# Performance Analysis of UMTS Power Saving Mechanism

Shun-Ren Yang
Dept. Comp. Sci. & Info. Engr.
National Chiao Tung University
300 Hsinchu, Taiwan, R.O.C.
sjyoun@csie.nctu.edu.tw

Yi-Bing Lin
Dept. Comp. Sci. & Info. Engr.
National Chiao Tung University
300 Hsinchu, Taiwan, R.O.C.
liny@csie.nctu.edu.tw

## Abstract

*This paper investigates the discontinuous reception (DRX) mechanism of Universal Mobile Telecommunications System (UMTS). DRX is exercised between the network and a mobile station (MS) to save the power of the MS, which is controlled by two parameters: the inactivity timer threshold and the DRX cycle. Analytic model is proposed to study the effects of these two parameters on output measures including the expected queue length, the expected packet waiting time, and the power saving factor. Our study quantitatively shows how to select appropriate inactivity timer and DRX cycle values for various traffic patterns.*

**Keywords:** Discontinuous reception (DRX), Power saving, Universal Mobile Telecommunications System (UMTS)

## 1 Introduction

*Universal Mobile Telecommunications System* (UMTS) [7] supports mobile multimedia applications with high data transmission rates. Figure 1 illustrates a simplified UMTS architecture, which consists of the *Core Network* and the *UMTS Terrestrial Radio Access Network* (UTRAN). The core network is responsible for switching/routing calls and data connections to the external networks, while the UTRAN handles all radio-related functionalities. The UTRAN consists of *Radio Network Controllers* (RNCs) and *Node Bs* (i.e., base stations) that are connected by an ATM network. A *Mobile Station* (MS) communicates with Node Bs through the radio interface based on the WCDMA (Wideband CDMA) technology [7].

In UMTS, MS power consumption is a serious problem for wireless data transmission. Most existing wireless mobile networks (including UMTS) employ *Discontinuous Reception* (DRX) to conserve the power of MSs. DRX allows an idle MS to power off the radio receiver for a predefined period (called the *DRX cycle*) instead of continuously listening to the radio channel. In MOBITEX [10], CDPD [5, 9] and IEEE 802.11 [8], the network announces the list of the MSs who have pending packets at the scheduled time instants. The sleeping MSs wake up at the scheduled times to receive the announcements. UMTS DRX [2, 4] enhances the above mechanism by allowing an MS to negotiate its own DRX cycle length with the network. Therefore, the network is aware of sleep/wake-up scheduling of each MS, and delivers the paging message when the MS wakes up. This paper investigates the performance of the UMTS DRX. We first introduce the UMTS DRX mechanism. Then we propose analytic model[1] for UMTS DRX. Based on the proposed model, the DRX performance is investigated by numerical examples.

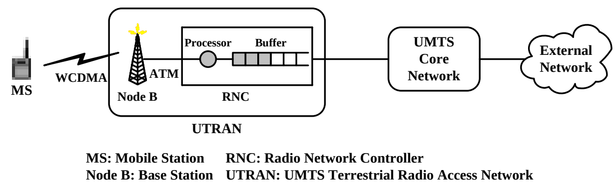


**Figure 1. A simplified UMTS network architecture**

## 2 UMTS DRX Mechanism

The UMTS DRX mechanism is realized through the *Radio Resource Control* (RRC) finite state machine exercised between the RNC and the MS [1]. There are two modes in this finite state machine (see Figure 2). In the **RRC Idle** mode, the MS is tracked by the core network without involving the UTRAN. When an RRC connection is established between the MS and its serving RNC, the MS enters the **RRC Connected** mode. This mode consists of

[1]Due to space limitation, the analytic model is described concisely in this paper. The interested readers are referred to [14] for the details.

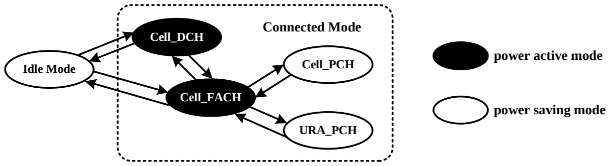


**Figure 2. The RRC state diagram**

four states. If the MS obtains a dedicated traffic channel for the RRC connection, it enters the **Cell_DCH** state. On the other hand, if the MS is allocated a common or shared traffic channel (i.e., the channel is shared by several MSs), it enters the **Cell_FACH** state. The data communication activities can only be performed in these two states. In the **Cell_PCH** state, no uplink access is possible, and the MS selects a Paging Channel (PCH) to monitor paging messages from the RNC. In the above three RRC states, the MS performs location update whenever it moves to a new cell (i.e., the radio coverage of a Node B). If the MS receives packets infrequently, the UTRAN may eliminate the cell update overhead by instructing the MS to move to the **URA_PCH** state. In this state, the MS performs location update for every *UTRAN Registration Area* (URA) crossing. Details of cell and URA updates can be found in [13].

In the **Cell_DCH** and **Cell_FACH** states, the MS receiver is always turned on to receive packets. These states correspond to the *power active mode*. In the **RRC Idle** mode, **Cell_PCH** and **URA_PCH** states, the DRX is exercised to reduce the MS power consumption. These states/mode correspond to the *power saving mode*. The MS receiver activities are described in terms of three periods:

**The busy period.** During packet transmission (i.e., the "server" is "busy"), the UMTS core network sends the packets to an MS through the RNC and Node B. The incoming packets are first stored in the RNC buffer before they are delivered to the MS. Since the MS is in the power active mode, the RNC processor immediately transmits packets in the *First In First Out* (FIFO) order. Due to high error-rate and low bit-rate nature of radio transmission, the *Stop-And-Wait Hybrid Automatic Repeat reQuest* (SAW-Hybrid ARQ) flow control algorithm [3] is exercised between the Node B and the MS to guarantee successful radio packet delivery. The SAW-Hybrid ARQ algorithm works as follows. When the Node B sends a packet to the MS, it waits for a positive acknowledgment (ack) from the MS before it can transmit the next packet. The Node B may receive negative acknowledgments (naks) from the MS, which indicate that some errors have occurred (e.g., the transmitted packet is damaged). In this case, the Node B re-transmits the packet until an ack is received.

**The inactivity period.** If the RNC buffer becomes empty, the RNC inactivity timer is activated. If any packet arrives at the RNC before the inactivity timer expires, the timer is stopped. The RNC processor starts to transmit packets, and another busy period begins. Note that the MS is in the power active mode in both the busy and inactivity periods, where the MS receiver is turned off.

**The sleep period.** If no packet arrives before the inactivity timer expires, the MS enters the power saving mode and the MS receiver is turned off. The MS sleep period contains at least one DRX cycles. At the end of a DRX cycle, the MS wakes up to listen to the PCH. If some packets have arrived at the RNC during the last DRX cycle (i.e., the paging indicator for this MS is set), the MS starts to receive packets and the sleep period terminates. Otherwise, the MS returns to sleep until the end of the next DRX cycle. In the power saving mode, the RNC processor will not transmit any packets to the MS.

Based on the above description, we propose an analytic model for the UMTS DRX mechanism. As illustrated in Figure 1, the UMTS core network sends the packets to an MS through the RNC and Node B. We assume that packet arrivals to the RNC form a Poisson stream with rate $\lambda_a$. The RNC processor sends the packets to the Node B through an ATM link. The Node B then forwards the packets to the MS by the WCDMA radio link. Compared with WCDMA radio transmission, ATM is much faster and more reliable. Therefore the ATM transmission delay is ignored in our analytic model, and the RNC and the Node B are treated as a FIFO server. Let $t_x$ denote the time interval between when a packet is transmitted by the RNC processor and when the corresponding ack is received by the RNC processor. Let $t_I$ be the threshold of the RNC inactivity timer, and $t_S$ be the MS sleep period. The UMTS DRX is modeled as a variant of the $M/G/1$ queue with multiple vacations [12], where $t_x$ represents the service time (the period between when a packet is sent from the UTRAN to the MS and when the UTRAN receives the ack from the MS), and $t_S$ corresponds to the server vacations. Our model is different from the existing $M/G/1$ vacation model due to the introduction of the inactivity timer threshold $t_I$. In our model, the server can not enter vacation mode immediately after the queue is empty. The following output measures are derived:

- mean queue length: the expected number of packets buffered in the UTRAN, including the one in delivery and those waiting in the RNC buffer

- mean packet waiting time: the expected waiting time of a packet in the RNC buffer before it is transmitted to the MS

- power saving factor: the probability that the MS receiver is turned off when exercising the UMTS DRX mechanism

## 3 Queue Length and Packet Waiting Time

This section derives the generating function for the queue length distribution and the Laplace Transform for the packet waiting time. Denote $L_n$ as the queue length of the RNC buffer immediately after the $n$th packet completes service and departs (i.e., at the time when the $n$th ack is received by the RNC processor). $L_n = 0$ implies that the RNC buffer is empty after the $n$th packet has been received by the MS. In this case, the RNC inactivity timer is activated. Suppose that $Q_n$ packets arrive at the RNC before the inactivity timer expires. If $Q_n = 0$, the MS enters the power saving mode. Let $R_n$ be the number of packets that arrive during the sleep period. The probability mass functions for $Q_n$ and $R_n$ are denoted as $q_m = \Pr[Q_n = m]$ (where $m = 0, 1, 2, \ldots$) and $r_l = \Pr[R_n = l]$ (where $l = 1, 2, 3, \ldots$), respectively. Let $A_{n+1}$ be the number of packets that arrive during the service time of the $n + 1$st packet. The relationship between $L_{n+1}$, $L_n$, $A_{n+1}$, $Q_n$ and $R_n$ is expressed as

$$L_{n+1} = \begin{cases} L_n + A_{n+1} - 1, & \text{for } L_n \geq 1 \\ A_{n+1}, & \text{for } L_n = 0, Q_n > 0 \\ R_n + A_{n+1} - 1, & \text{for } L_n = 0, Q_n = 0 \end{cases} \quad (1)$$

The above equation indicates that $L_{n+1}$ is independent of $L_m$ for $m < n$, and the sequence of the random variables $\{L_n; n = 1, 2, \ldots\}$ constitutes a *Markov chain* [11]. Let $L$ be the queue length in the steady state. The steady state distribution for this Markov chain is defined as

$$\pi_k = \Pr[L = k] = \lim_{n\to\infty} \Pr[L_n = k], \quad \text{for } k = 0, 1, 2, \ldots$$

which can be solved by using $\sum_{k=0}^{\infty} \pi_k = 1$ and the balance equations

$$\pi_k = \sum_{j=0}^{\infty} \pi_j \Pr[L_{n+1} = k | L_n = j] \quad (2)$$

where $\Pr[L_{n+1} = k | L_n = j]$ is the state transition probability. Denote $a_k = \Pr[A_n = k]$ for $n \geq 1$ and $k \geq 0$. Based on (1), $\Pr[L_{n+1} = k | L_n = j]$ is expressed as

$$\begin{cases} a_{k-j+1}, & \text{for } j \geq 1, k \geq j-1 \\ 0, & \text{for } j \geq 1, 0 \leq k < j-1 \\ \left[(1-q_0)a_k + q_0 \times \left(\sum_{l=1}^{k+1} r_l a_{k-l+1}\right)\right], & \text{for } j = 0, k \geq 0 \end{cases} \quad (3)$$

Substitute (3) into (2), $\pi_k$ is expressed as

$$\pi_k = \pi_0 \left[(1-q_0)a_k + q_0 \left(\sum_{l=1}^{k+1} r_l a_{k-l+1}\right)\right] + \sum_{j=1}^{k+1} \pi_j a_{k-j+1}, \quad k \geq 0 \quad (4)$$

Let $\Pi(z) = \sum_{k=0}^{\infty} \pi_k z^k$ be the generating function for the $\pi_k$ distribution. From (4), we have

$$\Pi(z) = (1-q_0)\pi_0 \sum_{k=0}^{\infty} a_k z^k + q_0 \pi_0 \sum_{l=1}^{\infty} r_l z^{l-1} \sum_{k'=0}^{\infty} a_{k'} z^{k'} + \left[\frac{\Pi(z) - \pi_0}{z}\right] \sum_{k'=0}^{\infty} a_{k'} z^{k'} \quad (5)$$

Let $A(z) = \sum_{k=0}^{\infty} a_k z^k$ be the probability generating function for $a_k$ (the probability that $k$ packets arrive during a packet service time $t_x$). Suppose that the $t_x$ distribution has the Laplace Transform $f_x^*(s)$, mean $1/\lambda_x$ and variance $V_x$. From Theorem 4.2 in [6], we have

$$A(z) = f_x^*(\lambda_a - \lambda_a z) \quad (6)$$

Let $R(z) = \sum_{l=1}^{\infty} r_l z^l$ be the generating function for the $r_l$ distribution. From (6), (5) is rewritten as

$$\Pi(z) = \left\{(1-q_0)\pi_0 + q_0 \pi_0 \left[\frac{R(z)}{z}\right] + \left[\frac{\Pi(z) - \pi_0}{z}\right]\right\} f_x^*(\lambda_a - \lambda_a z) \quad (7)$$

Let $R = \lim_{n\to\infty} R_n$. Since $\Pi(1) = 1$, we derive $\pi_0$ from (7) as

$$\pi_0 = \frac{1-\rho}{1 - q_0 + q_0 E[R]} \quad (8)$$

where $\rho = \lambda_a/\lambda_x$. Substituting (8) into (7), we have

$$\Pi(z) = \frac{[1 - z(1-q_0) - q_0 R(z)](1-\rho) f_x^*(\lambda_a - \lambda_a z)}{(1 - q_0 + q_0 E[R])[f_x^*(\lambda_a - \lambda_a z) - z]} \quad (9)$$

The Laplace Transform $f_w^*(s)$ for the packet waiting time $t_w$ is derived as follows. Following the FIFO scheduling policy, the RNC queue length seen by a departing packet is precisely the number of packets that arrived during the response time $t_r$ of the packet, where

$$t_r = t_w + t_x \quad (10)$$

Let $f_r^*(s)$ be the Laplace Transform of $t_r$. Similar to the derivation of $A(z)$ (Theorem 4.2 in [6]),

$$\Pi(z) = f_r^*(\lambda_a - \lambda_a z) \quad (11)$$

From (10) and the convolution property of the Laplace Transform, we have

$$f_r^*(\lambda_a - \lambda_a z) = f_w^*(\lambda_a - \lambda_a z) f_x^*(\lambda_a - \lambda_a z) \qquad (12)$$

From (9), (11) and (12), we have

$$f_w^*(s) = \left\{ \frac{\lambda_a q_0 [1 - R(1 - s/\lambda_a)] + s(1 - q_0)}{1 - q_0 + q_0 E[R]} \right\} \times \left[ \frac{(1-\rho)}{\lambda_a f_x^*(s) - \lambda_a + s} \right] \qquad (13)$$

Assume that the length of each DRX cycle $t_D$ in a sleep period is independent and identically distributed with mean $1/\lambda_D$, variance $V_D$ and Laplace Transform $f_D^*(s)$. From [14],

$$R(z) = \frac{f_D^*(\lambda_a - \lambda_a z) - f_D^*(\lambda_a)}{1 - f_D^*(\lambda_a)} \qquad (14)$$

and

$$E[R] = \frac{\lambda_a}{[1 - f_D^*(\lambda_a)]\lambda_D} \qquad (15)$$

Assume that the inactivity timer threshold $t_I$ has the density function $f_I(t)$, mean $1/\lambda_I$, variance $V_I$ and Laplace Transform $f_I^*(s)$. From the Poisson distribution

$$q_0 = \int_{t=0}^{\infty} \left[ \frac{e^{-\lambda_a t}(\lambda_a t)^0}{0!} \right] f_I(t) dt = f_I^*(\lambda_a) \qquad (16)$$

Substitute (14), (15) and (16) into (9) and (13), we obtain

$$\begin{aligned} \Pi(z) = & \{\lambda_D (1 - z[1 - f_I^*(\lambda_a)])[1 - f_D^*(\lambda_a)] \\ & -\lambda_D f_I^*(\lambda_a)[f_D^*(\lambda_a - \lambda_a z) - f_D^*(\lambda_a)]\} \\ & \div \{\lambda_D [1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] \\ & +\lambda_a f_I^*(\lambda_a)\} \\ & \times \left[ \frac{(1-\rho) f_x^*(\lambda_a - \lambda_a z)}{f_x^*(\lambda_a - \lambda_a z) - z} \right] \qquad (17) \end{aligned}$$

and

$$\begin{aligned} f_w^*(s) = & \{\lambda_D \lambda_a f_I^*(\lambda_a)[1 - f_D^*(s)] \\ & +\lambda_D s[1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)]\} \\ & \div \{\lambda_D [1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] \\ & +\lambda_a f_I^*(\lambda_a)\} \\ & \times \left[ \frac{(1-\rho)}{\lambda_a f_x^*(s) - \lambda_a + s} \right] \qquad (18) \end{aligned}$$

From (17) and (18), the expected number of packets $E[L]$ and the mean packet waiting time $E[t_w]$ are expressed as

$$\begin{aligned} E[L] = & \frac{\lambda_a^2 f_I^*(\lambda_a)(1 + V_D \lambda_D^2)}{2\{\lambda_D^2 [1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] + \lambda_a \lambda_D f_I^*(\lambda_a)\}} \\ & + \frac{\lambda_a^2 (1 + V_x \lambda_x^2)}{2(1-\rho)\lambda_x^2} + \rho \qquad (19) \end{aligned}$$

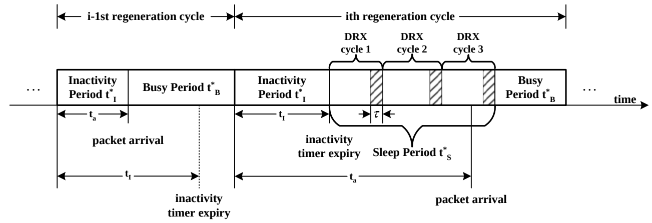


**Figure 3. The regeneration cycles for MS activities**

and

$$\begin{aligned} E[t_w] = & \frac{\lambda_a f_I^*(\lambda_a)(1 + V_D \lambda_D^2)}{2\{\lambda_D^2 [1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] + \lambda_a \lambda_D f_I^*(\lambda_a)\}} \\ & + \frac{\lambda_a (1 + V_x \lambda_x^2)}{2(1-\rho)\lambda_x^2} \qquad (20) \end{aligned}$$

## 4 Power Saving Factor

This section derives the power saving factor $P_s$. We draw the timing diagram of MS receiver activities in Figure 3. In this figure, the MS receiver activities are characterized by a *regenerative process* [11], where a regeneration cycle consists of an inactivity period $t_I^*$, a sleep period $t_S^*$ and a busy period $t_B^*$. We note that at the end of every DRX cycle, the MS must wake up for a short period $\tau$ so that it can listen to the paging information from the network. Therefore the "power saving" period in a DRX cycle is $t_D - \tau$. Suppose that there are $N$ DRX cycles in a sleep period. From Theorem 3.7.1 in [11],

$$P_s = \frac{E[t_S^*] - E[N]\tau}{E[t_I^*] + E[t_S^*] + E[t_B^*]} \qquad (21)$$

$E[t_I^*]$, $E[t_S^*]$, $E[N]$ and $E[t_B^*]$ are derived as follows. In Figure 3, $t_a$ is the time interval between when the RNC inactivity timer is activated and when the next packet arrives. Thus, $t_I^* = \min(t_a, t_I)$. From the memoryless property of Poisson process [11], $t_a$ is exponentially distributed with rate $\lambda_a$. Therefore,

$$E[t_I^*] = E[\min(t_a, t_I)] = \left(\frac{1}{\lambda_a}\right) [1 - f_I^*(\lambda_a)] \qquad (22)$$

$E[t_S^*]$ is derived as follows. If $t_a \geq t_I$, then $t_S^* = t_S$ and $R$ packets arrive during the $t_S$ period. Let $f_S^*(s)$ be the Laplace Transform of $t_S$. From Theorem 4.2 in [6],

$$f_S^*(s) = R(1 - s/\lambda_a) \qquad (23)$$

From (14) and (23), we have

$$f_S^*(s) = \frac{f_D^*(s) - f_D^*(\lambda_a)}{1 - f_D^*(\lambda_a)} \qquad (24)$$

From (24), the mean sleep period $E[t_S^* | t_a \geq t_I]$ is

$$E[t_S^* | t_a \geq t_I] = E[t_S] = -\left.\frac{df_S^*(s)}{ds}\right|_{s=0} = \frac{1}{[1 - f_D^*(\lambda_a)]\lambda_D} \quad (25)$$

Note that $t_a < t_I$ with probability $1 - q_0$. From (25), we have

$$E[t_S^*] = \frac{q_0}{[1 - f_D^*(\lambda_a)]\lambda_D} \quad (26)$$

Substitute (16) into (26) to yield

$$E[t_S^*] = \frac{f_I^*(\lambda_a)}{[1 - f_D^*(\lambda_a)]\lambda_D} \quad (27)$$

The expected value $E[N]$ is derived as follows. Since a $t_S^*$ period consists of $N$ DRX cycles $t_D$, from the Wald's theorem [11], we have

$$E[t_S^*] = E[N]E[t_D] = E[N]/\lambda_D \quad (28)$$

Substitute (27) into (28) to yield

$$E[N] = \frac{f_I^*(\lambda_a)}{1 - f_D^*(\lambda_a)} \quad (29)$$

We derive $E[t_B^*]$ as follows. If $t_a < t_I$ (with probability $1 - q_0$), $t_S^* = 0$ and $t_B^*$ is exactly the same as the busy period $t_B$ of an $M/G/1$ queue. From [6]

$$E[t_B^* | t_a < t_I] = E[t_B] = \frac{\rho}{\lambda_a(1 - \rho)} \quad (30)$$

where $\rho = \lambda_a/\lambda_x$. If $t_a \geq t_I$ (with probability $q_0$), $t_S^* > 0$, and $R$ packets arrive during the $t_S^*$ period. In this case, $t_B^*$ is the sum of $R$ $t_B$ periods. From the Wald's theorem, we have

$$E[t_B^* | t_a \geq t_I] = E[R]E[t_B] \quad (31)$$

Substitute (30) and (15) into (31) to yield

$$E[t_B^* | t_a \geq t_I] = \frac{\rho}{(1 - \rho)[1 - f_D^*(\lambda_a)]\lambda_D} \quad (32)$$

From (30) and (32), we have

$$E[t_B^*] = (1 - q_0)\left[\frac{\rho}{\lambda_a(1 - \rho)}\right] + q_0\left\{\frac{\rho}{(1 - \rho)[1 - f_D^*(\lambda_a)]\lambda_D}\right\} \quad (33)$$

Substitute (16) into (33) to yield

$$E[t_B^*] = \frac{\rho\left\{\lambda_D[1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] + \lambda_a f_I^*(\lambda_a)\right\}}{\lambda_a\lambda_D[1 - f_D^*(\lambda_a)](1 - \rho)} \quad (34)$$

From (22), (27), (29) and (34), (21) is rewritten as

$$P_s = \frac{\lambda_a f_I^*(\lambda_a)(1 - \rho)(1 - \lambda_D\tau)}{\lambda_D[1 - f_I^*(\lambda_a)][1 - f_D^*(\lambda_a)] + \lambda_a f_I^*(\lambda_a)} \quad (35)$$

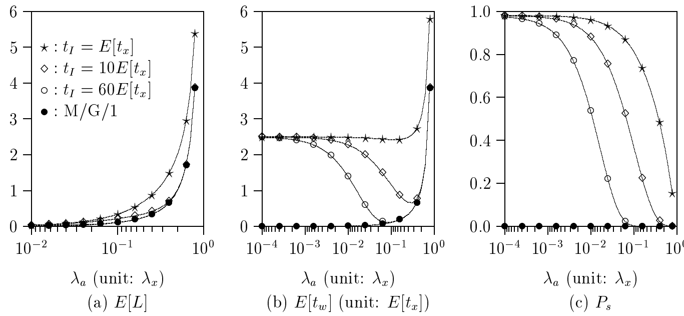


**Figure 4. Effects of $\lambda_a$ and $t_I$ ($V_x = \frac{1}{\lambda_x^2}$, $t_D = 5E[t_x]$, $\tau = 0.1E[t_x]$)**

## 5 Numerical Examples

This section investigates the DRX performance based on the analytic model. Figures 4-6 plot the $E[L], E[t_w]$ and $P_s$ curves. In these figures, $t_x$ has the Gamma distribution with variance $V_x$, and $t_I$ and $t_D$ are fixed. The parameter settings are described in the captions of the figures.

**Effects of $\lambda_a$.** Figure 4(a) indicates that the mean queue length $E[L]$ increases as $\lambda_a$ increases. For $\lambda_a < 0.1\lambda_x$, $E[L]$ is insignificantly affected by the change of $\lambda_a$. When $\lambda_a$ approaches $\lambda_x$, the resulting queueing system becomes unstable, and $E[L]$ grows without bound. Figure 4(b) plots the mean packet waiting time $E[t_w]$ normalized by the mean packet service time $E[t_x]$. The "•" curve shows intuitive result that for an $M/G/1$ queue, $E[t_w]$ is an increasing function of $\lambda_a$. For DRX, $E[t_w]$ curves decrease and then increase as $\lambda_a$ increases. This phenomenon is explained as follows. For $\lambda_a < 0.1\lambda_x$, $E[t_w]$ is affected by the power saving mode operation. Specifically, when $\lambda_a$ approaches $0$, the MS is always in the power saving mode. From (20), every arrival packet is expected to wait for

$$\lim_{\lambda_a \to 0} E[t_w] = \frac{t_D}{2} \quad (36)$$

In Figure 4(b), $t_D = 5E[t_x]$. From (36), $\lim_{\lambda_a \to 0} E[t_w] = 2.5E[t_x]$, which is the value we observe in the figure. As $\lambda_a$ increases, it is more likely that the MS is in the power active mode when packets arrive. In this case, more packets are processed without experiencing the sleep periods, and $E[t_w]$ decreases as $\lambda_a$ increases. On the other hand, if $\lambda_a$ approaches $\lambda_x$, the packet traffic load exceeds the transmission capability, and $E[t_w]$ increases as $\lambda_a$ increases. Figure 4(c) shows the intuitive result that the power saving factor $P_s$ is a decreasing function of $\lambda_a$.

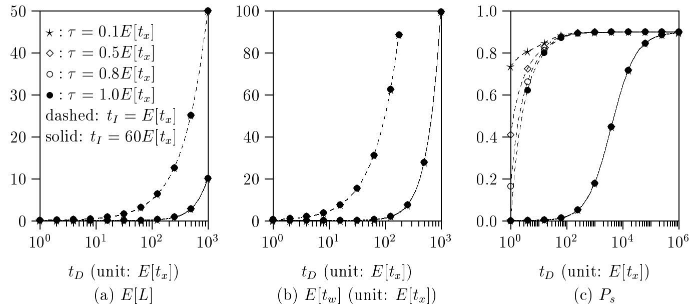


**Figure 5. Effects of $t_D$ and $\tau$ ($V_x = \frac{1}{\lambda_x^2}$, $\lambda_a = 0.1\lambda_x$)**

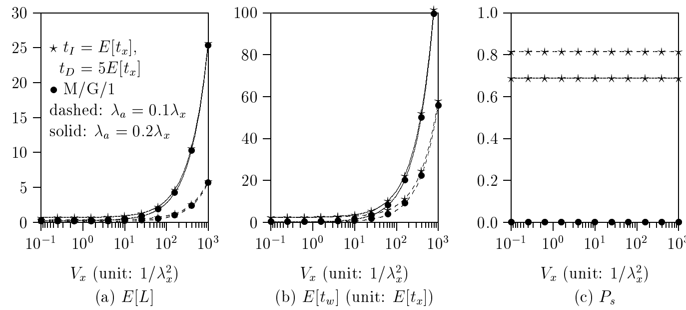


**Figure 6. Effects of $V_x$ ($\tau = 0.1E[t_x]$)**

**Effects of $t_I$.** Figure 4 indicates that by increasing the inactivity timer threshold $t_I$, $E[L]$, $E[t_w]$ and $P_s$ decrease. When $t_I \rightarrow \infty$, the MS never enters the power saving mode, and the system is the same as an $M/G/1$ queue. When $\lambda_a$ is small (e.g., $\lambda_a < 10^{-3}\lambda_x$), the inactivity timer always expires before the next packet arrives. Therefore the output measures are insignificantly affected by the change of $t_I$.

**Effects of $t_D$.** Figure 5 indicates that $E[L]$, $E[t_w]$ and $P_s$ are increasing functions of $t_D$. We observe that when $t_D$ is small (e.g., $t_D < 10E[t_x]$ for the dashed curves in Figures 5(a) and (b)), decreasing $t_D$ will not improve the $E[L]$ and $E[t_w]$ performance. On the other hand, when $t_D$ is large (e.g., $t_D > 100E[t_x]$ for the dashed curves in Figure 5(c)), increasing $t_D$ will not improve the $P_s$ performance. Therefore, for $t_I = E[t_x]$ (i.e., the dashed curves), $t_D$ should be selected in the range $\Big[10E[t_x], 100E[t_x]\Big]$.

**Effects of $\tau$.** It is clear that $E[L]$ and $E[t_w]$ are not affected by $\tau$. Figure 5(c) illustrates the impact of $\tau$ on $P_s$. When $t_D$ is large, $\tau$ (the cost of wakeup) is a small portion of a DRX cycle, which only has insignificant impact on $P_s$. When $t_I$ is large and $t_D$ is small, the MS receiver is almost always turned on and $P_s \simeq 0$. In this case, the $\tau$ impact is also insignificant. When both $t_I$ and $t_D$ are small, $P_s$ is significantly increased as $\tau$ decreases.

**Effects of $V_x$.** Figure 6 illustrates that $E[L]$ and $E[t_w]$ are increasing functions of the variance $V_x$ of the packet transmission delay $t_x$. This effect is well known in queueing systems. On the other hand, $P_s$ is not affected by $V_x$. Therefore, the effect of $V_x$ can be ignored when tuning the DRX parameters for power saving.

## 6 Conclusions

This paper investigated the UMTS discontinuous reception (DRX) mechanism for MS power saving. The DRX mechanism is controlled by two parameters: the inactivity timer threshold $t_I$ and the DRX cycle $t_D$. We proposed a variant $M/G/1$ queueing model with vacations to study the effects of $t_I$ and $t_D$ on output measures including the expected queue length, the expected packet waiting time, and the power saving factor. Our analytic model is different from the existing $M/G/1$ vacation model due to the introduction of $t_I$ (and therefore the server can not enter the vacation mode immediately after the queue is empty). Several numerical examples were presented to quantitatively show how to select appropriate $t_I$ and $t_D$ values for various traffic patterns. Our study indicated that with proper parameter settings, UMTS DRX can effectively reduce the MS power consumption.

## Acknowledgment

This work was supported by the Mediatek Fellowship.

## References


[1] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; RRC Protocol Specification for Release 1999. Technical Specification 3G TS 25.331 version 3.5.0 (2000-12), 2000.

[2] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Services and Systems Aspects; General Packet Radio Service (GPRS); Service Description; Stage 2. Technical Specification 3G TS 23.060 version 3.6.0 (2001-01), 2000.

[3] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; UTRA

High Speed Downlink Packet Access. Technical Specification 3G TR 25.950 version 4.0.0 (2001-03), 2001.

[4] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; UE Procedures in Idle Mode and Procedures for Cell Reselection in Connected Mode. Technical Specification 3G TS 25.304 version 5.1.0 (2002-06), 2002.

[5] CDPD Forum. Cellular Digital Packet Data System Specification: Release 1.1. Technical report, CDPD Forum, Inc., January 1995.

[6] J.N. Daigle, *Queueing Theory for Telecommunications*. Addison-Wesley, 1992.

[7] H. Holma and A. Toskala, *WCDMA for UMTS*. John Wiley & Sons, Inc., 2000.

[8] IEEE. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Draft Standard 802.11 D3.1, April 1996.

[9] Y.-B. Lin and Y.-M. Chuang, Modeling the Sleep Mode for Cellular Digital Packet Data. *IEEE Communications Letters*, 3(3):63–65, March 1999.

[10] RAM Mobile Data. Mobitex Interface Specification. Technical report, RAM Mobile Data, 1994.

[11] S.M. Ross, *Stochastic Processes, 2nd ed.* John Wiley, New York, 1996.

[12] H. Takagi, *Queueing Analysis - Volume 1: Vacation and Priority Systems, Part 1*. Elsevier Science Publishers B.V., 1991.

[13] S.-R. Yang and Y.-B. Lin, A Mobility Management Strategy for UMTS. *International Conference on Information Networking (ICOIN)*, South Korea 2003.

[14] S.-R. Yang and Y.-B. Lin, Modeling UMTS Discontinuous Reception Mechanism. Technical report, National Chiao Tung University, 2003.