [1]. The mobile broadband networks are realizable based on LTE specifications, which enables mobile users to experience higher data rate with lower transmission latency. Since the growth of battery performance cannot catch up with the improvement from data rate, energy saving techniques become unavoidable to be adopted in data transmission technologies. Therefore, the discontinuous reception (DRX) has been specified in 3GPP LTE standard which intends to decrease the power consumption of user equipments (UEs). The evolved NodeB (eNB) will coordinate with the UE to activate DRX operation by radio resource control (RRC) while the UE is in RRC_CONNECTED state. Thus the UE is allowed to discontinuously monitor the physical downlink control channel (PDCCH) on which the downlink/uplink (DL/UL) transmissions are assigned. Since the UE can turn off its receiver circuit when it does not listen to PDCCH, the energy consumption of UE can consequently be reduced. The UE wakes up to read the PDCCH periodically when the DRX operation is configured. One major feature of LTE DRX is that the DRX cycle length can be extended after a short period of time. More details about the DRX operation will be described in the following sections.

The performance of DRX operation can be influenced by the status of network traffic that is affected by either the user behavior or backbone networks. Therefore, the parameters of a power saving mechanism should be configured based on different traffic behaviors. Most existing studies for traffic-based sleep cycle adjustment are conducted in the ealier specified IEEE 802.16 standards for WiMax systems. The sleep cycle length of IEEE 802.16e standard can be binary exponentially increased and fixed corresponding to the power saving class (PSC) I and II, respectively [2], and there are existing researches published to enhanced energy saving performance. The work in [3] adaptively controls the initial and final sleep cycle lengthes of PSC I; while the authors of [4] proposed an algorithm to dynamically switch between these two PSCs based on a semi-Markov decision process. Moreover, the approach in [5] adjusts the sleep window length every cycle in sleep mode of IEEE 802.16m systems [6], which is evolved from the IEEE 802.16e standard.

However, these power saving schemes proposed for IEEE 802.16 standards can not be directly utilized in the LTE systems. For example, since the sleep mode operation of IEEE 802.16m specifies that the sleep window can be reconfigured every sleep cycle directly in the MAC layer, the scheme proposed in [5] can adjust the sleep window length without additional signaling overhead. However, the parameters of DRX operation is set by the RRC which resides on a higher network layer in the LTE architecture. The signaling cost can be huge if the lengthes of DRX cycle are designed to be adjusted every time based on the network traffic. Therefore, a traffic-based DRX cycles adjustment (TDCA) scheme is proposed in this paper, which adaptively controls DRX cycles of LTE system according to the traffic estimation. The target of proposed TDCA scheme is to enhance the energy saving performance with the consideration of packet delay constraints. In order to avoid reconfiguring DRX parameters every cycle by the RRC, the decision time instant at which the TDCA scheme adjusts DRX cycles depends on traffic arrivals. A partially observable Markov decision process (POMDP) is employed to conjecture the traffic status and provides the selection policy for sleep cycle length. Simulation results show that the proposed TDCA scheme can enhance power saving efficiency of DRX operation; while the delay requirements of UE can still be preserved.

II. Problem Formulation

The 3GPP LTE standard specifies the DRX operation to prolong the battery lifetime of UE. However, the traffic status

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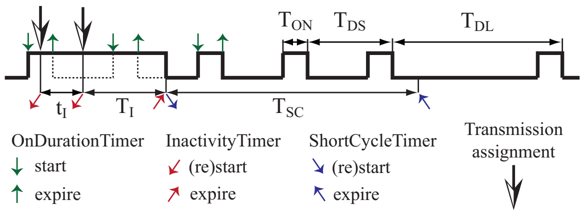

Fig. 1. Illustration of DRX operation.

and DRX parameters will directly influence the UE's energy consumption. Therefore, the proposed TDCA scheme intends to adaptively adjust the DRX cycles according to the traffic status. In order to introduce the TDCA scheme, the DRX operation is firstly illustrated. Then, the traffic model considered in the TDCA scheme will be briefly described. Finally, the DRX cycles decision (DCD) problem is formulated.

A. Discontinuous Reception (DRX)

The DRX operation is described in LTE MAC specification [1]. A UE has to read the PDCCH to determine whether the resource is allocated in either downlink or uplink direction. The DRX operation activated by RRC allows a UE to discontinuously monitor the PDCCH. It indicates that a UE can turn off its receiver circuit to save energy when it is not instructed to monitor PDCCH. Several timers that are used to control the DRX operation are described as follows, and the interaction among the timers with transmission assignments is shown in Fig. 1.

1) ***InactivityTimer.*** The InactivityTimer will start or restart when a transmission assignment appears on PDCCH. If there has no transmission assignment after the threshold T_I, the InactivityTimer expires.
2) ***OnDurationTimer.*** The OnDurationTimer will start at every DRX cycle. When the short DRX cycle is configured, the cycle length is T_{DS}. If the long DRX cycle is used, T_{DL} is set as the cycle length. The OnDurationTimer will expire after the period T_{ON}.
3) ***ShortCycleTimer.*** The ShortCycleTimer will start or restart when the InactivityTimer expires, and the UE sets T_{DS} as the configured DRX cycle at the same time. If the start/expiration of InactivityTimer does not happen within the duration of T_{SC}, the ShortCycleTimer will expire and the cycle length is extended to T_{DL}. In the following paragraph, since T_{SC} is a multiple of T_{DS}, the maximum number of short DRX cycles N_{SC} is utilized to replace T_{SC} as the threshold of ShortCycleTimer, where $N_{SC} = T_{SC}/T_{DS}$.

Note that the InactivityTimer and OnDurationTimer are adopted to control the UE's power activity. The UE will not monitor the PDCCH if both timers are paused or stopped. The ShortCycleTimer is utilized to determine the time at which the UE should extend the DRX cycle from T_{DS} to T_{DL}.

B. Traffic Model

The discrete-time Markov-modulated Poisson process (dMMPP) [7] is introduced as the traffic model since it can capture the characteristic of Internet traffic more than the traditional Poisson model. The non-real time traffic is modeled as a dMMPP with a state space $\mathcal{S} = \{s_1, \ldots, s_m, \ldots, s_M\}$. The state s_m represents a Poisson traffic with the rate λ_{s_m}. The states transit as a Markov chain with a transition probability matrix $\mathbf{T} = \{q_{m,n}|$ the transition probability from s_m to $s_n\}$.

C. DRX Cycles Decision Problem

The dominating parameters within DRX cycles, i.e., T_{DS}, N_{SC}, and T_{DL}, will significantly influence the performance of DRX operation under different traffic loads. An unfeasible setting of these parameters may cause high packet delay or low energy saving performance, which will lead to unsatisfactory user experiences including poor QoS on packet transmissions or quick battery drain. Therefore, the DRX cycles decision (DCD) problem is formulated as follows.

Given the sequences of selectable T_{DS}, N_{SC}, and T_{DL}, how to configure these three DRX parameters to maximize the energy saving efficiency under a non-real time downlink traffic? The constraint of mean packet delay δ_D should be obeyed in the meanwhile.

In this problem, it is assumed that the transmission assignments are only influenced by downlink packet arrivals. The sleep ratio, which will be described later, is utilized to evaluate the energy saving performance.

III. Proposed Traffic-based DRX Cycles Adjustment (TDCA) Scheme

The TDCA scheme is proposed to resolve the DCD problem. DRX parameters can be updated via MAC configuration defined in LTE RRC [8], which can adjust the length of DRX cycles. Based on the knowledge of traffic, the TDCA scheme will configure a feasible setting of DRX cycles to balance the energy saving efficiency and mean packet delay. The DRX cycles are adjusted at the time while the InactivityTimer expires since it is also the time for a UE to begin discontinuously monitoring the PDCCH. Note that this time instant is defined as a decision point d_t. Therefore, the short DRX cycle T_{DS}, the maximum number of short DRX cycles N_{SC}, and the long DRX cycle T_{DL} can be reconfigured at each d_t. However, since it is difficult to capture complete traffic information, only packet arrivals at specific time intervals can be observed to estimate the traffic status. Hence, a partially observable Markov decision process (POMDP) framework [9] is employed to adjust the DRX cycles with given policy based on insufficient traffic information. In the following subsections, the procedure of traffic status estimation will be explained based on POMDP at first. The evaluation metrics will consequently be derived, which is utilized to obtain the solution for DCD problem. The selection policy for DRX cycles will be described at the end.

A. Traffic Status Estimation

Based on the dMMPP, the set of traffic states $\mathcal{S}$ and the transition probability matrix $\mathbf{T}$ correspond to a finite set of states and the state-transition function in the POMDP

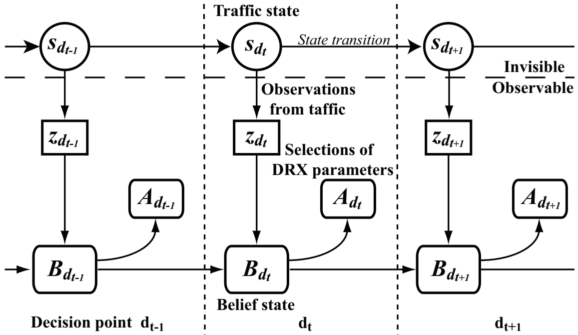

Fig. 2. Schematic diagram of POMDP model for TDCA scheme.

framework, respectively. The actual traffic state s_{d_t}, where $\forall s_{d_t} \in \mathcal{S}$, at each decision point d_t is not available. In order to estimate present traffic status at each decision point d_t, traffic information has to be collected within the time period τ_{d_t} from d_{t-1} to d_t. The number of arrived packets in this period is recorded as n_{d_t}. Therefore, the observations for the POMDP framework is defined as $z_{d_t} = \{n_{d_t}, \tau_{d_t}\}$. According to the traffic information, a set of observation function is defined as $\mathcal{O}_{d_t} = \{o_{d_t}(s_1), \ldots, o_{d_t}(s_m), \ldots, o_{d_t}(s_M)\}$. The weighting function $o_{d_t}(s_m)$ at d_t is utilized to represent the possibility for the present traffic state s_{d_t} to be s_m. Based on the Poisson property of a traffic state, the weighting denotes the probability that the number of packet arrivals is n_{d_t} during τ_{d_t} in state s_m, which can be expressed as

$$o_{d_t}(s_m) = Pr(z_{d_t}|s_m) = \frac{(\lambda_{s_m}\tau_{d_t})^{n_{d_t}} e^{-\lambda_{s_m}\tau_{d_t}}}{n_{d_t}!}. \quad (1)$$

Since the optimal solution may not exist when only the observations are considered in POMDP, the belief state is introduced to obtain the suboptimal results by estimating the traffic status. The belief state $\mathcal{B}_{d_t} = \{b_{d_t}(s_1), \ldots, b_{d_t}(s_m), \ldots, b_{d_t}(s_M)\}$ is a probability distribution over traffic states in $\mathcal{S}$, and $b_{d_t}(s_m)$ is the probability that the present state s_{d_t} is s_m at decision point d_t. Note that $b_{d_t}(s_m) \geq 0$, $\forall s_m \in \mathcal{S}$ and $\sum_{\forall s_m \in \mathcal{S}} b_{d_t}(s_m) = 1$. Based on the observations and state transition probabilities, each element of the belief state $\mathcal{B}_{d_t}$ is formulated as

$$\begin{aligned} b_{d_t}(s_m) &= Pr(s_m|\mathcal{B}_{d_{t-1}}, z_{d_t}) \\ &= \frac{Pr(z_{d_t}|\mathcal{B}_{d_{t-1}}, s_m) Pr(s_m|\mathcal{B}_{d_{t-1}})}{Pr(z_{d_t}|\mathcal{B}_{d_{t-1}})} \\ &= \frac{o_{d_t}(s_m) \sum_{\forall s_n \in \mathcal{S}} q_{n,m} b_{d_{t-1}}(s_n)}{\sum_{\forall s_m \in \mathcal{S}} o_{d_t}(s_m) \sum_{\forall s_n \in \mathcal{S}} q_{n,m} b_{d_{t-1}}(s_n)} \end{aligned} \quad (2)$$

by applying the Bayes rule. Obviously, the belief state represents the present traffic status updated from the previous estimation, both the observations and state transitions are utilized to construct its probability distribution. Therefore, a belief state can summarize the statistics of entire process history which will be updated at each decision point d_t.

Fig. 2 further illustrates the schematic diagram of POMDP model for TDCA scheme. The present traffic state s_{d_t} at

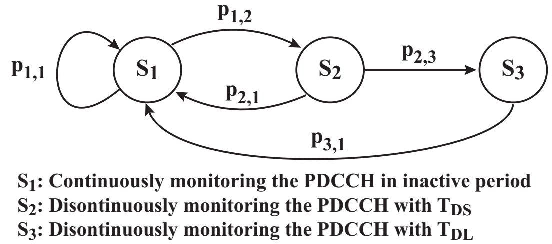

Fig. 3. A semi-Markov process for DRX operation.

each decision point d_t is considered unavailable; while the traffic information, such as τ_{d_t} and n_{d_t}, can be collected as the observations z_{d_t}. Based on the observations and previous estimation of traffic status, the belief state $\mathcal{B}_{d_t}$ is updated to describe the current traffic status. Afterwards, an action is taken from each action set $\mathcal{A}_\phi = \{a_{\phi,1}, a_{\phi,2}, \cdots, a_{\phi,|\mathcal{A}_\phi|}\}$ where $\phi \in \{DS, SC, DL\}$. The action $a_{DS,i}$ and $a_{DL,k}$ represent that the short DRX cycle is configured as $T_{DS,i}$ and the long DRX cycle is set as $T_{DL,k}$, respectively. The maximum number of short DRX cycles will be chosen as $N_{SC,j}$ if the action $a_{SC,j}$ is selected. Therefore, the actions determined at the decision point d_t is defined as $A_{d_t} = \{a_{DS,d_t}, a_{SC,d_t}, a_{DL,d_t}\}$ corresponding to a DRX parameter set $D_{d_t} = \{T_{DS,d_t}, N_{SC,d_t}, T_{DL,d_t}\}$, where $a_{\phi,d_t} \in \mathcal{A}_\phi, \forall \phi$. The decision policy for actions will be explained in subsection C.

B. Evaluation Metrics

In order to take appropriate actions, i.e., the selections of DRX parameters T_{DS}, N_{SC}, and T_{DL}, it is necessary to evaluate the performance over different parameter combinations in any traffic state. The works in [10] and [11] have analyzed and modeled the former UMTS DRX operation based on the Poisson traffic and bursty data traffic, respectively. The performance of LTE DRX operation with bursty data traffic is discussed in [12] by considering the DRX operation as a semi-Markov process, which was firstly adopted in [11]. Therefore, the evaluation metrics with a Poisson traffic will be performed by modifying the work mentioned above in order to fit into the POMDP framework. For given actions in a set $A_{i,j,k} = \{a_{DS,i}, a_{SC,j}, a_{DL,k}\}$, the sleep ratio and mean packet delay will be formulated corresponding to a DRX parameter set $D_{i,j,k} = \{T_{DS,i}, N_{SC,j}, T_{DL,k}\}$ in a traffic state s_m with Poisson rate λ_{s_m}.

A semi-Markov process for the DRX operation is illustrated in Fig. 3. State S_1 indicates that UE is in the inactivity period, i.e., the InactivityTimer is running and UE continuously listens to the PDCCH. States S_2 and S_3 represent that UE discontinuously monitors the PDCCH with the short and long DRX cycle, respectively. The stationary distribution is defined as $\Pi = \{\pi_1, \pi_2, \pi_3\}$, where $\sum_{w=1}^{3} \pi_w = 1$. The mean holding time of semi-Markov process is defined as $E[H_w]$ for $w \in \{1, 2, 3\}$, which represents the mean of time duration for UE to stay in state S_w. $E[H_2']$ is the mean of time duration for a UE actually reduces the power in short DRX cycle and $E[H_3^{'}]$ in long DRX cycle, respectively. Since the bursty data traffic can be simplified to Poisson model, the stationary distribution and mean holding time can be derived by modifying the equations of [12]. Therefore, the sleep ratio can be obtained as

$$\overline{SR}(\lambda_{s_m}, D_{i,j,k}) = \frac{\pi_2 E[H_2^{'}] + \pi_3 E[H_3^{'}]}{\sum_{w=1}^{3} \pi_w E[H_w]} \tag{3}$$

by adopting the parameters $T_{DS,i}$, $N_{SC,j}$, $T_{DL,k}$, and λ_{s_m} into the modified equations.

The packet delay is caused by the short and long DRX cycle. The mean delay by short DRX cycle is noted as $E[W_{DS}]$ and long DRX cycle as $E[W_{DL}]$, respectively. As a result, considering the probabilities of which state a packet arrives in, the mean packet delay for a given set $D_{i,j,k}$ with the Poisson rate λ_{s_m} is approximated as

$$\overline{D}(\lambda_{s_m}, D_{i,j,k}) = \frac{\pi_2 E[H_2^{'}]E[W_{DS}] + \pi_3 E[H_3^{'}]E[W_{DL}]}{\sum_{w=1}^{3} \pi_w E[H_w]}. \tag{4}$$

C. Selection Policy for DRX Cycles

According to the evaluation metrics derived in previous subsection, a selection policy for DRX cycles based on the SR is selected for the proposed TDCA scheme. Given a mean packet delay constraint δ_D, a reward function $\mathcal{R}$ of the POMDP framework is utilized to represent the benefit of an action set $A_{i,j,k}$ in traffic state s_m. Thus, a reward assignment algorithm illustrated in Algorithm 1 is utilized to determine the reward function $\mathcal{R}$. A reward of $A_{i,j,k}$ in s_m is defined as $r(s_m, A_{i,j,k})$, which can be obtained via Algorithm 1 and calculated by (3). Notice that the mean packet delay constraint δ_D is taken into account in order to discard unfeasible action set $A_{i,j,k}$. The mean packet delay of such actions, which is determined by (4), may violate the constraint δ_D.

Algorithm 1: *Reward Assignment Algorithm*

Input: $\mathcal{S}$, $\mathcal{A}_{DL}$, $\mathcal{A}_{SC}$, $\mathcal{A}_{DS}$, constraint δ_D
Output: reward function $\mathcal{R}$
foreach $s_m \in \mathcal{S}$ **do**
  foreach $a_{DS,i} \in \mathcal{A}_{DS}$ **do**
    foreach $a_{SC,j} \in \mathcal{A}_{SC}$ **do**
      foreach $a_{DL,k} \in \mathcal{A}_{DL}$ **do**
        if $\overline{D}(\lambda_{s_m}, D_{i,j,k}) \leq \delta_D$ **then**
          $r(s_m, A_{i,j,k}) \leftarrow \overline{SR}(\lambda_{s_m}, D_{i,j,k})$
        else
          $r(s_m, A_{i,j,k}) \leftarrow \overline{SR}_{min}$
        end
      end
    end
  end
end

The optimal solution to the DCD problem is unavailable since the actual traffic state is unavailable. However, the unobservable traffic state can be estimate since the belief state is employed in POMDP framework. Besides, the reward of given actions in a traffic state is calculated in advance. Therefore, the suboptimal DRX cycles selection at decision point d_t can be decided based on both the reward and belief state. The T-step function is used to form the objective function in the POMDP. In order to decrease computational complexity, one-step value function $V_1(s_m, A_{i,j,k})$ is applied in the TDCA scheme and is defined as

$$V_1(s_m, A_{i,j,k}) = r(s_m, A_{i,j,k}). \tag{5}$$

Therefore, from (2) and (5), the objective function Ψ at decision point d_t can be derived as

$$\Psi(\mathcal{B}_{d_t}, A_{i,j,k}) = \sum_{\forall s_m \in \mathcal{S}} b_{d_t}(s_m) V_1(s_m, A_{i,j,k}). \tag{6}$$

Note that the meaning of one-step value function can be treated as the score if actions in $A_{i,j,k}$ are taken in s_m. On the other hand, the objective function Ψ denotes the average score at d_t according to the estimated traffic status, which is the belief state $\mathcal{B}_{d_t}$. Therefore, a set of actions A_{d_t} can be selected via

$$A_{d_t} = \arg \max_{\forall A_{i,j,k}} \Psi(\mathcal{B}_{d_t}, A_{i,j,k}). \tag{7}$$

at d_t. It is instinctive that the selected actions will acquire the best score, i.e., with the highest sleep ratio. The corresponding DRX parameter set D_{d_t} can consequently be configured at decision point d_t.

IV. Performance Evaluation

In this section, simulations are conducted to evaluate the performance of proposed TDCA scheme, which will be compared with the fixed DRX operation without adaptively adjusting DRX parameters. Simulations are implemented via a MATLAB event-driven simulator, and a single eNB/UE pair with a non real-time DL traffic is considered in the simulation environment. The service time X is assumed to be 1 subframe considering a DL packet arrival will generate one transmission assignment. The threshold of InactivityTimer T_I and OnDurationTimer T_{ON} are set as 20 subframes for all cases. Other selectable parameters are defined as follows: $T_{DS} \in \{50, 100, \cdots, 500\}$ subframes, $N_{SC} \in \{1, 2, \cdots, 5\}$ cycles, and $T_{DL} \in \{100, 200, \cdots, 2000\}$ subframes. As specified in the LTE standard, the selected T_{DL} will always be longer than T_{DS}, and the duration of a subframe is 1 ms.

Fig. 4 compares the TDCA scheme with three fixed DRX cases by evaluating the sleep ratio and mean packet delay over various packet arrival rates. The fixed DRX parameter sets for cases 1, 2, and 3 are $\{T_{DS}, N_{SC}, T_{DL}\} = \{500, 2, 1500\}$, $\{200, 2, 600\}$, and $\{100, 2, 300\}$, respectively. The delay constraint in TDCA scheme is set as $\delta = 75$ subframes. In case 1, although higher sleep ratio can be achieved by choosing longer DRX cycles, the mean packet delay is observed to be much larger than the given delay constraint $\delta = 75$. On the other hand, shorter DRX cycles are selected in case 3 which can fulfill the requirement of mean packet delay constraint.

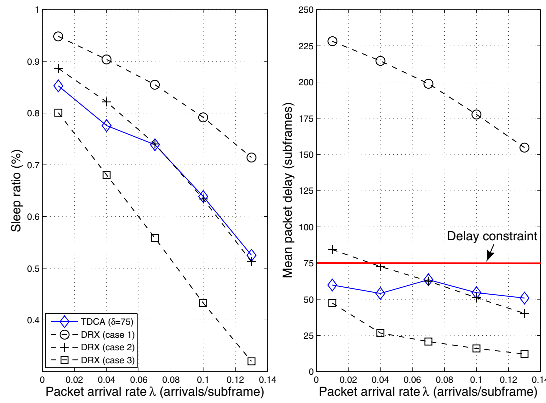

Fig. 4. Performance verification of proposed TDCA scheme.

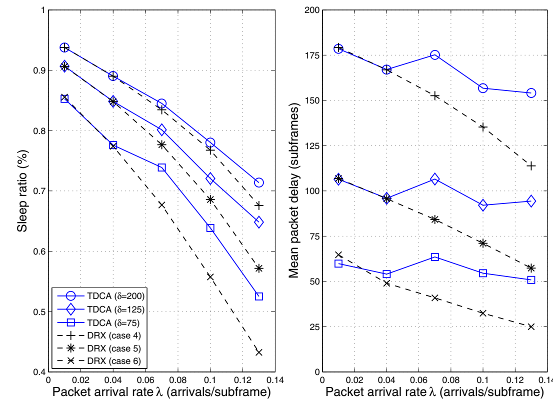

Fig. 5. Performance comparison among the proposed TDCA scheme with different delay constraints and fixed DRX operation with different parameter sets.

However, poor power saving performance is observed in case 3 due to low sleep ratio. It can be seen that the performance of proposed TDCA scheme can satisfy the delay constraint with $\delta = 75$ with feasible sleep ratio. Based on given delay constraint, the proposed TDCA scheme can provide dynamic adjustment of DRX parameters under different traffic loads.

The performance of TDCA scheme among different delay constrains is illustrate in Fig. 5. For each case of TDCA scheme, a fixed DRX case is selected for performance comparison, i.e., TDCA with $\delta = 200$ and case 4 with $\{400, 2, 1200\}$, TDCA with $\delta = 125$ and case 5 with $\{250, 2, 750\}$, and TDCA with $\delta = 75$ and case 6 with $\{150, 2, 450\}$. Note that the compared fixed DRX case is chosen to possess similar performance as the TDCA scheme under light traffic loading. Note that the up-and-down behavior of mean packet delay for the TDCA scheme is owing to the discrete manner of selectable DRX parameters. It can be observed that the TDCA scheme can utilize the margin of mean delay constraint to gain more sleep ratio. For example, the performances between the TDCA with $\delta_D = 75$ and case 6 are almost the same while the packet arrival rate λ is less than 0.04. In other words, the TDCA scheme with $\delta_D = 75$ may actually select its DRX parameters as those fixed values chosen by case 6. On the other hand, with higher traffic loading, the TDCA scheme can provide better performance than fixed values of DRX parameters because the TDCA scheme can dynamically adjust DRX parameters while the constraint is still be satisfied. Furthermore, by observing these three TDCA cases, the sleep ratio is increased under less strict delay constraint which shows the tradeoff between the sleep ratio and mean packet delay. The merits of proposed TDCA scheme can therefore be observed.

V. Conclusions

In this paper, in order to maximize the energy efficiency, a traffic-based DRX cycles adjustment (TDCA) scheme is proposed to adjust the DRX parameters according to traffic estimation. The partially observable Markov decision process (POMDP) is employed to conjecture the traffic status and provide the selection policy for DRX parameters. Simulation results show that the proposed TDCA scheme enhances the DRX operation with higher energy saving capability while the packet delay constraint can still be satisfied.

References

[1] *3GPP Technical Specification Group Radio Access Network, Evolved Universal Terrestrial Radio Access (E-UTRA) - Medium Access Control (MAC) protocol specification (Release 10)*, 3GPP TS 36.321 V10.0.0, Dec. 2010.

[2] *IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interference for Fixed Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*, IEEE Standard 802.16e-2005, Feb. 2006.

[3] M.-G. Kim, J.-Y. Choi, and M. Kang, “Adaptive Power Saving Mechanism Considering the Request Period of Each Initiation of Awakening in the IEEE 802.16e System,” *IEEE Communications Letters*, vol. 12, no. 2, pp. 106–108, Feb. 2008.

[4] L. Kong, G. K. W. Wong, and D. H. K. Tsang, “Performance Study and System Optimization on Sleep Mode Operation in IEEE 802.16e,” *IEEE Trans. Wireless Communications*, vol. 8, no. 9, pp. 4518–4528, Sep. 2009.

[5] C.-H. Hsu, K.-T. Feng, and C.-J. Chang, “Statistical Control Approach for Sleep Mode Operations in IEEE 802.16m Systems,” *IEEE Trans. Vehicular Technology*, vol. 59, no. 9, pp. 4453–4466, Nov. 2010.

[6] *DRAFT Amendment to IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interference for Broadband Wireless Access Systems - Advanced Air Interface*, IEEE P802.16m/D12, Feb. 2011.

[7] T. Yoshihara, S. Kasahara, and Y. Takahashi, “Practical Time-scale Fitting of Self-similar Traffic with Markov-modulated Poisson Process,” *Telecommunication Systems*, vol. 17, no. 1-2, pp. 185–211, 2001.

[8] *3GPP Technical Specification Group Radio Access Network, Evolved Universal Terrestrial Radio Access (E-UTRA) - Radio Resource Control (RRC) protocol specification (Release 10)*, 3GPP TS 36.331 V10.0.0, Dec. 2010.

[9] A. C. Cassandra, “Exact and Approximate Algorithms for Partially Observable Markov Decision Processes,” Ph.D. dissertation, Brown Univ., Providence, RI, May. 1998.

[10] S.-R. Yang and Y.-B. Lin, “Modeling UMTS Discontinuous Reception Mechanism,” *IEEE Trans. Wireless Communications*, vol. 4, no. 1, pp. 312–319, Jan. 2005.

[11] S.-R. Yang, S.-Y. Yan, and H.-N. Hung, “Modeling UMTS Power Saving with Bursty Packet Data Traffic,” *IEEE Trans. Mobile Computing*, vol. 6, no. 12, pp. 1398–1409, Dec. 2007.

[12] L. Zhou, H. Xu, H. Tian, Y. Gao, L. Du, and L. Chen, “Performance Analysis of Power Saving Mechanism with Adjustable DRX Cycles in 3GPP LTE,” *Proc. IEEE VTC-fall*, pp. 1–5, Sep. 2008.