SELECTION OF DRX SCHEME FOR VOICE TRAFFIC IN LTE-A NETWORKS: MARKOV MODELING AND PERFORMANCE ANALYSIS

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(Communicated by Jinyan Fan)

Abstract. Power saving is a leading issue in the User Equipment (UE) for limited source of power in Long Term Evolution-Advanced (LTE-A) networks. Battery power of an UE gets exhaust quickly due to the heavy use of many service applications and large data transmission. Discontinuous reception (DRX) is a mechanism used for power saving in UE in the LTE-A networks. There are scope of improvements in conventional DRX scheme in LTE-A networks for voice communication. In this paper, a DRX scheme is chosen by selecting optimal parameters of DRX scheme, while keeping Quality of Service (QoS) delay requirements. Further, delay analysis for first downlink packet is performed. Moreover, expressions for delay distribution and expected delay of any downlink packet, are obtained and represented graphically. Based on analytical model, the trade-off relationship between the power saving and queueing delay is investigated.

1. Introduction. The Fourth Generation (4G) emerging wireless technologies, such as Long Term Evolution-Advanced (LTE-A) and Worldwide Interoperability for Microwave Access (WiMAX) endeavour a high bandwidth and wide coverage of area for data transfer [20, 14]. However, with these enhancements in technologies, growth in making the User Equipment (UE) energy efficient remained slow. Thus, it is needed to provide improvement in energy efficiency of LTE-A networks enabled UE [19]. Several methods and schemes such as Discontinuous Reception (DRX) in LTE/LTE-A and idle/sleep mode in WiMAX are used to reduce the power consumption [13].

The objective of a DRX scheme for voice traffic is to switch UE into sleep mode for maximum length of time and keeping the Quality of Service (QoS) requirement on delay of a packet within a fixed range. Aforementioned fixed range is 150 ms by a voice packet which is the maximal tolerable delay. LTE/LTE-A DRX mechanism has two modes, RRC_CONNECTED and RRC_IDLE as the Radio Resource Control...
(RRC) modes [15]. An User Equipment (UE) is in RRC$_{CONNECTED}$ mode if RRC connection has been established, otherwise it is in RRC$_{IDLE}$ mode. In RRC$_{CONNECTED}$ mode, UE may be configured with an UE specific DRX, at the lower layers. In RRC$_{IDLE}$ mode connection, an UE specific DRX is configured by upper layers. Also, an UE’s power consumption changes, when its mode of connection is changed, i.e., from RRC$_{CONNECTED}$ to RRC$_{IDLE}$ [5].

Aforementioned, an UE during DRX mechanism can be in any of the mode, i.e., RRC$_{CONNECTED}$ or RRC$_{IDLE}$. However, for this work, it is assumed to be in the latter mode as, it is trivial mode for UE’s, in which multiple applications are always running in the background [5].

In previous years, most of the work conducted in area of power saving is based on Best Effort (BE) traffic and Non Real Time Variable Rate (NRT-VR) traffic [17]-[4]. In recent time, a lot of work have been proposed, to improve power saving schemes [21]. An optimal sleep mode selection scheme has been designed [12]. Most of the conventional DRX schemes for UE give upto 50 – 60% power saving, that can be observed in [18].

In LTE-A networks, converging real time voice traffic is challenged due to the progressive interactive services in Internet Protocol (IP) data networks. In comparison to classical IP services such as e-mail, web browsing, etc., voice over IP demands from the network a high QoS. Accurate knowledge and characteristic of the traffic may over come the issues of QoS up to some extent. ON-OFF models have been popularly used with modelling of voice traffic, where the periods of talk spurts are modelled as ON state and the periods of silences are modelled as OFF state [3]. Often voice traffic has been modelled using ON-OFF source models. To model transitions between ON-OFF states the literature has normally proposed Markovian approximations, which are tractable mathematically [3]. For queueing analysis, exponential (or geometric) distribution is presumed implicitly for the duration of both ON and OFF states [6].

In LTE-A networks, DRX scheme allows an UE to enter into sleep mode while it is subscribed with evolved Node-B (eNB) which leads to more amount of power saving. Thus, how to model and optimize DRX scheme in LTE-A networks for power saving has engrossed many research interests [22]. The limitation for conventional DRX scheme is that some DRX parameters are ignored and properties of voice traffic are not exploited for the benefit of power saving.

The idea of enabling DRX scheme by exercising the characteristics of voice traffic in LTE networks, is initiated in [1]. We have employed their idea for one-way and two-way communication in voice traffic. On the consideration of conventional DRX scheme and their shortcomings for voice traffic in LTE-A networks, a DRX scheme is obtained in this paper. Utilizing the properties of voice traffic lead us to select optimal parameters of DRX scheme which gives more power saving over conventional DRX schemes in LTE-A networks. However, in conversational model, voice traffic is considered, which includes packet arrival at fixed time intervals if both the parties are talking and no packet arrival if both parties are silent [11]. The obtained model has incorporated all DRX parameters defined in 3GPP standard.

The rest of this paper is organized as follows: preliminaries are explained in Section 2. CTMC model description of two-way communication is presented in Section 3. Selection of optimal parameters of DRX scheme are described in Section 4. In Section 5, performance evaluation is presented for the model in one-way and
two-way communication. Delay for first downlink packet is obtained in Section 6. The concluding remarks are conferred in Section 7.

2. Preliminaries. The Third Generation Partnership Project (3GPP) LTE wireless networks provide power saving mechanism called DRX scheme. The basic structure of DRX scheme in LTE is shown in Figure 1. The time spent during DRX scheme is divided into two parts awake period and sleep period.

![Figure 1. Basic structure of DRX scheme](image)

The awake period includes inactivity timer period and active period whereas sleep period includes two types of sleep periods, short DRX cycle and long DRX cycle \([22]\). Further, a DRX cycle consists of an ON duration, a small time interval during which the UE monitors physical channel, known as Physical Downlink Control Channel (PDCCH). The working of UE receiver during inactivity timer period, short DRX cycle and long DRX cycle in conventional DRX scheme is given as the following: Inactivity timer is the pre-determined time period for which UE waits before going into sleep mode if there is no packet arrival before inactivity timer period is expired. When UE receives/send a packet, it always reset the inactivity timer period.

*Short DRX cycle* consists of two parts short sleep period \((T_s)\) and ON period (also known as listening period). If there is no packet indication from PDCCH in ON period, then UE keeps on entering into next short DRX cycles. Further, after some pre-determined number \((N_s)\) of short DRX cycles, UE enters into long DRX cycle. *Long DRX cycle* consists of two parts ON period and long sleep period \((T_L)\). If there is no packet indication from PDCCH in ON period, then UE keeps on entering into long DRX cycles for some pre-determined number \((N_L)\) of times \([9, 2]\). The UE powers down most of its component during sleep periods.

*DRX short cycle timer* \((N_s)\) denotes the number of short DRX cycles to follow before proceeding to long DRX cycle which are pre-fixed \([5]\). The transition from inactivity period to short DRX cycle is regulated by inactivity timer period \((T_{IB})\), while the transition from short to long DRX cycles under power saving mode is regulated by \(N_s\). When there is no data activity, UE enters short DRX cycle. Further, \(N_s\) begins with the \(T_s\)’s termination. Thus, DRX scheme consists of active period, inactivity timer, short DRX cycles and long DRX cycles.
DRX mode starts with the initiation of inactivity timer period \((T_{IB})\). If there is no packet arrival for the UE in the \(T_{IB}\) timer then UE enters power saving mode. Otherwise, inactivity timer period is re-initiated. If packets arrive at the eNB during short DRX sleep period or long DRX sleep period, then UE is not in a condition to receive the message. The UE receives only during their next ON duration which is also referred as listening period. Therefore, it leads to precipitation of delayed packets, as packets have to wait for next ON duration. Further, number of short and long DRX cycles in conventional DRX scheme are fixed.

The shortcomings of conventional DRX scheme which lead us to obtain a DRX scheme for voice traffic in LTE-A networks are the following:

- On the basis of available wireless networks, eNB determines DRX parameters for the UE. When applications in UE actually starts to generate packets, parameters are configured initially by the eNB in LTE networks which may not be suitable for that application. In general, when the UE turn on a logical connection, known as bearer, these parameters are fixed, with Packet Data Network Gateway (P-GW). In this work, we have selected parameters in view of speech model considered for one-way and two-way communication. Modified Brady model is considered in two-way communication which includes short silence gaps \([3]\). These short silence gaps are examined to have realistic approach towards the modeling.
- Voice traffic has properties different from other traffics such as data, video etc. Voice streams exhibits low data rates and burstiness as compared to other traffics, then its treatment should be different from other traffics in the network \([11]\).
- In conventional DRX scheme, number of repeating short DRX cycles or long DRX cycles are pre-determined fixed numbers. Initially short DRX cycle start and repeat itself till packets are coming which is a random number. Thus, in this work, we consider that random number of DRX cycles take place at once. Moreover, after \(N_S\) random number of short DRX cycles, long DRX cycle start and repeats itself, if no packet arrive at buffer. Hence, \(N_S\) is a random number.
- Conventional DRX scheme has positive inactivity timer period which leads to more power consumption. In speech model, as communication begins, packets start arriving at an average interval of 20ms \([6]\). The instant at which eNB made a connection with UE, DRX cycle starts \([1]\). Thus, a positive inactivity timer period is not required and we set inactivity timer period equals to zero for this model.

These DRX parameters are selected based on the applications type such as power, resource savings maximization and traffic considered. When DRX is enabled, there may be an extended delay at receiving end, since UE may be in DRX sleep state at the time of data arrival at eNB, and the eNB would have to wait for the transmission until the UE becomes ON. Hence, the DRX parameters have to be carefully selected such that packet delay is minimized and power saving is maximized.

3. CTMC model for one-way and two-way voice communication. In this section, first we discuss one-way communication ON-OFF model as shown in Figure 2 for voice traffic. Then we discuss the two-way communication model for voice traffic.
The considered one-way communication ON-OFF model consists of two distinct parts: talkspurts \((T_1)\) period and silence period \((T_2)\) of voice traffic having exponential distribution with mean 352 ms and 650 ms, respectively.

![Figure 2. One-way communication ON-OFF model for voice traffic](image)

Now, we discuss Continuous Time Markov Chain (CTMC) specific to two-way voice communication, which is also known as modified Brady model. Let \(X(t)\) be the state of the two parties in communication at time \(t\). Then \(\{X(t), t \geq 0\}\) is a discrete state continuous time stochastic process and is modeled as a Continuous time Markov chain (CTMC) with the assumption that Markov property is satisfied at all time points. Figure 3 shows the state transition diagram for CTMC \(\{X(t), t \geq 0\}\). Model is divided into four parts (quadrants), each quadrant containing two defined states. Eight-state modified Brady model is studied with ON-OFF characteristics of two-way communication [16, 10].

Let \(A\) and \(B\) be two parties in communication. This communication is divided into eight distinct states and are defined as follows:

\[
S = \{S_i : i = 1, 2, \ldots, 8\}
\]

where

- \(S_1\): \(A\) Talks, \(B\) Silent,
- \(S_2\): Double Talk, \(A\) is interrupted,
- \(S_3\): Double Talk, \(B\) is interrupted,
- \(S_4\): Mutual Silence, \(A\) spoke Last,
- \(S_5\): Mutual Silence, \(B\) spoke Last,
- \(S_6\): \(B\) Talks, \(A\) Silent,
- \(S_7\): Short Silence Gap while \(A\) Talks, \(B\) Silent,
- \(S_8\): Short Silence Gap while \(B\) Talks, \(A\) Silent.

### Table 1. List of transition rates per second

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\alpha_1)</th>
<th>(\alpha_5)</th>
<th>(\alpha_3)</th>
<th>(\alpha_2)</th>
<th>(\alpha_7)</th>
<th>(\alpha_4)</th>
<th>(\alpha_6)</th>
<th>(\alpha_8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha_{1,4})</td>
<td>0.833</td>
<td>0.489</td>
<td>2.157</td>
<td>2.324</td>
<td>27.62</td>
<td>2.222</td>
<td>1.044</td>
<td>0.278</td>
</tr>
</tbody>
</table>

We consider the DRX scheme of party B’s UE. When party B speaks, uplink traffic from an UE to a Base Station (BS) is generated. When party A speaks, downlink traffic from the BS to the UE of party B is generated. \(S_4, S_5, S_7\) and \(S_8\) are states of mutual silence as represented in Figure 2. Aforementioned model provides a sight on communication between two parties. It allows a party to be in any of the 8 states, on the basis of whether the party considered is talking, listening,
or both the parties are talking and so on [16, 10]. State $S_1$ means party A is talking and party B is silent. If party A also gets silent, the process moves from $S_1$ to $S_4$ or if party B starts talking then it moves from $S_1$ to $S_2$. Another transition possible from state $S_1$ is to state $S_7$ which take place when there are short silence gaps of length less than 200 ms. In this way, state transition diagram can be observed in Figure 3.

Let $\alpha_{i,j}$'s be the transition rates from $S_i$ to $S_j$. These rates are shown in in Table 1 [16]. Then

$$Q = [\alpha_{i,j}], \ i, j \in \{1, 2, \ldots, 8\}$$

is the infinitesimal generator matrix obtained for CTMC. Define the vector

$$\pi = (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)$$

where $\pi_i = \lim_{t \to \infty} \pi_i(t)$ is limiting probability of being in $S_i$. Then, the corresponding steady state equations are given by

$$\pi Q = 0, \ \sum_{j=1}^{8} \pi_j = 1.$$  \hspace{1cm} (3)

![Figure 3. State transition diagram for two-way communication](image)

**Figure 3.** State transition diagram for two-way communication

![Figure 4. Packet arrival in one-way communication voice traffic](image)

**Figure 4.** Packet arrival in one-way communication voice traffic
4. **Selection of optimal parameters for the DRX scheme.** How optimal parameters are chosen in DRX scheme for voice traffic are described as follows:

- An important characteristic of voice traffic is that one packet is generated every 20 ms during talkspurt and no packets is generated during silence period as depicted in Figure 4 [11]. To save power, inactivity timer period is set to zero. It follows that after one packet is received, UE immediately moves to power saving mode. Initially, when a packet is indicated short DRX cycles start to take place. Inactivity timer period ($T_{IB}$) is set to zero because till the time any of the party talks, next packet will keep on coming at every 20ms interval. And, during the mutual silence gaps between the communication, UE moves to long DRX cycle. It follows that after one packet is received, then UE immediately move to power saving mode without waiting. Extra energy dissipation in $T_{IB}$ time is eliminated.

- We have considered that UE can take random number of short DRX cycles and long DRX cycles. However, if packets are coming after each 20 ms then short DRX cycles will keep going on whereas if both the parties are mutually silent then long DRX cycles will keep on occurring. Hence, depending on the length of talkspurt or silence period in communication, the number of short DRX cycles and long DRX cycles will be random. In this way, UE can significantly save its power consumption. As long as party A or party B talks, short DRX cycle goes repetitively. This phenomenon occurs in $S_1$, $S_2$, $S_3$ and $S_6$. When both parties A and B are silent, UE enters long DRX cycles, it will also be a random number depending on the length of silence period. Hence, $S_4$, $S_5$, $S_7$, $S_8$ are the states of mutual silence.

5. **Performance evaluation based on the DRX scheme.** In this section, first we discuss parameter values considered for the proposed DRX scheme. Second, power consumption is evaluated for an UE, in one-way communication for voice traffic in LTE-A networks. Third, power consumption is evaluated for two distinct cases, based on two-way communication for voice traffic in LTE-A networks as depicted in Figure 3. Finally, performance of the UE with proposed DRX scheme is compared with, the UE without a power saving scheme.

For the purpose of performance evaluation, the parameter values of several components are fixed as per the requirements of the DRX scheme. The value of parameters are given in Table 2. Length of a frame in LTE-A networks for transmission is 10 ms in time division duplexing (TDD) mode (see Figure 5), [7].

The commonly used values for average talkspurt time and silence period are 650 ms and 352 ($\approx 350$) ms for one-way communication, respectively [6]. Therefore, average number of short DRX cycles and long DRX cycles are 18 and 17 respectively, when their respective lengths are 20 ms and 40 ms. Since, after completion of last short DRX cycle, UE waits for one more cycle before moving to long DRX cycle for one-way communication. Hence, 19 average number of short DRX cycles are considered for one-way communication. Figure 4 shows an overview of voice traffic arrival.

As mentioned in Table 2, in order to get maximum power saving, length of short DRX cycle is defined as 20 ms considering packetization interval of 20 ms for voice traffic and frame size of 10 ms for LTE-A networks. In each short DRX cycle, first 5 ms time is considered for awake interval and remaining 15 ms is considered for short sleep period. Further, out of initial 5 ms, first 2.5 ms is considered for uplink packet transmission and latter is considered for downlink packet transmission.
Table 2. Parameters in DRX Scheme

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half frame Duration (ms)</td>
<td>5</td>
</tr>
<tr>
<td>Duplexing</td>
<td>TDD</td>
</tr>
<tr>
<td>cDRX ON duration timer (ms)</td>
<td>1</td>
</tr>
<tr>
<td>DRX inactivity timer period (ms)</td>
<td>0 – 100</td>
</tr>
<tr>
<td>Short DRX cycle length (ms)</td>
<td>20</td>
</tr>
<tr>
<td>Long DRX cycle length (ms)</td>
<td>40 – 100</td>
</tr>
<tr>
<td>Average silence period (ms)</td>
<td>650</td>
</tr>
<tr>
<td>(in one-way communication)</td>
<td></td>
</tr>
<tr>
<td>Average talking period (ms)</td>
<td>350</td>
</tr>
<tr>
<td>(in one-way communication)</td>
<td></td>
</tr>
<tr>
<td>Power consumption in awake mode (mJ/ms)</td>
<td>0.24</td>
</tr>
<tr>
<td>Power consumption in sleep mode (mJ/ms)</td>
<td>0.02</td>
</tr>
<tr>
<td>Additional energy consumption(µJ)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 5. Frame structure and DRX cycle in LTE-A networks
Power consumption per frame in awake mode and sleep mode are 1.2\(mJ\) and 0.1\(mJ\), respectively and additional energy consumption is 0.2\(\mu J\) for switching the states, both from sleep and on duration, and vice versa [1]. Hence, 0.24\(mJ\), 0.02\(mJ\), 0.2\(\mu J\) per millisecond, respectively. Before the time UE starts to idling during DRX scheme, the UE remains in continuous reception for \(T_{IB}\) time [7].

For voice services in LTE-A networks, length of long DRX cycle is set in multiples of length of short DRX cycle. Further in Table 2, it is shown that length of long DRX cycle is taken as 40 ms to avoid the prolonged delay of packets. For real-time communication, voice traffic limit the maximal acceptable round trip delay to 200-300 ms, i.e., one-way delay required to lie in the range of 100-150 ms for satisfactory performance [11]. As a consequence, if packet comes in buffer at the start of long DRX cycle, it can be delayed at the maximum length of 150 ms to reach another destination. When a party, say, party A starts communication, then a packet has to go through three transmissions, UE of party A to base station (BS) of party A, BS of party A to BS of party B (vaguely short time) and BS of party B to UE of party B. Figure 5 shows the proposed DRX scheme with corresponding selected parameter values.

Hence, in each 20 ms of short DRX cycle, UE is saving energy for 15 ms and in each 40 ms time of long DRX cycle it is listening in last 1 ms of ON period. If there is a packet in buffer to deliver then it will be delivered otherwise system will again transit to next long DRX cycle. Consequently, in long DRX cycle, length of awake time is 1 ms and saves power for the remaining long sleep period of length 39 ms. ON period of a long and a short DRX cycles is kept same, i.e., 1 ms.

Notations:

- \(T_{\text{sleep}}^{S}\) sleep period during a short DRX cycle,
- \(T_{\text{sleep}}^{L}\) sleep period during a long DRX cycle,
- \(T_{\text{awake}}^{S}\) awake period during a short DRX cycle,
- \(T_{\text{awake}}^{L}\) awake period during a long DRX cycle,
- \(N_{S}\) average number of short DRX cycles during DRX scheme,
- \(N_{L}\) average number of long DRX cycles during DRX scheme,
- \(P_{\text{sleep}}\) power consumption per second during the sleep period,
- \(P_{\text{awake}}\) power consumption per second during the awake period,
- \(P_{\text{switch}}\) power consumption per second during the switching from sleep duration to the on duration and vice versa,
- \(N_{\text{switch}}\) average number of switches from sleep duration to the on duration and vice versa.

These values vary for distinct cases.

Consider power consumption ratio :=

\[
\frac{(T_{\text{sleep}}^{S} \times N_{S} + T_{\text{sleep}}^{L} \times N_{L}) \times P_{\text{sleep}}}{(T_{\text{sleep}}^{S} + T_{\text{awake}}^{S}) \times N_{S} + (T_{\text{sleep}}^{L} + T_{\text{awake}}^{L}) \times N_{L} \times P_{\text{awake}}} + \frac{(T_{\text{awake}}^{S} \times N_{S} + T_{\text{awake}}^{L} \times N_{L}) \times P_{\text{awake}} + P_{\text{switch}} \times N_{\text{switch}}}{(T_{\text{sleep}}^{S} + T_{\text{awake}}^{S}) \times N_{S} + (T_{\text{sleep}}^{L} + T_{\text{awake}}^{L}) \times N_{L} \times P_{\text{awake}}}.
\]

5.1. Power saving in one-way communication for voice traffic in LTE-A networks. Power consumption is defined as the average energy consumed per unit time by an UE. First, we discuss the computation of power saving in one-way
communication for voice traffic in LTE-A networks, assuming that packets will be delivered in active periods only. Let $E_0$ and $P_0$ be the power consumption per unit time and power saving percentage for an UE in one-way communication for voice traffic in LTE-A networks, compared with the UE having no power saving scheme, respectively. Then, we have

$$P_0 = (1 - E_0) \times 100\%.$$

The parameter values considered for one-way communication are given as follows:

- $T_{\text{sleep}_S} = 15 \text{ ms}$, $T_{\text{sleep}_L} = 39 \text{ ms}$, $T_{\text{awake}_S} = 5 \text{ ms}$, $T_{\text{awake}_L} = 1 \text{ ms}$, $N_S = 19$, $N_L = 17$, $P_{\text{sleep}} = 0.02 \text{mJ/ms}$, $P_{\text{awake}} = 0.24 \text{mJ/ms}$, $P_{\text{switch}} = 0.002 \text{mJ/ms}$, $N_{\text{switch}} = 36$.

Hence,

$$E_0 = 0.180, \quad P_0 = 81.95\%.$$ (4)

5.2. Power saving in two-way communication for voice traffic in LTE-A networks. Now, we consider two-way communication for voice traffic in LTE-A networks. On the basis of modified Brady model, it is partitioned in two possible cases, Case I and Case II.

Let $E_I$, $E_{II}$ be the power consumption for an UE in Case I and Case II, respectively. Suppose the percentage of power saving of an UE with obtained DRX scheme in Case I, Case II be $P_I$, $P_{II}$, respectively as compared to UE with no power saving scheme. Then, for $i = I, II$,

$$P_i = (1 - E_i) \times 100\%.$$

Now, we evaluate mean sojourn time at each state of the given CTMC for the purpose of finding power consumption. For $i \in E$, let $\tau_i'$ be the mean sojourn time in state $S_i$, and $\tau_i$ be the number of sleep cycle exhausted in state $S_i$. Then, $\tau_i'$ is given by

$$\tau_i' = \left( \sum_{j=1, j \neq i}^{8} \alpha_{i,j} \right)^{-1} 1000 \text{ ms}.$$

<table>
<thead>
<tr>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
<th>$\tau_4$</th>
<th>$\tau_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_6$</td>
<td>$\tau_3$</td>
<td>$\tau_5$</td>
<td>$\tau_8$</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

Next, we obtain power saving percentage for an UE with proposed DRX scheme compared to UE with no power saving scheme for the following two cases: **Case I: Voice service in two-way communication, when party A or B, or both are talking**

In this case, downlink and uplink both take place simultaneously. We assume that, whenever a packet comes in buffer, it will be delivered at that instant of
PERFORMANCE ANALYSIS OF THE DRX SCHEME OBTAINED

...time. $S_1$, $S_2$, $S_3$ and $S_6$ are the states in which at least one of the party talks. The parameter values considered for two-way communication are given as follows:

$T_{\text{sleep},S} = 15 \text{ ms}$, $T_{\text{sleep},L} = 0 \text{ ms}$, $T_{\text{awake},S} = 5 \text{ ms}$, $T_{\text{awake},L} = 0 \text{ ms}$, $N_S = \tau_i$, $N_L = 0$, $P_{\text{sleep}} = 0.02\text{mJ/ms}$, $P_{\text{awake}} = 0.24\text{mJ/ms}$, $P_{\text{switch}} = 0.002\text{mJ/ms}$, $N_{\text{switch}} = \tau_i$.

Thus, when at least one of the party talks, then power saving percentage is obtained as follows:

For $i = 1, 2, 3, 6$, $\tau_i = \left\lceil \frac{\tau_i'}{20} \right\rceil$.

Hence,

$E_I = 0.313$, $P_I = 68.70\%$. (5)

Case II: Voice service in two-way communication, when parties A and B, both are silent

In this case, neither downlink nor uplink take place. Since, $S_4$, $S_5$, $S_7$, $S_8$ are the states of mutual silence, we calculate the power saving in these states. The parameter values considered for two-way communication when both the parties are silent are given as follows:

$T_{\text{sleep},S} = 0 \text{ ms}$, $T_{\text{sleep},L} = 39 \text{ ms}$, $T_{\text{awake},S} = 0 \text{ ms}$, $T_{\text{awake},L} = 1 \text{ ms}$, $N_S = 0$, $N_L = \tau_i$, $P_{\text{sleep}} = 0.02\text{mJ/ms}$, $P_{\text{awake}} = 0.24\text{mJ/ms}$, $P_{\text{switch}} = 0.002\text{mJ/ms}$, $N_{\text{switch}} = \tau_i$.

Thus, when both the parties are silent mutually, then power saving percentage is obtained as follows: For $i = 4, 5, 7, 8$, $\tau_i = \left\lceil \frac{\tau_i'}{40} \right\rceil$.

Hence,

$E_{II} = 0.106$, $P_{II} = 89.35\%$. (6)

Table 4. Limiting probabilities

<table>
<thead>
<tr>
<th>$\pi_1$</th>
<th>$\pi_2$</th>
<th>$\pi_4$</th>
<th>$\pi_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_6$</td>
<td>$\pi_3$</td>
<td>$\pi_5$</td>
<td>$\pi_8$</td>
</tr>
<tr>
<td>0.3289</td>
<td>0.0236</td>
<td>0.0839</td>
<td>0.06472</td>
</tr>
</tbody>
</table>

Table 3 shows the values of $\tau_i$'s obtained. Now, to analyze the behaviour of power consumption in long run, set of equations (3) are solved to obtain the limiting probabilities which are given in Table 4.

Let $E_L$ be the expected power consumption in long run and $e_j$ be the power consumption at state $j$, $j \in E$. Latter is obtained as follows:

$e_1 = e_2 = e_3 = e_6 = E_I$, $e_4 = e_5 = e_7 = e_8 = E_{II}$. 


$E_L$ and $P_L$ are given as follows:

\[ E_L = \sum_{j=1}^{8} \pi_j e_j = 0.252, \]
\[ P_L = 74.81\%. \] (7)

Now, to investigate the behaviour of conventional DRX scheme, when inactivity timer period is greater than zero and length of short DRX cycle is 40 ms, then for two-way communication, we consider the following parameters:

\[ T_{IB} = 20 \text{ ms}, \ T_A = 1 \text{ ms}, \ T_S = 39 \text{ ms}, \ E_{\text{change}} = 2\mu J/\text{ms}. \]

In Case I of two-way communication, when at least one of the party is talking, UE waits for $T_{IB}$ time to check for packet indication. It will receive a packet quickly and then these inactivity timer period cycles of length 20 ms keep on going till the communication lasts. Therefore,

\[ E_I = 1, \ P_I = 0\%. \]

In Case II, when both the parties are mutually silent, UE will wait for first 20 ms and receives no packet arrival, and then, it move to short DRX cycles of length 40 ms. Therefore,

\[ E_{II} = 0.19, \ P_{II} = 81\%, \]
\[ e_1 = e_2 = e_3 = e_6 = 1, \]
\[ e_4 = e_5 = e_7 = e_8 = 0.1064. \]

$E_L$ and $P_L$ are given as follows:

\[ E_L = \sum_{j=1}^{8} \pi_j e_j = 0.8606, \]
\[ P_L = 13.94\%. \] (8)

The observations made from the performance evaluation for the DRX scheme obtained are given as follows:

- Table 5 shows the variation of power saving in one-way and two-way communication with respect to increase in the length of long DRX cycle. It is easy to observe from this table that with the increases in the length long DRX cycle there is immense power saving gain for UE with DRX scheme over the UE with no DRX scheme.
- From Table 5, we also observe that power saving percentage in case of voice service in one-way communication is significantly more, in comparison to the case of voice services in two-way communication.
- On evaluating the power saving gain when $T_{IB} = 20 \text{ ms}$ and length of short DRX cycle is 40 ms, we note that $P_I$ becomes zero $P_{II}$ remains same. That is, we observe that on including positive length of inactivity timer period ($T_{IB} = 20 \text{ ms}$), average power saving falls to 13.94% in two way communication.
- Long DRX cycles reduce the power consumption of the UE but increase the delay experienced by packets. Whereas, short DRX cycles reduce the delay experienced by packets but increase the power consumption in comparison.
Table 5. Power saving percentage comparison for DRX scheme in one-way and two-way voice communication

<table>
<thead>
<tr>
<th>Length of Long DRX cycle (ms)</th>
<th>One-way $P_0$ (%)</th>
<th>Two-way $P_L$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>81.96</td>
<td>74.78</td>
</tr>
<tr>
<td>60</td>
<td>84.31</td>
<td>75.0041</td>
</tr>
<tr>
<td>80</td>
<td>85.75</td>
<td>75.12</td>
</tr>
<tr>
<td>100</td>
<td>86.72</td>
<td>75.19</td>
</tr>
</tbody>
</table>

5.3. Delay analysis. In this section, we calculate the mean delay for the first downlink packet. The LTE-A networks OFDMA/TDD structure adopts the frame unit structure, with 1 frame being equal to 10 ms. Size of the length of sleep period is measured in terms of frame units.

Let $T_n =$ Length of $n$th DRX cycle, $n = 1, 2, \ldots$

During mutual silence period, long DRX cycles get start by indication of PDCCH at the UE. Thus,

$$T_n = 40 \text{ms for } n = 1, 2, \ldots$$

$$= 4 \text{frame.}$$

Let $W_n =$ Amount of time at the end of $n$th long DRX cycle,

Then, $W_0 = 0$, and

$$W_n = \sum_{i=1}^{n} T_i,$$

$$= 4n(\text{frame}), \ n = 1, 2, \ldots$$

The assumptions made for the delay analysis are given as follows:

- The eNB always authorize the required bandwidth for voice traffic.
- Packets gathered in queue during sleep are served in the next listening (ON) period of long DRX cycle.
- Packets arriving during awake mode do not experience any queueing delay in short DRX cycles of length 20 ms.

The steady state probability of UE to be in mutual silence period, denoted by $P_{ms}$, is defined as

$$P_{ms} = \pi_4 + \pi_5 + \pi_7 + \pi_8.$$ 

Also, define

$$\lambda_u = \text{average uplink packet generation rate},$$

$$\lambda_d = \text{average downlink packet generation rate}.$$
Therefore, we get
\[ \lambda_u = \frac{1}{P_{ms}} [\pi_4 \lambda_{4,6} + \pi_5 \lambda_{5,6} + \pi_7 \lambda_{7,2} + \pi_8 \lambda_{8,6} + \pi_8 \lambda_{8,3}], \]
\[ \lambda_d = \frac{1}{P_{ms}} [\pi_4 \lambda_{4,1} + \pi_5 \lambda_{5,1} + \pi_7 \lambda_{7,1}]. \]

Thus,
\[ \lambda_u + \lambda_d = \text{Pure arrival rate of a packet during mutual silence period.} \]

Now, since the size of a frame is 10 ms for LTE-A networks. Therefore, during talkspurts period voice packets are generated after every two frames (i.e., 20 ms). A silence period starts when a silence suppression generates a session insertion description (SID) packet at the beginning. Two consecutive SID packets (both uplink and downlink) leads to the confirmation of a mutual silence period. Thus, as the second consecutive SID packet arrive, the sleep period starts [10].

Figure 6. When sleep period is terminated by a packet

5.4. **Delay for any downlink packet (D).** It is time duration counted (in the frame unit) from the frame when a packet arrives at the eNB to the first frame when it is served in the next listening period.

Arrival of a downlink packet is based on the following two ways:

Case (i) : A downlink packet arrive during sleep before uplink packet. Also, this happens before the current long DRX cycle expires. Hence, UE wakes up immediately at the reception of uplink packet. It occurs in states 4 and 7, and can be observed from Figure 3 (i.e., when after a silence gap party B start to talk).

Case (ii) : A downlink packet arrives but no uplink packet arrives during sleep. Therefore, UE waits until the next listening period of long DRX cycle arrives. It occurs in states 5 and 8 (i.e., when after a silence gap party B start to talk whereas party A remains silent), can be noted in Figure 3.

Let
\[ n^*(r) = \min\{n : r \leq W_n\}, r = 1, 2, \ldots. \]

Now, we define the following two random variables
Now, we define $p$ at state 8. Performance then state 8 yields no delay of packets as uplink packets are generated depicted in Figure 3 for modified Brady model. We are analyzing the party B’s $r$, $b$,

From Case i) and ii), $D$ is defined as

$$D = \begin{cases} 
4(n^*(Z) - 1) + Y - Z & \text{w.p. } q_a^{r,k} \text{ (in Case i)} \\
4(n^*(Z)) + 1 - Z & \text{w.p. } q_b^r \text{ (in Case ii)},
\end{cases}$$

where $q_a^{r,k} = \frac{p_a^{r,k}}{P_{delay}}$ and $q_b^r = \frac{p_b^r}{P_{delay}}$,

$$P_{delay} = \sum_{r=2}^{\infty} \sum_{k=r-4(n^*(r)-1)+1}^{\infty} p_a^{r,k} + \sum_{r=2}^{\infty} p_b^r.$$
5.5. Expected delay. Thus, expected delay obtained is given by

\[ E[D] = \sum_{r=2}^{\infty} \sum_{k=r-4(n^*(r)-1)+1} q_{a}^{r,k}(4(n^*(r)-1) + k - r) + \sum_{r=2}^{\infty} q_{b}^{r}(4n^*(r) + 1 - r). \]

Figure 7 gives the trade-off between expected delay and time frames during two-way communication. We observe that expected delay increases initially and then decreases with time. It shows that over the time expected delay becomes ignorable for UE with proposed DRX scheme.

6. Conclusion and future work. In this paper, an DRX scheme is obtained by exploiting characteristics of voice traffic. Performance analysis is presented for an UE with voice traffic service in two-way communication in LTE-A networks. From the performance analysis, we have shown that UE with optimally selected parameters of DRX scheme saves 81%, 74% in one-way and two-way voice communication, respectively, in comparison to UE with no power saving scheme. Furthermore, an UE having optimally selected parameters of DRX scheme and, inactivity timer period being equal to 20 ms saves 13% less as compared to conventional DRX scheme in two-way voice communication. We have deduced that power saving in case of voice services in one-way communication is significantly more, in comparison to the case of voice services in two-way communication. DRX scheme obtained in this paper is limited to voice traffic only. In future, we intend to extend this work for traffic other than voice services and, compare this work with the model for real time traffic. Also, we plan to perform validation using NS-2 simulation.

Acknowledgments. Authors are thankful to the editor and two anonymous reviewers for their valuable suggestions and comments which helped improve the paper to great extent and gratefully acknowledges for the financial support received from the Department of Telecommunications (DoT), India. Further, Anupam is
supported through a senior research fellowship from Council of Scientific and Industrial Research (CSIR), India.

REFERENCES


Received August 2016; revised November 2017.

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