Analysis of Discontinuous Reception Power Saving with Radio Resource Control States Transition in LTE Networks

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Abstract

The 3GPP long term evolution(LTE) not only offer high bandwidth for data transfer but also exhaust the User Equipment(UE)'s battery life quickly. In order to save the UE's battery Life, discontinuous reception(DRX) is specified to reduce the UE's power consumption, DRX allow the UE to turn off RF module when there is no data need to transfer. This work focus on analysis DRX mechanism with different RRC states, we use a simple numerically analytical to model this. We divided the time period for power-saving operation into several independent parts to derive the power consumption and the transmission delay. To analysis the power advisably, we introduce the real power consumption through the power model. We evaluate the performance that the UE is more power effectively when enters RRC_IDLE in lower arrival rate, and there is trade-off between the power and the transmission delay.

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Chapter 1

Introduction

The fourth generation (4G) wireless technologies, such as Long Term Evolution (LTE) of Universal Mobile Telecommunications System (UMTS) offer high bandwidth for data transfer to support various applications. The LTE has downlink peak date rate of 100Mbps and uplink peak data rate of 50Mbps by adopting some novel technologies (e.g., MIMO and OFDMA). However, the high complexity of these new technologies may exhaust the UE battery power quickly. Figure 1.1 shows LTE network architecture between evolved Node B (eNB) and UE. In order to extend UE's battery lifetime, DRX is specified in 3GPP LTE standard to reduce the power consumption of UE [1] [2]. In DRX operation, the UE periodically wakes up to monitor new packet arrival in physical downlink control channel (PDCCH). If packets arrive, UE stays active until no more packets are received for a period of time.

In [3–5], they considered the DRX operation with different channel conditions, following the CQI to change the DRX parameters for performance improvement. In [6–9], they introduced some ways to improvement VoIP performance in the DRX operation. And the *LaVoLTE* is proposed in [10],

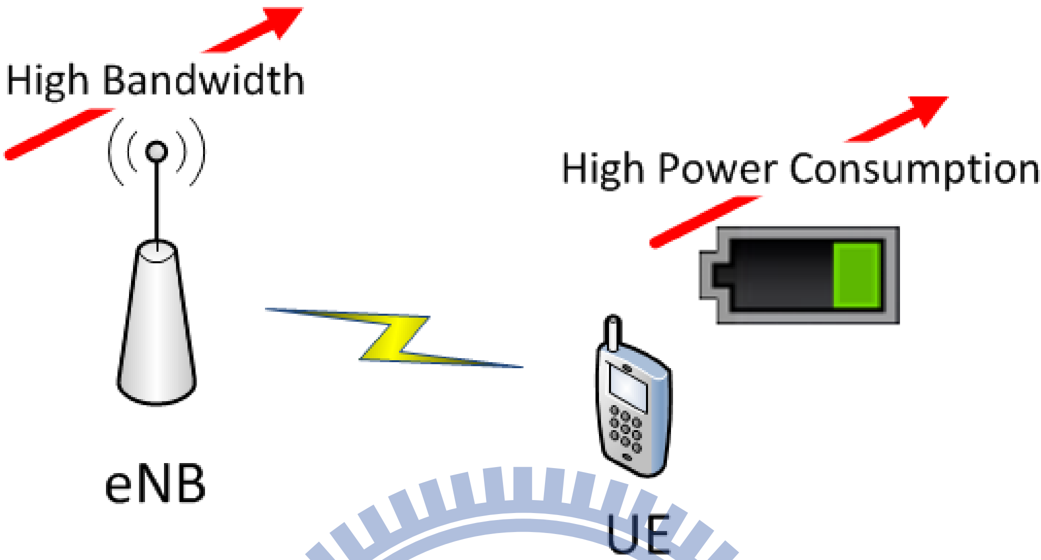

Figure 1.1: LTE network architecture between eNB and UE.

based on time series prediction and enhanced eNodeB architecture to determine DRX opportunities during video streaming over Real Time Protocol (RTP) in a TDD-LTE network without compromising the QoS. In [11], to power down energy consuming circuits in RF and BB, they proposed a Fast Control Channel Decoding (FCCD) that the UE is not Nscheduled to receive downlink data in the current TTI. In [12], they studied the characteristics of different types of services. In [13], they introduced the DRX operation under different RRC states. According to [14], RRC states has dramatically impacts on UE's power consumption and packet transmission delay. For the performance of DRX, several analytical studies have been conducted. Yang et al. [15, 16] proposed a Markov chain model of the DRX in UMTS system where packet arrivals follow a Poisson process. Mihov et al. used semi-Markov process to model the DRX in LTE system [17]. In [18], they use the Markov model to build an algorithm that selects DRX parameters under the QoS constraints. Jin and Qiao proposed an accurate analytical model to avoid sophisticated steps [19].

DRX operation can manage UEs to achieve suitable battery consumption in both RRC_CONNECTED and RRC_IDLE states in Evolved Universal Terrestrial Radio Access Network (E-UTRAN). Radio Resource Control (RRC) is a protocol that communicates between the UE and the eNB, which is part of LTE air interface control plane. It provides lots of functionalities, such as paging, connection maintenance, security, QoS management, etc.. Under the same condition, UE may trigger different operations depending on its RRC state. For example, if the signal quality from one neighboring eNBs is better than the serving eNB, UE will trigger handover (HO) operation if the UE is in RRC_CONNECTED state or perform a cell reselection if the UE is in RRC_IDLE state.

1.1 Problem and Solution

In this thesis, we focus on the DRX operation, and we also consider the influence from RRC states transition, which is an important operation in LTE system. We present a simple analytical model to analyze the efciency of DRX operation and the inuence of the RRC states transition. Our proposed model is similar to [19], but is more general in the 3GPP LTE-A power saving operation since the RRC operation is taken into consideration.

1.1.1 Simple Analytical Model

To achieve this goal, we divide the DRX and RRC operations into several parts, and we can derive them separately before we combine the results. As the same as [15], we assume packet arrival intervals and transmission time follow exponential and general distribution, respectively. The eNB allocates a single-transmission RLC buffer for each UE, and the transmission buffer size is infinite. To derive the power consumption, we divide the time period into sleeping state with RRC states transition and active state. Then, we can easily obtain the expected time duration of any state. Then, we can have two results, i.e., power saving factor with RRC states transition and real power consumption. We also derive the transmission delay by considering two states: immediate-transmitting state and buffering-and-forwarding state. The immediate-transmitting state can be modeled by a M/G/1 queuing system, and the buffering-and-forwarding state is derived, completely. The analytical results show that there is much higher probability that the UE enters RRC_IDLE at lower packet arrival rate, and the power consumption is relatively low at same time.

1.2 Thesis Outline

The rest of the article is organized as follows. We introduce the DRX operation and the RRC states transition in Chapter 2. We also introduce our system model in Chapter 3. Then, a analytical model has been proposed to analyze the power consumption and the transmission delay in Chapter 4. To verify our analytical, we simulate the DRX and RRC operation in Chapter 5. The numerically results of analytical model are shown in Chapter 6. Finally, Chapter 7 concludes this thesis.

Chapter 2

Background

In this chapter, we firstly survey related works to Discontinuous Reception(DRX) operation and Radio Resource Control(RRC) in LTE network. Then, we introduce their operation in next two sections. And the power model of UE is introduced in last section.

2.1 Literature Survey

DRX and RRC mechanisms will operate in different forms, which depends on the characteristics of traffic. Consequently, it has impacts on UE's power consumption. For an effective investigation on the sufficiency of the LTE DRX mechanisms, traffic analysis is of high importance. Thus, in [12], they studied the characteristics of different types of services. In [13], they introduced the DRX operation under different RRC states. According to [14], RRC states has dramatically impacts on UE's power consumption and packet transmission delay. For the performance of DRX, several analytical studies have been conducted. Yang et al. [15, 16] proposed a Markov chain model of the DRX in UMTS system where packet arrivals follow a Poisson pro-

Table 2.1: Comparison of Various Analytical Model in DRX operation.

DRX Operation	Queueing [15–17]	Numerical [19]	Our Proposed
DRX Parameters	○	○	○
Power-saving Factor	○	○	○
Transmission Delay	○	○	○
Real Power Consumption	×	×	○
Cross Layer Analysis	×	×	○

cess. Mihov et al. used semi-Markov process to model the DRX in LTE system [17]. In [18], they use the Markov model to build an algorithm that selects DRX parameters under the QoS constraints. Jin and Qiao proposed an accurate analytical model to avoid sophisticated steps [19].

2.1.1 Discontinuous Reception(DRX) Mechanism Operation

In Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Discontinuous reception (DRX) is managed by the Radio Resource Control(RRC) [1]. DRX is a process of turning off a radio receiver when it does not expect to receive incoming messages. DRX can be enabled for UEs in RRC_IDLE or RRC_CONNECTED mode. Here focus on the DRX in RRC_CONNECTED since in RRC_IDLE state the UE does not have any sessions.

In RRC_CONNECTED state, RRC controls DRX by configuring the following parameters [2]: DRX inactivity timer (C_I), DRX retransmission timer, DRX start offset, On duration timer, long DRX cycle (C_L), number of short DRX cycle (N) and short DRX cycle (C_S).

Figure 2.1 shows the LTE DRX operation in RRC_CONNECTED.

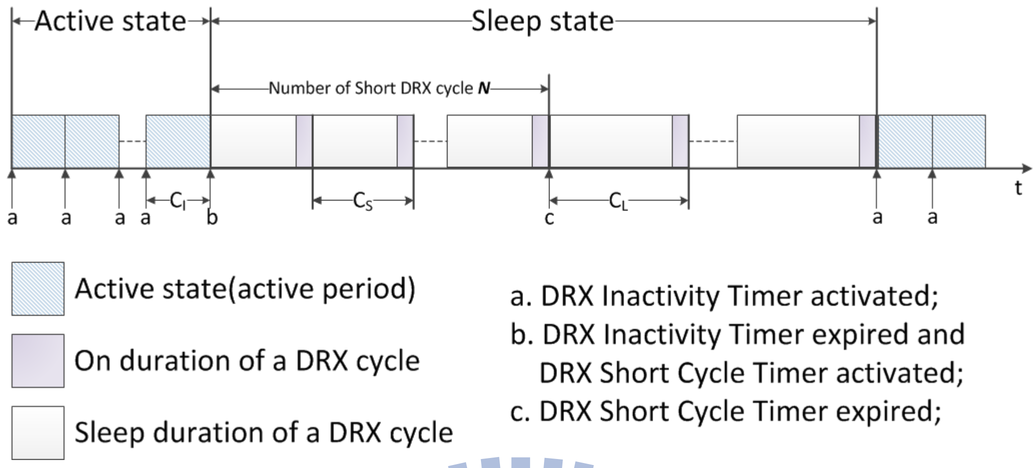

Figure 2.1: Illustration of LTE DRX operation in RRC_CONNECTED.

Inactivity Timer (C_I): the time in number of consecutive subframes (without the scheduled traffic) to wait before enabling DRX. This timer is reset to zero and enabled immediately after successful reception of physical downlink control channel (PDCCH). Before the expiration of DRX inactivity timer, if the PDCCH indicates a downlink transmission, another DRX inactivity timer is activated. Or else, the expiration of DRX inactivity timer ends, then short DRX cycle is activated and the UE enters sleep state.

Short DRX Cycle (C_S): the first DRX cycle to be followed after enabling DRX. UE can turn off the RF module in this cycle.

Number of Short DRX Cycle (N): this parameter indicates the number of initial DRX cycles to follow the short DRX cycle before transitioning to the long DRX cycle.

Long DRX Cycle (C_L): the DRX cycle to be followed after N short DRX cycles.

ON Duration Timer: the number of frames over which the UE shall read the DL control channel every DRX cycle before entering the power saving mode. This timer is less than C_S and C_L. In this thesis, to simplify our analytical model, we don't consider this parameter.

DRX Offset: to obtain the starting subframe number for DRX cycle.

Retransmission Timer: the maximum number of subframes the UE should wait before turning off the circuits if a retransmission of data is expected from the eNB.

2.1.2 Radio Resource Control(RRC)

Radio Resource Control(RRC) protocol layer exists in UE and evolved node-B(eNB), it is part of LTE air interface control plane. In DRX mode, the UE powers down most of its circuitry when there are no packets to be transmitted/received. During this time UE listens to the downlink (DL) occasionally and may not keep in sync with uplink (UL) transmission depending on whether the UE is registered with an eNB (RRC_CONNECTED) or not (RRC_IDLE). In the RRC_IDLE state, the UE is registered with the evolved packet system (EPS) mobility management (EMM) but does not have an active session. In this state the UE can be paged for DL traffic. UE can also initiate UL traffic by requesting RRC connection with the serving eNB. In the RRC_CONNECTED state DRX mode is enabled during the idle periods during the packet arrival process. Figure 2.2 shows different RRC states in LTE networks.

2.1.3 UE's Power Model in LTE

To calculate the real power consumption, we introduce a power model in Table 2.2 [14]. We notice that the power consumption in RRC_IDLE is much lower than that in RRC_CONNECTED. In addition, the network re-entry time is denoted as $T_{REENTRY}$ to indicate the delay of the UE entering network from RRC_IDLE to RRC_CONNECTED.

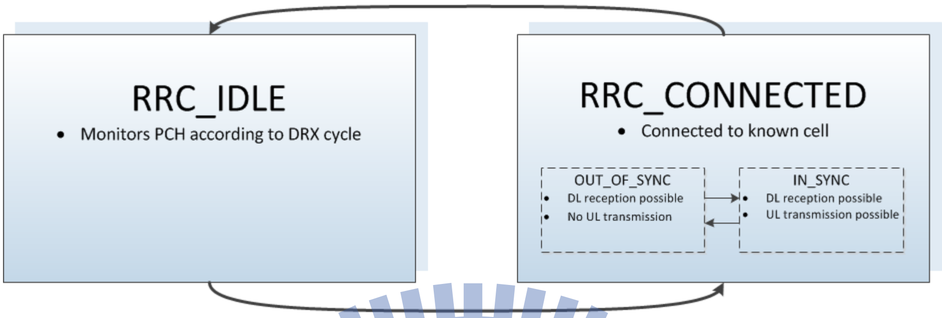

Figure 2.2: Different RRC states in LTE networks.

Table 2.2: LTE power model.

	Power (mW)	Duration (ms)
Short DRX On in RRC_CONNECTED	1680.2±15.7	1.0±0.1
Long DRX On in RRC_CONNECTED	1680.1±14.3	1.0±0.1
Off Duration in RRC_CONNECTED	1060.0±3.3	N/A
Low power state in RRC_IDLE	11.4±0.4	N/A
DRX On in RRC_IDLE	594.3±8.7	$T_{REENTRY}$:260.1

Chapter 3

System Models

Figure 3.1 shows the DRX operation with RRC state transition in 3GPP LTE, we use active and sleeping (with RRC states transition) states to derive the power consumption. As shown in this figure, we define four operational states for proper analysis which is introduced upon. Additionally, we define *activity period* by the time duration from time instant that the Radio Network Controller(RNC) begins to transmit packets under the condition that the RNC is not transmitting packets in either active or sleeping state to the time instant that RNCs buffer becomes empty due to the completion of packet transmissions. The *first activity period* is defined by the activity period, following DRX cycles. Meanwhile, the 3GPP LTE Advanced standard specifies that the *inactivity period* is the time duration when an inactivity timer is activated.

3.1 System Architecture

Two results are obtained as follow: One is the power-saving factor with RRC states transition which is defined as the sleeping time over overall operation

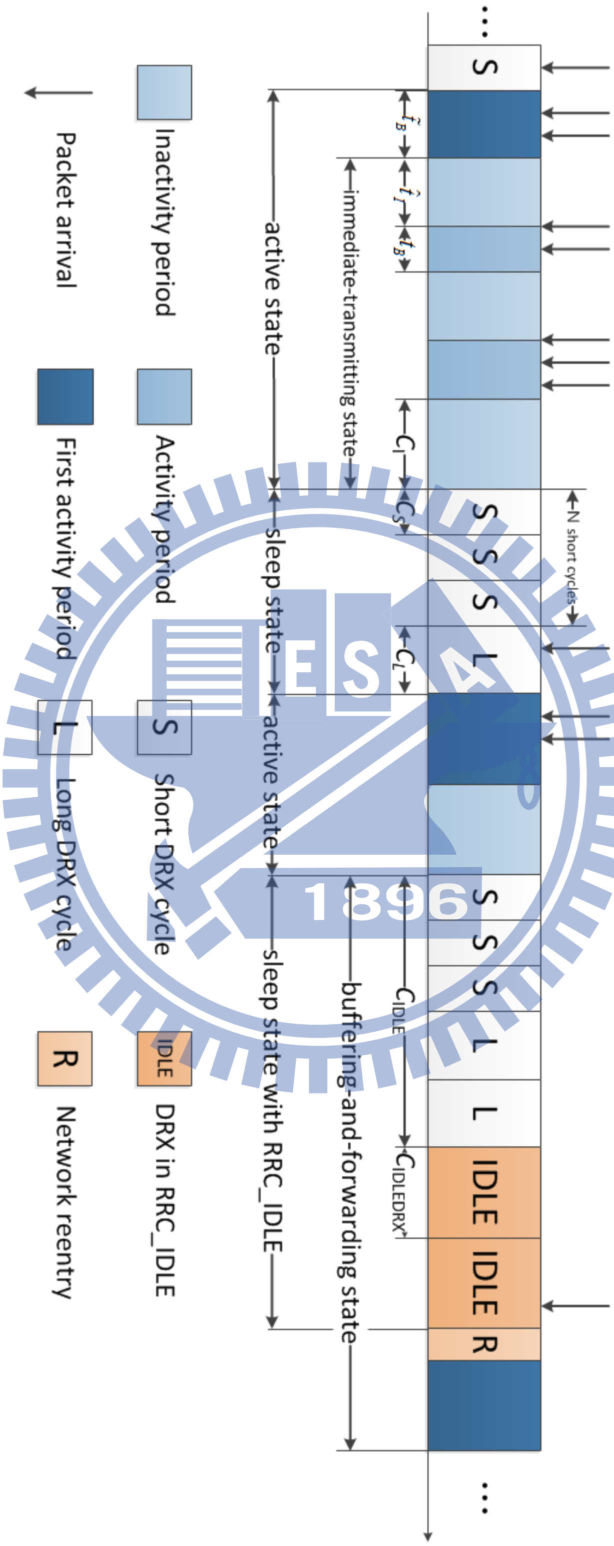

Figure 3.1: 3GPP LTE-A wireless networks DRX operation with RRC states transition.

time. Furthermore, immediate-transmitting and buffering-and-forwarding states are introduced to derive the transmission delay with RRC states transition.

3.2 Active State and Sleeping State

We first consider power-saving operation in the steady state. The steady-state power-saving operation is divided into two stationary parts, i.e., the operation in active and sleeping (with RRC states transition) states, respectively. As we will explain later, the proposed approach gives us an easy way to derive the expected time duration that the UE spends in each stationary part. Once we obtain the time durations in active and sleeping (with RRC states transition) states, it is simple to have the power-saving factor. Then, we continue to use these time durations to derive the average packet transmission delay.

In active state, the UE receives packets during activity periods or waits for new packet arrivals until inactivity timer timeout. For example, when RNC's buffer becomes empty after completing buffered packet transmissions, the UE activates an inactivity timer prior to the beginning of sleeping state. Unless there arrives a new packet within the timer expiration, the UE enters sleeping state. Otherwise, a new activity period begins for the UE to receive the newly arrived packets. The activity period can be extended as long as more packets arrive at the RNC during ongoing packet transmission times. Therefore, in active state, the activity period interleaved with the inactivity period repeats until the inactivity timer expires.

And sleeping (with RRC states transition) state begins with the inactivity timer's expiration. In sleeping (with RRC states transition) states, the UE monitors new packet arrivals by periodically receiving indication messages every DRX cycle. If the UE notices new packet arrivals, the operational state transits to active state for the UE to receive those packet during the activity period. Optionally, a short cycle can be employed for more frequent packet arrivals than a long DRX cycle. Long DRX cycle begins after maximum number (N) of short DRX cycles has no receive any new packet. When there is still no transmission of packets for an extended period of time, (C_IDLE), the eNB initiates RRC connection release. Accordingly, the UE enters RRC_IDLE state at same time.

3.3 Immediate-Transmitting State and Buffering-and-forwarding State

After considering the power-saving operation in the steady state, we also consider the transmission delay which is divided into two stationary parts, i.e., immediate-transmitting state and buffering-and-forwarding state.

When the UE is in immediate-transmitting state, the packets suffers delay due to residual time. Residual time is defined by the time required to complete packet transmissions of all packets remaining in the transmission buffer, as well as ongoing packet transmission when a packet arrives at an arbitrary time. We find out that the delay due to the residual time is modeled by a M/G/1 queuing system. The *Pollaczek-Khinchine (PK)* formula presents packet transmission delay for a typical M/G/1 queuing system [20].

In buffering-and-forwarding state, the RNC does not transmit but buffers packets during sleeping state and thereafter transmits the buffered packets during active state. By using the feature, we derive the delay for the case when the UE is in buffering-and-forwarding state. Again, we apply the

M/G/1 queuing model to the derivation of packet transmission delay when the RNC forwards buffered packets in buffering-and-forwarding state.

3.4 Performance Metrics

To analyze the DRX operation with RRC states transition aptly, we introduce three types of definition, power-saving factor with radio resource control states, transition, real power consumption with radio resource control states transition and transmission delay with radio resource control states transition.

3.4.1 Power-saving Factor with Radio Resource Control States Transition

In the previous study [15–17,19,21], they use power-saving factor to analyze the power consumption. The definition of the power-saving factor is the percentage of time UE spends in sleep, which is an indicator of the power saving performance the DRX mechanism achieves. It is formulated by

$$\frac{E[T_D]}{E[T_A]+E[T_D]} \tag{3.1}$$

where T_A is the time of UE stays in the active state, and T_D is the UE stays in DRX operation in RRC_CONNECTED.

However, there has some different in our case. Due to consider the RRC effect, we modify this factor and dene power saving factor with RRC states transition as the sleeping time ratio, compared with the overall operation time. Then, it can be formulated by

$$\frac{E[T_D]+E[T_{IDLE}]}{E[T_A]+E[T_D]+E[T_{IDLE}]} \tag{3.2}$$

where T_{IDLE} is the UE stays in RRC_IDLE.

3.4.2 Real Power Consumption with Radio Resource Control States Transition

In addition to power saving factor, we introduce a simple way to calculate the real power consumption. p_{active}, p_{drx} and p_{idle} are the power consumption in three different states: active state, DRX in RRC_CONNECTED, and DRX in RRC_IDLE, respectively, which can be obtained from the truly power consumption, as shown in TABLE 2.2. Then, the real power consumption with RRC states transition can be formulated by

$$\begin{aligned} &\frac{1}{E[T_A]+E[T_D]+E[T_{IDLE}]} \\ &\times(p_{active}E[T_A]+p_{drx}E[T_D]+p_{idle}E[T_{IDLE}]). \end{aligned} \tag{3.3}$$

3.4.3 Transmission Delay with Radio Resource Control States Transition

The original definition of transmission delay is the waiting time of a packet call delivery experiences before UE wakes up. In our case, we also consider the RRC states transition in the transmission delay. To analyze delay more aptly, the network re-entry time is denoted as $T_{REENTRY}$ to indicate the delay of the UE entering network from RRC_IDLE to RRC_CONNECTED.

Chapter 4

Proposed Analytical Model

4.1 Assumptions

We assume that packet arrival intervals are modeled as an exponentially distributed random variable with mean $1/\lambda$, and transmission times are general distribution with $E[\mathrm{X}] = \tau$ for a single packet. The traffic intensity $\rho = \lambda\tau$. In addition, we know that the number of packet arrivals can be modeled with the Poisson process since packet arrivals follow an exponential distribution. Then, we simply derive the average number packet arrivals during the transmission time for a single packet by $\sum_{n=0}^{\infty} \frac{(\lambda\tau)^n}{n!} e^{-\lambda\tau} = \lambda\tau = \rho$.

4.2 Definitions

Random variable $\hat{t}_I$ represents the time of inactivity timer which starts when there is no data to transmit but stops due to a new packet arrival. Random variable t_B represents the subsequent activity period after the inactivity timer stops. Random variable $\tilde{t}_B$ represents the transmission time for the buffered packets during the last sleep state before the first activity period. Random variable T_A, T_D and T_{IDLE} indicate the times that the UE stays in active state, DRX operation state, and RRC_IDLE state. According to 3GPP LTE specification, C_I, C_S, C_L, $C_{IDLEDRX}$ represent inactivity timer, short DRX cycle, long DRX cycle, and DRX cycle in RRC_IDLE. Considering the impact of situation where the UE enters RRC_IDLE state, we adopt C_{IDLE} as the control timer from RRC_CONNECTED to RRC_IDLE.

4.3 Power consumption

To analyze the power aptly, we introduce two types of definitions, power-saving factor with RRC states transition and real power consumption. For this purpose, we have to derive $E[T_A]$, $E[T_D]$, and $E[T_{IDLE}]$. First, the power-saving factor with RRC states transition is formulated by

$$\frac{E[T_D] + E[T_{IDLE}]}{E[T_A] + E[T_D] + E[T_{IDLE}]}. \tag{4.1}$$

The duration of active state will be extended when there are some packets arrived before inactivity timer (C_I) expires, and the inactivity timer will restart again. Accordingly, we can derive the new packet arrival probability by $\int_0^{C_I} \lambda e^{-\lambda t} dt = 1 - e^{-\lambda C_I}$. The duration of sleep state can be derived in the similar way. When there are some packets arrived within the short DRX cycle (C_S) or long DRX cycle (C_L), the UE will enter active state and the timer will stop counting. Otherwise, the time period of sleeping state will be extended. Thus, we can derive the probability of the UE staying in short DRX cycle by $\int_{C_S}^{\infty} \lambda e^{-\lambda t} dt = e^{-\lambda C_S}$ on the condition of no packet arrived within the short DRX cycle. The probability of the UE staying in long DRX cycle can be derived by $\int_{C_L}^{\infty} \lambda e^{-\lambda t} dt = e^{-\lambda C_L}$, similarly. The probabilities of the UE leaving active state, short DRX cycle, and long DRX cycle can also be derived by $1-$

$\int_0^{C_I} \lambda e^{-\lambda t} dt = e^{-\lambda C_I}$, $1 - e^{-\lambda C_S}$, and $1 - e^{-\lambda C_L}$, respectively. Additionally, we derive the probability of the UE leaving RRC_IDLE by $1 - \int_{C_{IDLE}}^{\infty} \lambda e^{-\lambda t} dt = 1 - e^{-\lambda C_{IDLE}}$. The sleeping state with RRC_IDLE consists of short DRX cycle, long DRX cycle, and the duration of RRC_IDLE. After figuring out these independent probabilities, we can represent the probabilities of active state and sleeping state with RRC_IDLE, respectively.

Probability of active state α_i

we adopt i to indicate how many times of inactivity timer restarts, which means there is still new packet arrived before inactivity timer expires. The probability of active state can be derived by

$$\alpha_i = (1 - e^{-\lambda C_I})^i e^{-\lambda C_I} \tag{4.2}$$

where $i \geq 0$.

Probability of sleeping state with RRC_IDLE δ_j

we adopt j to indicate the number of short and long DRX cycles. To indicate C_{IDLE} by unit of short DRX cycle, $L = (C_{IDLE} - C_S)/C_L$ is used to replace the time of the UE staying in long DRX cycle, then $N + L$ is the total cycle of short and long DRX cycles. The probabilities of the sleep state can be derived by (4.3).

$$\delta_j = \begin{cases} (e^{-\lambda C_S})^{j-1}(1-e^{-\lambda C_S}), & 1 < j \leq N \\ (e^{-\lambda C_S})^N (e^{-\lambda C_L})^{j-(N+1)}(1-e^{-\lambda C_L}), & N < j \leq N+L \\ (e^{-\lambda C_S})^N (e^{-\lambda C_L})^L (1-e^{-\lambda C_{IDLE}}), & N+L < j \end{cases} \tag{4.3}$$

Now, to derive the time durations for active state and sleeping state with RRC_IDLE, we assume that $E[t_S]$ and $E[t_L]$ are the average time where short and long DRX cycles last, and $E[t_{IDLE}]$ is the average time of the UE staying in RRC_IDLE. Therefore, we have

$$\begin{aligned} E[T_A] &= E[\tilde{t}_B] + \sum_0^\infty i\alpha_i(E[\hat{t}_I] + E[t_B]) + C_I \\ &= E[\tilde{t}_B] + (E[\hat{t}_I] + E[t_B])(e^{\lambda C_I} - 1) + C_I \end{aligned} \tag{4.4}$$

$$\begin{aligned} & E[T_D] + E[T_{IDLE}] = E[t_S] + E[t_L] + E[t_{IDLE}] \\ & = \sum_{j=1}^{N} j(e^{-\lambda C_S})^{j-1}(1-e^{-\lambda C_S})C_S \\ & + \sum_{j=N+1}^{N+L} (j-N)(e^{-\lambda C_S})^N (e^{-\lambda C_L})^{j-(N+1)} \\ & \times(1-e^{-\lambda C_L})C_L \\ & + \sum_{j=N+L+1}^{\infty} (j-(N+L))(e^{-\lambda C_S})^N \\ & \times(e^{-\lambda C_L})^L(1-e^{-\lambda C_{IDLE}})C_{IDLEDRX} \end{aligned} \tag{4.5}$$

Now, we proceed to derive $E[\hat{t}_I]$, $E[\tilde{t}_B]$ and $E[t_B]$. Since $\hat{t}_I$ follows a truncated exponential distribution, the probability density function (pdf) $f(t)$ is given by

$$f(t) = \begin{cases} \dfrac{1}{1-e^{-\lambda C_I}}\lambda e^{-\lambda t}, 0 \le t \le C_I \\ 0, \qquad C_I < t. \end{cases} \tag{4.6}$$

Then, we can derive $E[\hat{t}_I]$ by

$$\begin{aligned} E[\hat{t}_I] &= \int_0^{\infty} t f(t)dt \\ &= \tfrac{1}{\lambda} - \tfrac{1}{e^{\lambda C_I}-1} C_I. \end{aligned} \tag{4.7}$$

Random variable t_B starts when there is a new packet arrived and it will continue until all the buffered packets have been transmitted. Besides, we can model the number of packet arrivals as the Poisson process since packet arrivals follow an exponential distribution. Then, we can derive the average packet arrivals during the transmission time for a single packet by $\sum\limits_{n=0}^{\infty} \frac{(\lambda\tau)^n}{n!} e^{-\lambda\tau} = \lambda\tau = \rho$. It means that a single packet transmission produces additional ρ packets. In addition, it need $\tau\rho$ transmission time. Eventually, we got $E[t_B]$ by

$$E[t_B] = \sum_{n=0}^{\infty} \tau\rho^n = \frac{\tau}{1-\rho}. \tag{4.8}$$

Accordingly, random variable $\tilde{t}_B$ can be derived as the same way. $\tilde{t}_B$ indicates the first time period to transmit the packets buffered during the DRX cycle or RRC_IDLE state. We introduce $\lambda(E[T_D]+E[T_{IDLE}])$ to indicate the number of packets buffered at the beginning during the sleeping state with RRC_IDLE, and we can derive $E[\tilde{t}_B]$ by

$$E[\tilde{t}_B] = \lambda(E[T_D] + E[T_{IDLE}])\frac{\tau}{1-\rho} = (E[T_D] + E[T_{IDLE}])\frac{\rho}{1-\rho} \tag{4.9}$$

4.3.1 Power-saving Factor

Now, we can summarize the power-saving factor with RRC states transition as

$$\frac{E[T_D]+E[T_{IDLE}]}{E[T_D]+E[T_{IDLE}]+E[T_A]}$$

$$=\frac{(E[T_D]+E[T_{IDLE}])(1-\rho)}{(E[T_D]+E[T_{IDLE}])+\frac{1}{\lambda}(e^{\lambda C_I}-1)}$$

$$=\frac{\left(\begin{array}{l}\sum_{j=1}^{N} j(e^{-\lambda C_S})^{j-1}(1-e^{-\lambda C_S})C_S \\ +\sum_{j=N+1}^{N+L}(j-N)(e^{-\lambda C_S})^{N}(e^{-\lambda C_L})^{j-(N+1)}(1-e^{-\lambda C_L})C_L \\ +\sum_{j=N+L+1}^{\infty}(j-(N+L))(e^{-\lambda C_S})^{N}(e^{-\lambda C_L})^{L}(1-e^{-\lambda C_{IDLE}})C_{IDLEDRX}\end{array}\right)(1-\rho)}{\left(\begin{array}{l}\sum_{j=1}^{N} j(e^{-\lambda C_S})^{j-1}(1-e^{-\lambda C_S})C_S \\ +\sum_{j=N+1}^{N+L}(j-N)(e^{-\lambda C_S})^{N}(e^{-\lambda C_L})^{j-(N+1)}(1-e^{-\lambda C_L})C_L \\ +\sum_{j=N+L+1}^{\infty}(j-(N+L))(e^{-\lambda C_S})^{N}(e^{-\lambda C_L})^{L}(1-e^{-\lambda C_{IDLE}})C_{IDLEDRX}\end{array}\right)+\frac{1}{\lambda}(e^{\lambda C_I}-1)}. \tag{4.10}$$

4.3.2 Real Power Consumption

In addition to power-saving factor, we introduce a simple way to calculate the real power consumption. p_{active}, p_{drx} and p_{idle} are the power consumption in three different states: active state, DRX in RRC_CONNECTED, and DRX in RRC_IDLE, respectively, which can be obtained from the truly power consumption, as shown in TABLE 2.2. Then, the real power consumption with RRC states transition can be formulated by

$$\frac{1}{E[T_A]+E[T_D]+E[T_{IDLE}]} \times(p_{active}E[T_A]+p_{drx}E[T_D]+p_{idle}E[T_{IDLE}]). \tag{4.11}$$

4.4 Transmission Delay

In order to analyze the transmission delay with RRC states transition, we adopt the methodology proposed in [19] to divide whole operation into immediate-transmitting state and buffering-and-forwarding state. In immediate-transmitting state, we introduce a typical M/G/1 queuing system with Pollaczek-Khinchine formula to simply derive the average packet transmission delay ($E[D_I]$) [20]. The result is

$$E[D_I] = \frac{\lambda E[X^2]}{2(1-\rho)}. \tag{4.12}$$

In buffering-and-forwarding state, we consider two types of delay: the residual time, which can be solved as (4.12), similarly, and the packet buffering operation during the DRX cycle or RRC_IDLE state. These two types of delay resulted from the packets arrived during the DRX cycle or RRC_IDLE. To calculate the average number of waiting packet, we introduce two notations, $E[K]$ and $E[W]$. $E[K]$ is the average number of waiting packet in transmission buffer, and $E[W]$ is the average waiting time since packet arrived during the DRX cycle or RRC_IDLE. Then we can derive the packet buffering operation by

$$E[D_B] = E[W] + E[X]E[K] \tag{4.13}$$

where $E[K] = \lambda E[D_B]$, which is obtained from Little's Law. And we can derive $E[D_B]$ by

$$\begin{aligned} E[D_B] &= E[W] + E[X]E[K] \\ &= E[W] + \lambda\tau E[D_B] \\ &= E[W] + \rho E[D_B] \\ &= \tfrac{E[W]}{1-\rho}. \end{aligned} \tag{4.14}$$

When there are one or more packet arrivals during the DRX cycle or RRC_IDLE, it will start the first active period after the cycle ends. Such cycle becomes the last DRX cycle in sleeping state (with RRC_IDLE). So we need to derive the average time that the arrival packets in the last DRX cycle until the first active period starts. The packet arrival time in the last cycle is uniform distribution, which follows the property of the Poisson process [22]. According to the packets arrive at the DRX cycle or RRC_IDLE, we can obtain $E[W] = C_S/2$ (or $C_L/2$) or $C_{IDLEDRX}/2$. In addition, the network re-entry time is denoted as $T_{REENTRY}$ to indicate the delay of the UE entering network from RRC_IDLE to RRC_CONNECTED. The probabilities of the packets suffering from delay can be derived by

$$P_S = \frac{E[t_S]}{E[T_A] + E[T_D] + E[T_{IDLE}]} \tag{4.15}$$

$$P_L = \frac{E[t_L]}{E[T_A] + E[T_D] + E[T_{IDLE}]} \tag{4.16}$$

$$P_{IDLE} = \frac{E[t_{IDLE}]}{E[T_A] + E[T_D] + E[T_{IDLE}]} \tag{4.17}$$

From (4.12)-(4.17), we can obtain the average transmission delay with RRC states transition by

$$\begin{aligned}
E[D] &= (1 - P_S - P_L - P_{IDLE})E[D_I] \\
&\quad + P_S(E[D_I] + \frac{C_S}{2(1-\rho)}) + P_L(E[D_I] + \frac{C_L}{2(1-\rho)}) \\
&\quad + P_{IDLE}(E[D_I] + \frac{C_{IDLEDRX}}{2(1-\rho)} + T_{REENTRY}) \\
&= E[D_I] + \frac{1}{2}\frac{E[t_S]C_S + E[t_L]C_L + E[t_{IDLE}]C_{IDLEDRX}}{(E[T_D] + E[T_{IDLE}] + 1/\lambda(e^{\lambda C_I} - 1))} \\
&\quad + P_{IDLE}T_{RNENTRY}.
\end{aligned} \tag{4.18}$$

Chapter 5

Simulation and Analytical Results

To confirm correctness of the analytical model, we verify the analytical model by comparing analytical results with simulation results. We develop a simulator to simulate DRX operation with RRC states transition which is written by Java. For Simulation parameters, we have expected transmission time(τ), average packet arrival rate(λ),InactivityTimer(C_I), short DRX cycle(C_S), long DRX cycle(C_L), number of short DRX cycle(N), expended period of time that UE enters RRC_IDLE when there is no transmission of packets(C_{IDLE}), DRX cycle in RRC_IDLE($C_{IDLEDRX}$) and network re-entry time $T_{REENTRY}$.

5.1 Power Consumption and Transmission Delay Verify Between Simulation and Analytical Model

We simulate different C_{IDLE} to compare with the analytical model. As shown in Figure 5.1 and Figure 5.2, acceptable-matched results show that numerical equations are correctly derived. But there still has some mismatch which is caused by our simulator neglects some complicate factor. So the simulator still have to be improved actuality.

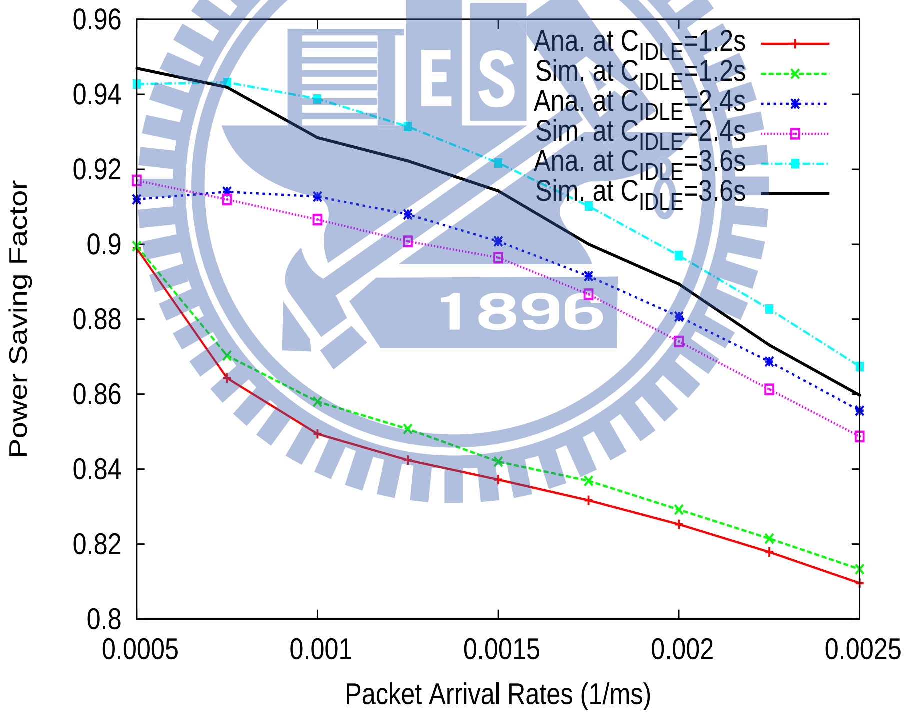

Figure 5.1: Comparison between the analytical model and the simulation results in different Power-saving factor with RRC states transition.

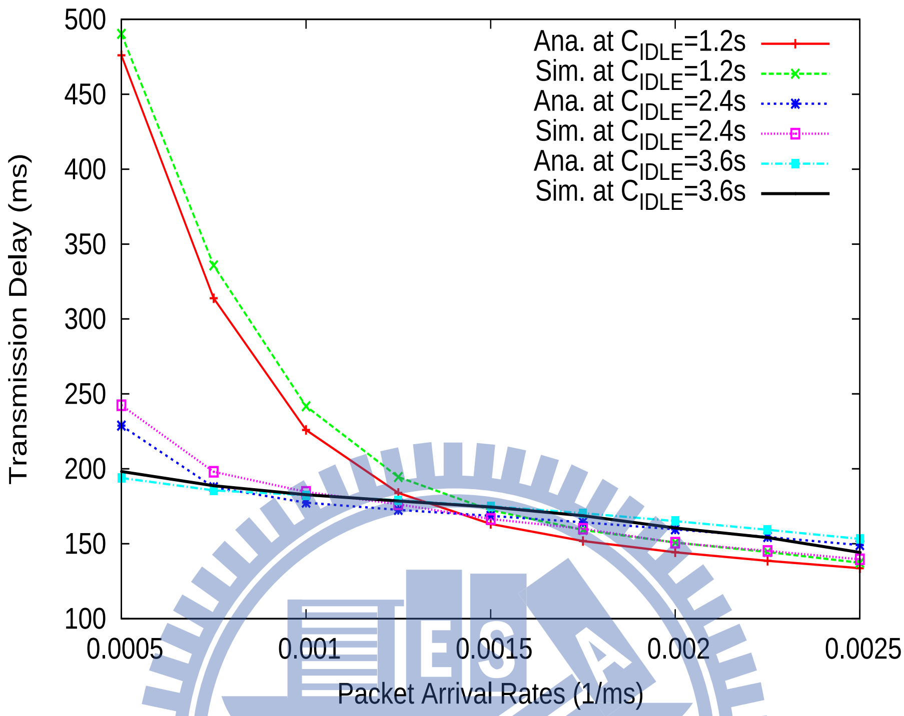

Figure 5.2: Comparison between the analytical model and the simulation results in different transmission delay with RRC states transition.

5.2 Analytical Parameters

To evaluate the impact of condition where UE enters RRC_IDLE state; in this chapter, we use MATLAB tool to obtain the numerical results from our derived model.The corresponding parameters are set as follows. We have packet transmission time $\tau = 0.1$ms, DRX InactivityTimer $C_I = 100$ms, short DRX cycle $C_S = 200$ms, long DRX cycle $C_L = 400$ms, and network re-entry time $T_{REENTRY} = 260$ms, which is setting by [14].

5.3 Power-saving Factor with RRC States Transition in Different C_{IDLE}

The power-saving factor with RRC states transition is illustrate in Figure 5.3. When $C_{IDLE} = 1.2$s, the UE will enter RRC_IDLE with higher probability at lower packet arrival rate. Nevertheless, when $C_{IDLE} = 4.8$s, the UE will enter RRC_IDLE with lower probability even at lower packet arrival rate. So we can manifest the UE is more power efficiency when $C_{IDLE} = 1.2$s. The effect of $E[T_{IDLE}]$ can be neglected when packet arrival rate increase gradually. According to the reason that the power consumption is dramatic different between RRC_IDLE and RRC_CONNECTED, which is illustrated in TABLE 2.2, we propose another way to indicate the power consumption appropriately.

To explain the reason why the power-saving factor in $C_{IDLE} = 1.2$s, Figure 5.4 shows the trend of $E[T_L]$ and $E[T_{IDLE}]$ in different C_{IDLE}, we can realize $E[T_L]$ is more outstanding than $E[T_{IDLE}]$ when the DRX effect increases.

5.4 Real Power Consumption with RRC States Transition in Different C_{IDLE}

To indicate the effect of power consumption, we calculate the real power consumption based on TABLE 2.2. In Figure 5.5, we observe that the time for the UE to enter RRC_IDLE become longer at lower packet arrival rate; it implies real power consumption is relatively low. In addition, power consumption is increased when $C_{IDLE} = 4.8$s, which is different from the trend of power-saving factor, as shown in Figure 5.3. It is obviously to see that the real power consumption model can express more reality than power-saving

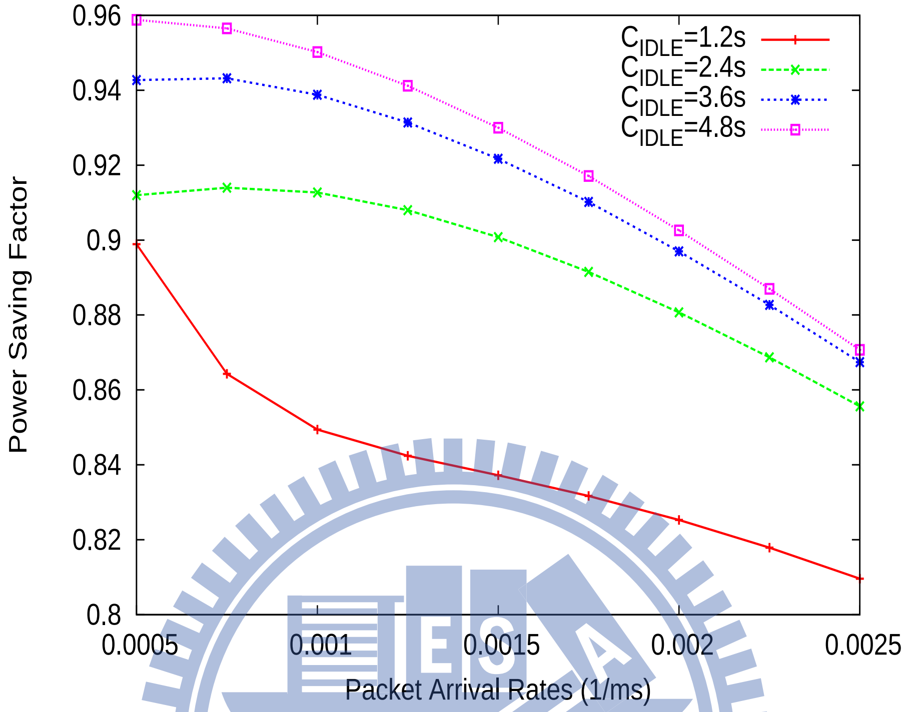

Figure 5.3: Power-saving factor with RRC states transition ($C_{IDLEDRX}$ = 1000 ms).

factor in this situation. And we can know if the user uses some applications like web or other some non-GBR(Guranteed Bit Rate) services, we suggest the C_{IDLE} can set in 1 or 2 seconds which can be more power-saving when the UE can stays in RRC_IDLE for longer time.

5.5 Transmission Delay with RRC States Transition in Different C_{IDLE}

Figure 5.6 depicts the average transmission delay under different packet arrival rate λ. The average transmission delay decreases as the packet arrival

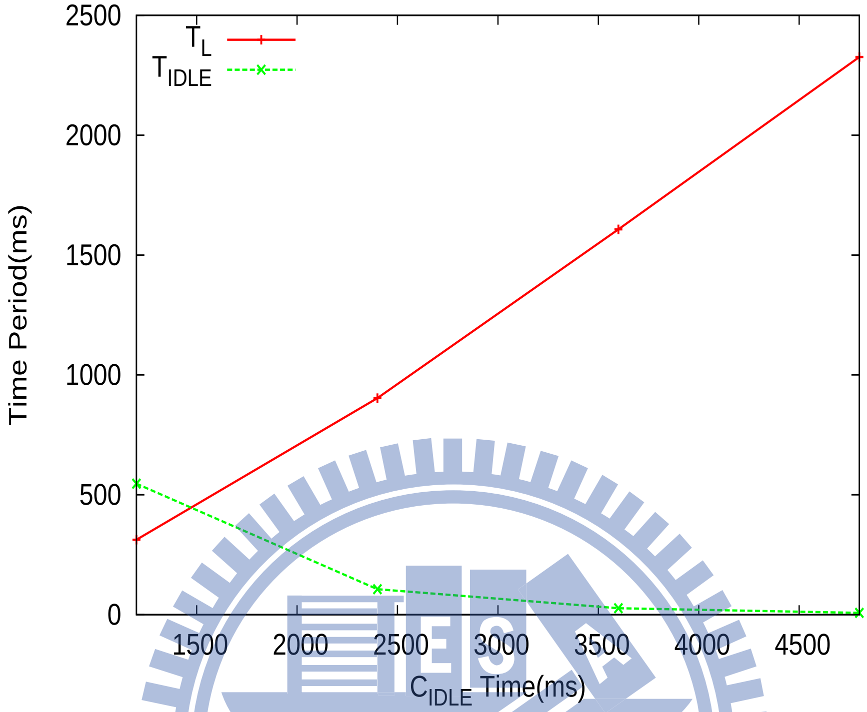

Figure 5.4: The trend of $E[T_L]$ and $E[T_{IDLE}]$ in different C_{IDLE}.

rate increases since the UE stays in RRC_IDLE state for shorter time. Furthermore, Figure 5.5 and Figure 5.6 show that there is a trade-off between the transmission delay and the real power consumption. And due to there is much higher delay when the UE enters RRC_IDLE, the applications like VoIP or other some GBR services do not aptly to enters RRC_IDLE.

5.6 Probability of the UE enters RRC_IDLE

We use Figure 5.7 as an evidence to show that the probability of staying in RRC_IDLE state for UE decreases as the the packet arrival rate increases. It implies that there is a high probability of entering the RRC_IDLE state when UE with lower packet arrival rate.

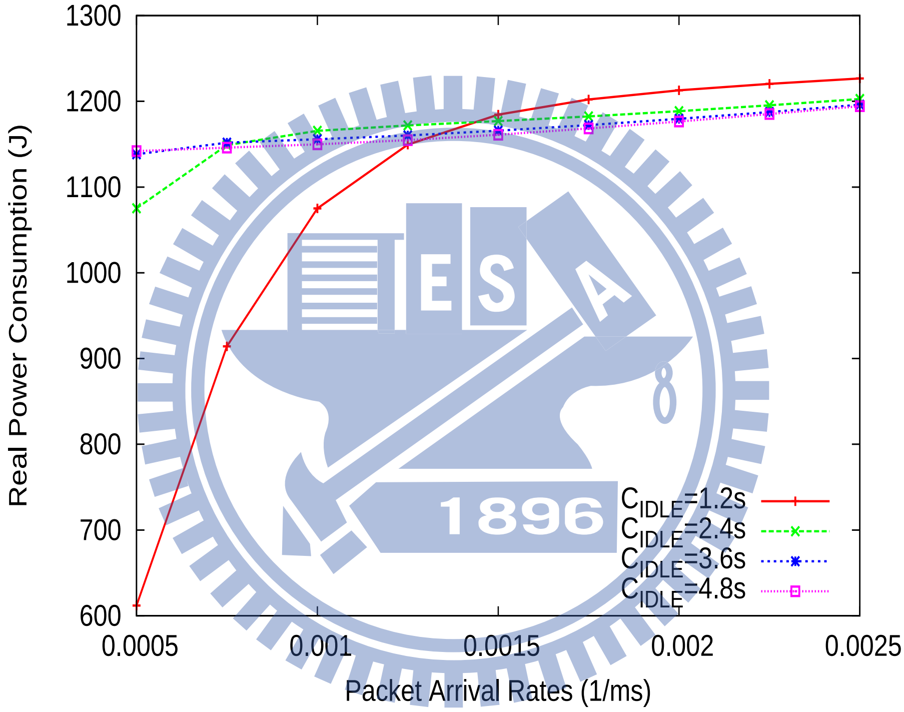

Figure 5.5: Real Power Consumption in 1 second.

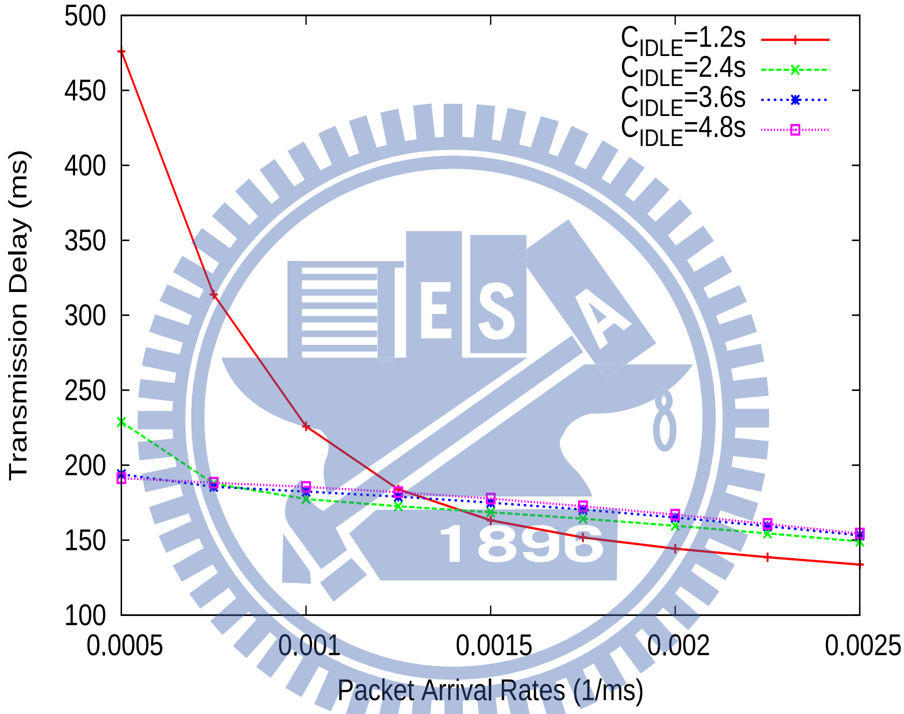

Figure 5.6: Average packet transmission delay with RRC states transition when N = 2 and $C_{IDLEDRX}$ = 1000 ms.

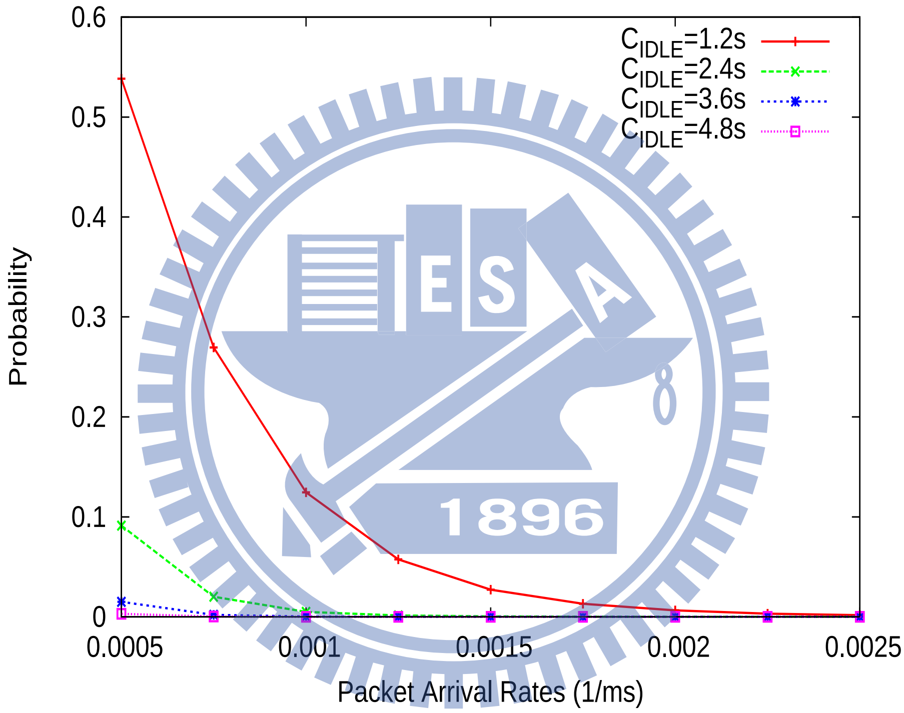

Figure 5.7: Probability of the UE enters RRC_IDLE.

Chapter 6

Conclusions

In this thesis, in order to realize the impact of RRC states transition on DRX mechanism, we derive some numerical functions to model this effect from simple probability theory. By dividing the DRX and RRC operations into several independent parts, we can calculate them separately and then combine the result eventually. We obtain the power saving factor with RRC effect, real power consumption, and packet transmission delay. The analytical results show that there is a trade-off between the power consumption and transmission delay, which has also been verified. Furthermore, under lower packet traffic arrival rate, the UE enters RRC_IDLE states with higher probability, thus it can save much more power. This work can be extended to determine the best DRX and RRC operation parameters.

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Vita

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