PERFORMANCE EVALUATION FOR THE ENERGY SAVING MODE FOR DRX IN LTE SYSTEMS

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Abstract
In this paper, we aim to evaluate the system performance of the energy saving mode for Discontinuous Reception (DRX) in Long Term Evolution (LTE) systems. We consider the digital nature of modern communications, and build a discrete-time queueing model with a two-stage vacation. By using the method of an embedded Markov chain, we analyze the system model in the steady-state, and derive the formulas for the handover ratio, the energy saving ratio and the response time of data frames. Moreover, we present numerical results to show how the system performance measures change with the system parameters. Finally, we demonstrate the influence of system parameters on the system performance, and investigate the trade-off between different performance measures.

1 Introduction
In order to meet the market challenge of mobile broadband technology, such as Worldwide Interoperability for Microwave Access (WiMAX), a Long Term Evolution (LTE) system has been initiated by the Third Generation Partnership Project (3GPP) [1]. With the technologies of the Orthogonal Frequency Division Multiplexing (OFDM), Frequency Division Multiple Address (FDMA) and Multi-input Multi-output (MIMO), the transmission rate of data frames and the throughput of users has improved, while the average response time of data frames has been reduced in LTE systems [2].

Additionally, in order to improve energy conservation in Mobile Stations (MS) in LTE systems, a Discontinuous Reception (DRX) mechanism is used in the Medium Access Control (MAC) specification [3]. When there is no data frame to be transmitted, the port connection is always kept active, but the transmission unit is closed and the system switches into the sleep state from the working state. Therefore, if there is a data frame to be transmitted, the MS will switch into the working state directly without rebuilding the connection with an evolved NodeB (eNB). DRX mechanisms can reduce the redundant energy consumption mechanisms of an MS and avoid signaling overhead introduced by frequent switches between the working state and the sleep state [4], [5].

Recently, many energy saving strategies in DRX have been investigated. In [6], Bontu et al. explained the energy saving methods for both a network attached mode and a network idle mode in LTE systems. Then, they defined the optimum criteria for different applications in the RRC_CONNECTED state and the RRC_IDLE state. With reasonable parameter settings in the DRX mechanism, the packet delay could be reduced with a restriction of energy saving ratio. By using the method of system simulation, the problems of high energy consumption and heavy signal overhead in mobile network services were analyzed in [7].

The system performance of Active DRX mechanism and optimized advice about the parameter configurations in DRX mechanism were presented. By considering the downlink packet arrivals at a User Equipment (UE) and uplink packet arrivals at an evolved node, Sangkyu et al. constructed a two-dimensional discrete time embedded Markov chain and investigated the trade-off between different performance measures in a DRX system [8]. In [9], Zhang et al. deliberated the DRX mechanism based on the TD-LTE system and built an energy conservation model by using a half-Markov chain method. They gave the formulas for the energy saving ratio and the average latency, and they also presented numerical experiments to investigate the system performance.

In this paper, in order to describe the energy saving mode of DRX in LTE systems, we build a discrete-time queueing model with a two-stage vacation. We also evaluate the system performance with numerical results. Finally, we investigate the trade-off between different performance measures in the energy saving mechanisms for DRX in LTE systems.

The remainder of this paper is organized as follows. The system model and its analysis are given in Section 2. In Section 3, formulas for the performance measures are derived. In Section 4, we demonstrate the influence of system parameters on the system performance with numerical results. Finally, conclusions are drawn in...
2 System Model and Analysis

2.1 Energy Saving Mode for DRX

The MS transmits data frames to the Base Station (BS) until the buffer of an MS is empty, and then the MS will switch into the sleep state from the awake state. The time period of the sleep state is divided into short sleep stages and long sleep stages. When the MS switches into the sleep state, it will enter into a short sleep stage first. If there is no data frame arrival during a short sleep stage, the MS will enter into another short sleep stage when the previous short sleep stage is over. If there is at least one data frame arrival in a short sleep stage, the MS will enter into the awake state when the short sleep stage is over. But if there is no data frame arrival by the time the number of short sleep stages reaches the threshold $K$, a long sleep stage will begin after the last short sleep stage is finished. If there is no data frame arrival during a long sleep stage, when this long sleep stage is over, the MS will start a new long sleep stage. Otherwise, the MS will enter into the awake state when the long sleep stage is over. This process will be repeated.

2.2 System Model

In the energy saving mechanism for DRX, the transmission channel is regarded as a server and the data frames to be transmitted are seen as consumers. The short sleep stage and the long sleep stage are considered as short vacation period $V_1$ and long vacation period $V_2$, respectively. The time lengths of the short vacation period $V_1$ and the long vacation period $V_2$ are denoted as $T_{V_1}$ and $T_{V_2}$, respectively. All the continuous vacation periods constitute a system vacation $V$, and the time length of the system vacation $V$ is denoted as $T_V$.

The time period for the data frames being transmitted continuously is seen as a busy period $B$, and the time length of $B$ is denoted as $T_B$. A busy cycle $R$ is defined as a time period from the instant that a busy period $B$ ends to the instant that the next busy period $B$ ends. Then a queuing model with two stages of vacations is built.

To comply with the digital nature of modern communication, we evaluate the system performance by using a discrete-time queuing model. In the discrete-time queuing model, the time axis is segmented into a series of equal intervals called slots. The arrivals and departures of data frames are supposed to happen only at the boundaries of slots. A single channel and an infinite capacity are considered in this model. The transmissions of data frames are supposed to follow a First-Come First-Served (FCFS) discipline.

We assume that the arrival process of data frames follows a Bernoulli distribution, i.e., the probability that there is a data frame arrival at the system in a slot is $p$ ($0 < p < 1$), and no data frame arrives at the system in a slot with probability $\bar{p}$ ($\bar{p} = 1 - p$). The transmission time $S$ of a data frame is supposed to follow a general distribution. Letting the transmission time $S$ of a data frame be an independent and identically random variable, the probability distribution $p_s$, the Probability Generating Function (PGF) $S(z)$ and the average value $E[S]$ of $S$ can be expressed as follows:

$$P\{S = k\} = s_k, \quad k = 1, 2, \ldots,$$

$$S(z) = \sum_{k=1}^{\infty} s_k z^k, \quad E[S] = \sum_{k=1}^{\infty} k s_k.$$

We choose the departure instants of data frames as the embedded Markov points and define the system state by the number of data frames at these embedded Markov points. So the system state at the embedded points constitutes an embedded Markov chain. The sufficient and necessary condition for this embedded Markov chain to be steady is $p = pE[S] < 1$.

If there is no data frame arrival in the vacation period, when the vacation period is over, the system will enter into the next vacation period. The busy period $B$ begins at the instant where a short vacation period or a long vacation period ends. Let $P_{V_1}$ be the probability that the system will switch into the awake state from a short vacation period, and $P_{V_2}$ be the probability that the system will enter into the awake state from a long vacation period. $P_{V_1}$ and $P_{V_2}$ can be given as follows:

$$P_{V_1} = 1 - \bar{p}^K T_{V_1}, \quad P_{V_2} = \bar{p}^K T_{V_1}. \quad (1)$$

Let $Q_B$ be the number of data frames queuing in the buffer at the beginning instant of a busy period $B$. By analyzing the beginning condition of a busy period $B$, we can obtain the probability distribution of $Q_B$ as follows:

$$P\{Q_B = i\} = \begin{cases} \frac{P_{V_1}}{1 - \bar{p}^K T_{V_1}} \sum_{i=1}^{T_{V_1}} \binom{T_{V_1}}{i} p^i \bar{p}^{T_{V_1} - i}, & 1 \leq i \leq T_{V_1} \\ \frac{P_{V_2}}{1 - \bar{p}^K T_{V_2}} \sum_{i=1}^{T_{V_2}} \binom{T_{V_2}}{i} p^i \bar{p}^{T_{V_2} - i}, & T_{V_1} + 1 \leq i \leq T_{V_2}. \end{cases} \quad (2)$$

The PGF $Q_B(z)$ of the $Q_B$ as follows:

$$Q_B(z) = \sum_{i=1}^{\infty} z^i P\{Q_B = i\} = P_{V_1} \cdot \frac{(pz + \bar{p})^{T_{V_1}} - \bar{p}^{T_{V_1}}}{1 - \bar{p}^{T_{V_1}}} + P_{V_2} \cdot \frac{(pz + \bar{p})^{T_{V_2}} - \bar{p}^{T_{V_2}}}{1 - \bar{p}^{T_{V_2}}}. \quad (3)$$
Differentiating Eq. (3) with respect to $z$ at $z = 1$, the average value $E[Q_B]$ of $Q_B$ can be given as follows:

$$E[Q_B] = Q'_B(z) |_{z=1} = p_{TV_1} \frac{p_{TV_1}}{1 - p_{TV_1}} + p_{TV_2} \frac{p_{TV_2}}{1 - p_{TV_2}}.$$  (4)

2.3 Performance Analysis

At the embedded point, the queue length $L^+$ can be decomposed into two parts, i.e., $L^+ = L_0 + L_d$. $L_0$ is the queue length of the classical Geom/G/1 model, and $L_d$ is the additional queue length introduced by the two-stage vacation in the system model.

The average value $E[L_0]$ of $L_0$ can be given as follows:

$$E[L_0] = \rho + \frac{p E[S (S-1)]}{2 (1-\rho)}.$$  (5)

By using the boundary state variable theory [10], the PGF of $L_d$ is given as follows:

$$L_d(z) = \frac{1 - Q_B(z)}{E[Q_B](1-z)}.  \quad (6)$$

Differentiating Eq. (6) with respect to $z$ at $z = 1$, the average value $E[L_d]$ of $L_d$ is obtained as follows:

$$E[L_d] = \frac{E[Q_B(Q_B - 1)]}{2E[Q_B]} = \frac{p_{TV_1} (1 - p_{TV_1}) T_{V_1} (T_{V_1} - 1)}{H} + \frac{p_{TV_2} (1 - p_{TV_2}) T_{V_2} (T_{V_2} - 1)}{H}.$$  (7)

where $H$ is given as follows:

$$H = 2 \left( p_{TV_1} (1 - p_{TV_1}) T_{V_1} + p_{TV_2} (1 - p_{TV_2}) T_{V_2} \right).$$

Combining Eqs. (5) and (7), the average value $E[L^+]$ of $L^+$ can be given as follows:

$$E[L^+] = E[L_0] + E[L_d]. \quad (8)$$

The waiting time $W$ of a data frame can be divided into two parts, i.e., $W = W_0 + W_d$. $W_0$ is the waiting time of the classical Geom/G/1 model, and $W_d$ is the additional waiting time introduced by the two-stage vacation in the system model.

The average waiting time $E[W_0]$ of $W_0$ can be given as follows:

$$E[W_0] = \frac{p E[S (S-1)]}{2 (1-\rho)}. \quad (9)$$

By using the boundary state variable theory [10], the PGF of $W_d$ is given as follows:

$$W_d(z) = \frac{p (1 - Q_B (1 - p^{-1} (1 - z)))}{E[Q_B](1-z)}. \quad (10)$$

Differentiating Eq. (10) with respect to $z$ at $z = 1$, the average value $E[W_d]$ of $W_d$ is obtained as follows:

$$E[W_d] = W'_d(z) |_{z=1} = \frac{p_{TV_1} (1 - p_{TV_2}) T_{V_1} (T_{V_1} - 1)}{H} + \frac{p_{TV_2} (1 - p_{TV_2}) T_{V_2} (T_{V_2} - 1)}{H}. \quad (11)$$

Combining Eqs. (9) and (11), the average value $E[W]$ of $W$ can be given as follows:

$$E[W] = E[W_0] + E[W_d]. \quad (12)$$

Note that the system vacation period $V$ consists of one or more short vacation periods $V_1$ with probability $p_{TV_1}$, and consists of $K$ short vacation periods $V_1$ and one or more long vacation periods $V_2$ with probability $p_{TV_2}$. Therefore, the average length $E[T_V]$ of the system vacation $V$ is given as follows:

$$E[T_V] = \frac{p_{TV_1} T_{V_1}}{1 - p_{TV_1}} + \frac{p_{TV_2} T_{V_2}}{1 - p_{TV_2}}. \quad (13)$$

By applying the boundary state variable theory [10], the average value $E[T_B]$ of the busy period $B$ is given as follows:

$$E[T_B] = E[Q_B] E[S] \frac{1}{1-\rho} = \left( \frac{p_{TV_1} T_{V_1}}{1 - p_{TV_1}} + \frac{p_{TV_2} T_{V_2}}{1 - p_{TV_2}} \right) \times \frac{\rho}{1 - \rho}. \quad (14)$$

Obviously, a busy cycle $R$ consists of a busy period $B$ and a system vacation $V$. Combining Eqs. (13) and (14), the average value $E[T_R]$ of the busy cycle $R$ is given as follows:

$$E[T_R] = E[T_B] + E[T_V] = \left( \frac{p_{TV_1} T_{V_1}}{1 - p_{TV_1}} + \frac{p_{TV_2} T_{V_2}}{1 - p_{TV_2}} \right) \times \frac{1}{1 - \rho}. \quad (15)$$

3 Performance Measures

Let $\beta$ be the handover ratio which accounts for the number of switches between the awake state and the sleep state per slot. Obviously, there is one switch in a busy cycle in this system. So the handover ratio $\beta$ can be given as follows:

$$\beta = \frac{1}{E[T_R]}.$$

The energy saving ratio $\gamma$ is defined as the energy conservation per slot due to the introduction of the sleep mode. Energy is consumed normally in the awake state and is saved in the sleep state. Moreover, energy will be consumed during the switching procedure from the sleep state to the awake state. Therefore, the $\gamma$ is given as follows:

$$\gamma = \frac{(C_A - C_S) E[T_V]}{E[T_R]} = C_W \beta.$$
where \( C_A \) and \( C_S \) are the energy consumptions per slot in the awake state and the sleep state, respectively. \( C_W \) is the energy consumption for each switch from the sleep state to the awake state.

We define the response time of a data frame as the time period from the arrival instant of a data frame to the departure instant of that same data frame. Obviously, the average response time \( \sigma \) is the sum of the average waiting time \( E[W] \) and the average transmission time \( E[S] \) of data frames. Therefore, \( \sigma \) is given as follows:

\[
\sigma = E[W] + E[S].
\]

4 Numerical Results

In this section, we present the numerical results to show how the system performance measures change with the system parameters. The parameters are set as follows: 1 slot = 1 ms, \( E[S] = 4 \) ms, \( \rho = 0.4 \), \( C_A = 800 \) mW, \( C_S = 50 \) mW, \( C_W = 1 \times 10^{-3} \) J.

Figure 1 examines how the handover ratio changes with respect to the threshold \( K \) of the short sleep stages for different time lengths \( T_{V2} \) of the long sleep stage by fixing the time lengths of the short sleep stage \( T_{V1} = 1 \) ms and \( T_{V1} = 3 \) ms, respectively.

![Figure 1: Change trend of the handover ratio.](image)

In Figs. 1 (a) and 1 (b), we see that for the same time lengths \( T_{V1} \) of the short sleep stage and \( T_{V2} \) of the long sleep stage, when the threshold \( K \) of the short stages increases, the handover ratio will increase. When the threshold \( K \) reaches a certain value, the value of the handover ratio will change lesser. Moreover, for a given threshold \( K \) of the short stages, the longer the long sleep stage is, or the smaller the short sleep stage is, the smaller the handover ratio will be.

Figure 2 examines how the energy saving ratio changes with respect to the threshold \( K \) of the short sleep stages for different time lengths \( T_{V2} \) of the long sleep stage by fixing the time lengths of the short sleep stage \( T_{V1} = 1 \) ms and \( T_{V1} = 3 \) ms, respectively.

![Figure 2: Change trend of the energy saving ratio.](image)

By comparing Figs. 2 (a) and (b), it is illustrated that for the same time length \( T_{V1} \) of the short sleep stage and \( T_{V2} \) of the long sleep stage, when the threshold \( K \) of the short stages increases, the energy saving ratio will decrease. When the threshold \( K \) reaches a certain value, the change trend of the energy saving ratio will become stable. Moreover, for a given threshold \( K \) of the short stages, the longer the long sleep stage is, or the longer the short sleep stage is, the higher the energy saving ratio will be.

Figure 3 examines how the average response time changes with respect to the threshold \( K \) of the short sleep stages for different time lengths \( T_{V2} \) of the long sleep stage by fixing the time lengths of the short sleep stage \( T_{V1} = 1 \) ms and \( T_{V1} = 3 \) ms, respectively.

![Figure 3: Change trend of the average response time.](image)

Figures 3 (a) and (b) show that for the same time lengths \( T_{V1} \) of the short sleep stage and \( T_{V2} \) of the long sleep stage, when the threshold \( K \) of the short
stages increases, the average response time will decrease. When the threshold $K$ reaches a certain value, the average response time will approach a certain value. Moreover, for a given threshold $K$ of the short stages, the longer the long sleep stage is, or the longer the short sleep stage is, the higher the average response time will be.

Concluding the numerical results shown in Figs. 1-3, we find that a greater threshold of the short sleep stages will increase the handover ratio and decrease the energy saving ratio, but will reduce the average response time of data frames; a lower threshold of the short sleep stages will decrease the handover ratio and increase the energy saving ratio, but will make the average response time of data frames longer. Therefore, there is a trade-off when designing the threshold of the short sleep stages in the energy saving mode of DRX mechanisms in LTE systems.

5 Conclusions

In this paper, according to the working principle of the energy saving mode of DRX mechanisms in LTE systems, a queuing model with a two-stage vacation was built. By using the method of an embedded Markov chain, the system model was analyzed in steady state, some performance measures in terms of the handover ratio, the energy saving ratio and the average response time of data frames were derived. With the numerical results of analysis, the influences of the threshold of the short sleep stages, the time lengths of the short sleep stage and the long sleep stage on the system performance were demonstrated mathematically. Moreover, the trade-off between different performance measures was investigated. The research in this paper has potential applications in the optimization of energy saving strategies for wireless communication networks.

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References