國立交通大學

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碩 士 論 文

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摘要

為了解決行動裝置的耗電問題，寬頻無線存取系統(Broadband Wireless Access, BWA)通常會提供省電機制以減少網路閒置時的耗電。其中 IEEE 802.16e 提供數種適合不同應用服務的省電類別(Power Saving Class)來降低耗能。在這個研究中，我們針對 WiMAX 網路上的 TCP 傳輸，進行耗電方面的研究。首先觀察 WiMAX 的媒體存取層在進行 TCP 傳輸時的額外耗電行為，再者對於一個長期處於傳輸的 TCP 連線的網路裝置，例如 FTP，分析討論在閒置等待 TCP 封包時的額外耗電。在本研究中我們透過實際的量測取得耗電參數與模型，結合網路分析器 NS2，來評估和分析 TCP 傳輸在 WiMAX 系統中的耗電情形。實驗結果顯示在高延遲的傳輸環境下，使用第二型態省電類別並採取代理伺服器，會比傳統的方法好 50%的省電效益。

Evaluation of Energy Efficiency for TCP Transmission over WiMAX

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Abstract

Broadband Wireless Access (BWA) system usually provides power saving mechanisms to save the energy consumption of a mobile device during idle. IEEE 802.16e suggests several Power Saving Classes for different type of applications to minimize the power consumption. In this work, we investigate the energy consumption of TCP transmission over WiMAX. First, we evaluate the extra energy consumption introduced by WiMAX MAC in transmitting TCP packets. Then, we consider a long TCP session such as FTP, and evaluate the power consumption of the WiMAX interface when the interface waits for incoming TCP packets.

We conduct a number of experiments in a real WiMAX test-bed and obtain the power consumption parameters and models of a WiMAX interface. These power consumption parameters are further fed into network simulator 2 (NS2) to evaluate the power consumption of WiMAX in transmitting TCP packets. Experimental and simulation results demonstrate that by applying sleep class type II and proxy server in BS can outperform traditional always-on approach by 50% in terms of energy efficiency.

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Chapter 1 Introduction

WiMAX is regarded as an important technology for broadband wireless communication and has become an essential peripheral interface for mobile device such as MID and phone. Using this technology, mobile subscriber station (MSS) has high data rate transmission and mobility with vehicular speed. But, power consumption is a critical issue because most of mobile devices are constrained by battery capacity. In order to reduce the power consumption, IEEE 802.16e specifies sleep mode operations for mobile devices [1].

Sleep mode is a state in which an MSS conducts pre-negotiated periods of absence from the serving BS air interface. Therefore, MSS can minimize the power usage and decrease the air interface resources. To provide different requirements of QoS-related connections, three types of Power Saving Classes (PSC) for sleep mode operations are defined. Each connection is associated to certain Power Saving Class and connections with a common demand property can be grouped into one Power Saving Class. At first an MSS and a BS have to negotiate the parameters of Power Saving Class, such as the time to sleep and listen, the length of a sleep period and a listen period. Then the MSS can sleep during sleep periods, and can wake up to receive message from BS during listen periods. If there are indication message at BS for the MSS, the MSS goes to normal mode to receive the packets. The sleep mode can be categorized into three classes.

- Power Saving Class of type I is recommended for connections of Best Effort (BE), Non-Real Time (non-RT) service types. For type I, if an MSS wakes up during listen periods and there is no packet to send or receive, the MSS doubles the period for the next sleep. This Power Saving Class is suitable for Web browsing which application behavior usually produces bursty traffic at once. Therefore, this type is adapted when TCP session is during idle.
- Power Saving Class of type II is recommended for connections of Unsolicited

Granted Service (UGS) and RT-VR service connection. For type II, an MSS only wake up for data transmission or reception in listen periods. Opposite to type I, the sleep and listen periods are fixed. This sleep mode is appropriate for real-time connection such as VoIP and video streaming services with periodic packet delivery.

- Power Saving Class of type III is recommended for multicast connections as well as for management operations. In this type, an MSS sleeps a specified length of period and then returns to normal operation. The sleep period may vary and is determined each time sleep operation begins.

For transmitting TCP traffic during active communication, an MSS usually requires always-on and cannot enter sleep mode. However, the wireless communication bandwidth varies over time due to MSS mobility and channel condition. Also, TCP flow and congestion control mechanism may be also activated to adjust the transmission and receiving speed due to wireless bandwidth change. To set WiMAX interface always-on may introduce extra power consumption while waiting for incoming or outgoing TCP packets. In this paper, we consider to set WiMAX into sleep class II and dynamically adjust the sleep and interleaving intervals for TCP transmission over WiMAX. Then, we evaluate the energy efficiency for TCP transmission under different configurations through experiments and simulations. To evaluate the energy efficiency for TCP transmission in multiple MSSs environment, NS-2 [1] simulation has been applied. However, to the best of our knowledge, it lacks the power consumption parameters in WiMAX. Therefore, we perform experiments in a real WiMAX test-bed to obtain power consumption parameters for the simulation. The simulation results demonstrate sleep class type II outperform traditional always-on approach in terms of energy efficiency.

The rest of paper is organized as follows. Section II briefly reviews the studies on energy efficiency for TCP transmission. The background of WiMAX sleep mode operations, scheduling scheme and TCP transmission are presented in section III. In section IV, the detail design and implementation of WiMAX simulator are described. Section V discusses the simulation results and summarizes this study in section VI.

Chapter 2 Related Work

TCP uses congestion control to avoid overloading the network. In traditional wired network, packet loses were treated as network congestion. However, wireless network may suffer severe losses due to bit error and handoffs. TCP reacts theses losses by triggering the congestion control which causes the end-to-end performance downgrading. TCP performance over wireless networks has been investigated for many years [3][4]. Transport layer approach [5][6][7] and link-layer approach [8][9] have been proposed. These solutions for wireless TCP problems try to eliminate the mis-congestion control effects and address the issue of high bit error rate.

TCP performance over WiMAX has been also studied [13]. To enhance TCP performance, [10] proposes a cross-layer optimization by exploiting WiMAX MAC framework. A specific scheduling for TCP-based best-effort service class is presented. Besides, ARQ setting in WiMAX MAC is also optimized to decrease the packet error rate. In [11][12], wireless link state is used to adaptively adjust TCP flow to improve TCP performance with lossy channel.

Consider power consumption for WiMAX in transmitting TCP, Power Saving Class I is recommended to adopt. Sleep interval is increased by binary truncated exponent (BTE) algorithm in Power Saving Class I. The lengths of sleep intervals also determine the average delay for packet reception and the energy consumption [15]. To balance the tradeoff between the energy consumption and the average delay, a probabilistic sleep interval decision (PSID) algorithm has been proposed [14]. PSID using the distribution function of the response packet's arrival time so that the response packet may arrive at the base station during each sleep interval with the same probability. The performance of PSC I has also been studied in [16], and the parameters of PSC I are evaluated via simulation tools.

These researches mainly address idle period while waiting for TCP burst traffic, such as web page accesses or instant message. Considering an active communication, the MSS assumes always-on and cannot enter sleep mode. Energy consumption for TCP transmission long session is not yet investigated. Moreover, it lacks of the support from measurements and experiments results.

Chapter 3 Technology Overview

3.1 TCP

TCP is designed to ensure reliable end-to-end transmission. TCP owns several characteristics in the following to provide reliability:

- Retransmission: The application data is broken into what TCP considers the best sized chunks to send. The unit of information passed by TCP to IP is called a segment. When TCP sends a segment it maintains a timer, waiting for the other end to acknowledge reception of the segment. If an acknowledgment is not received in time, the segment is retransmitted.
- Segments in order: Since TCP segments are transmitted as IP datagrams, and since IP datagrams can arrive out of order, TCP segments may arrive out of order. A receiving TCP re-sequences the data if necessary, passing the received data in the correct order to the application.
- Flow control: Each end of a TCP connection has a finite amount of buffer space. A receiving TCP only allows the other end to send as much data as the receiver has buffers for. This prevents a fast host from taking all the buffers on a slower host.
- Congestion control: When free bandwidth is available in the network, TCP uses a number of mechanisms to archive high performance. When congestions occur in the network, TCP slow down the send rate to avoid network collapsing. This mechanism controls the rate of data entering the network, keeping the data flow below a rate that would trigger collapse.

In the following sections, we introduce several mechanisms used in TCP to explain flow control and congestion control in detail.

3.1.1 Sliding window

Figure 1 shows the sliding window. The window advertised by the receiver is called the offered window. When data is sent and acknowledged, the window closes as the left edge advances to the right. The window opens when the right edge moves to the right, allowing more data to be sent. This happens when the receiving process on the other end reads acknowledged data, freeing up space in its TCP receive buffer. If the left edge reaches the right edge, it is called a zero window, which means buffers in receiver are full. This tops the sender transmitting any data. Through sliding window protocol, flow control in TCP prevents sender send data too fast for the receiver to process it.

Figure 1: TCP sliding window.

3.1.2 Slow start

In congestion control mechanism, TCP supports an algorithm called slow start. Slow start adds another window to the sender's TCP: the congestion window, called cwnd. The congestion window is initialized to one segment. Each time an ACK is received, the congestion window is increased by one segment. The sender can transmit up to the minimum of the congestion window and the advertised window. At some point the capacity of the network can be reached, and a router will start discarding packets. This tells the sender that its congestion window has gotten too large and TCP's timeout implies the congestion avoidance algorithms.

3.1.3 Congestion avoidance algorithm

Congestion avoidance and slow start require that two variables be maintained for each connection: a congestion window, cwnd, and a slow start threshold size, ssthresh. When congestion occurs, one-half of the current window size (the minimum of cwnd and the receiver's advertised window) is saved in ssthresh. Additionally, if the congestion is indicated by a timeout, cwnd is set to one segment. When new data is acknowledged by the other end, we increase cwnd. If cwnd is less than or equal to ssthresh, TCP uses slow start; otherwise TCP uses congestion avoidance. Slow start has cwnd start at one segment, and be incremented by one segment every time an ACK is received. Congestion avoidance dictates that cwnd be incremented by one each time an ACK is received.

3.2 WiMAX Sleep Mode Operations

This section explains the basic sleep mode operation of IEEE 802.16e power management. In WiMAX system, an MSS can go into sleep mode to reduce power consumption if there is no packet to send or receive. Before going to sleep mode, the MSS sends the sleep mode request (MOB_SLP-REQ) message to the BS. This message defines the requested sleep profile, such as Power Saving Class type, the size of start frame, initial-sleep window, final-sleep window, and listening window. After receiving the sleep mode response (MOB_SLP-RSP) message with permission, the MSS enters sleep mode at corresponding MAC frame. The sleep window is associated with different Power Saving Class types.

Figure 2 illustrates sleep mode operation for Power Saving Class type I. During the listen interval, the MSS wakes up to receive traffic indication (MOB_TRF-IND) message from BS. If there are no packets to receive or send, the MSS doubles the sleep period for next sleep. If MOB_TRF-IND indicates buffered packets for MSS, the MSS has to switch to awake-mode. Figure 3 shows sleep mode operation for type II. MSS only wakes up to receive and send packet in listen period. Figure 4 shows sleep mode operation for type III. The MSS sleeps for a defined sleep interval and then return to normal operation.

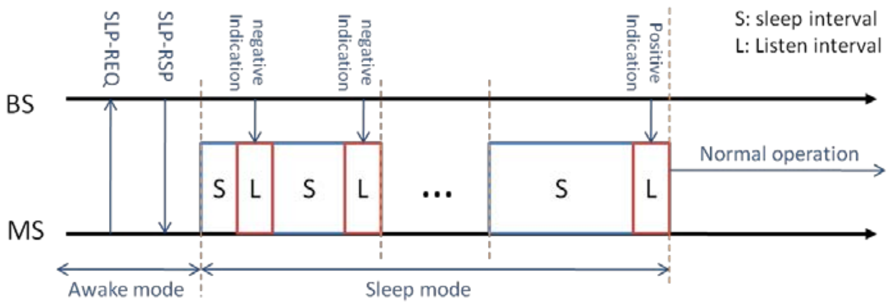

Figure 2: Power Saving Class type I.

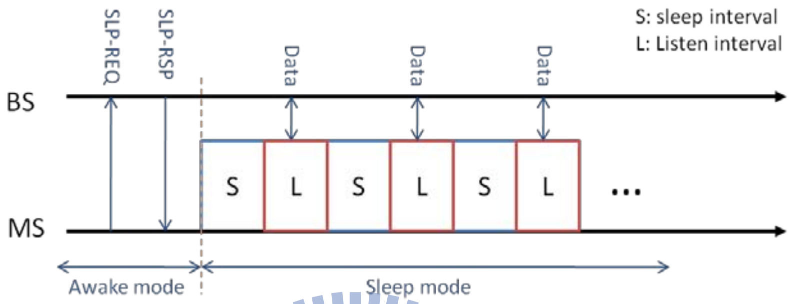

Figure 3: Power Saving Class type II.

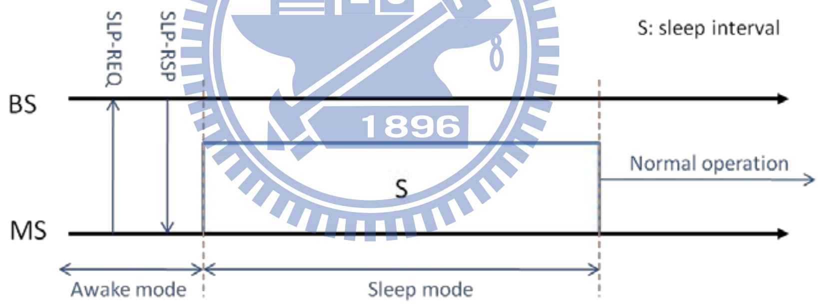

Figure 4: Power Saving Class type III.

3.3 WiMAX Schedule Classes

WiMAX specifies several scheduling services for data transfer to support different QoS requirement. Each connection is associated with a single scheduling service which determining by a set of QoS parameters that quantify aspects of its behavior. The scheduling services supported in WiMAX are described in the following:

- Unsolicited Grant Service (UGS): The UGS is designed for real-time service flows that transport fix-size data packets on a periodic basis. The BS offers fixed-size of transmission bandwidth. UGS is suitable for constant bit rate (CBR) traffic such as

VoIP service without silence suppression.

- Enhanced Real-time Polling Service (ertPS): The ertPS is designed for VoIP service with silence suppression. Different from UGS, ertPS offers amounts of DL or UL resources to the MSS dynamically, and allocates the bandwidth request in the UL bursts to the MSS. Therefore, the MSS can use bandwidth request to change UL allocation. This mechanism prevents the waste of uplink resources when there are no packets to transmit during silence time.
- Real-time Polling Service (rtPS): The rtPS is designed for real-time flows that generate variable size data packets on a periodic basis, such as video streaming. The BS offers periodical bandwidth requests in UL bursts to the MSS, and provides polling to the MSS for suitable UL bursts requirement.
- Non-real-time Polling Service (nrtPS): For non-real-time traffic, such as Web access. The BS grants unicast polls to nrtPS connections on a large time-scale, and an MSS that has packets to transmit should use contention-based bandwidth requests. Since the bandwidth request is not sent periodically, the bandwidth request might be lost due to collision and the delay for UL burst allocations cannot be guaranteed.
- Best Effort (BE): The BE is designed for applications that do not have specific delay requirements. Hence, this type of connection cannot provide any QoS.

Chapter 4 Design and Development of WiMAX Simulator

4.1 NS-2 Simulator

NS-2 is an event-driven simulator which is widely used at network research. The simulator is popular because many Internet protocols are implemented as modules to simulate network environments, such as TCP, routing, and multicast protocols over wired and wireless network. WiMAX Forum [20] also provides a WiMAX module for public, so the vendors and service providers can test applications performance over WiMAX networks. In ns-2, all modules are designed by using object-oriented programming language C++. The component stack of NS-2 with WiMAX modules is shown in Figure 5. At beginning, traffic generating agent simulates different kind of data traffic, such as HTTP, VoIP, and FTP. These data are classified by WiMAX classifier, and are transferred to different type of scheduling class queues. The data packets in queues are called mac service data unit (MSSDU) will be transmitted in proper OFDMA symbol time in WiMAX PHY module. When the MSS receives the MSSDU, it reassembles the packets and deliveries to upper layer. The detail components of the WiMAX module are described as the following.

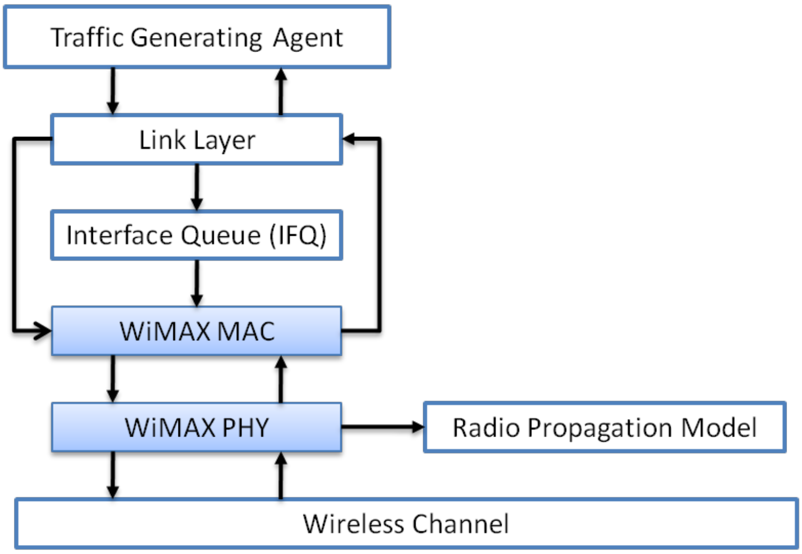

Figure 5: NS-2 architecture with WiMAX modules.

4.2 WiMAX Module

WiMAX Forum releases WiMAX module with the specification of the IEEE 802.16e standard and based on the NS-2 version 2.31. Figure 6 presents the framework of BS and it can be decomposed into several sub-modules as follows:

- Flow classifier: This module performs 802.16 MAC CS functions mapping arriving network service data units (SDUs) to the proper MAC service flow identifier (SFID) and connection identifier (CID). All incoming packets from the higher layers pass through this module before being directed to a queue corresponding to a CID.
- DL ARQ: If ARQ is enabled in the simulation, this module maintains their status such as the ARQ counter, timer, etc.
- DL/UL scheduling: The role of the scheduling function is to decide the priority of each flow and schedule proper number of data packets for transmission. This module support different type of scheduling service, such as UGS, ertPS, rtPS, nrtPS, and BE. DL schedule at BS allocates bandwidth for data connections in the following order: UGS, rtPS (only to meet minimum reserved bandwidth), and nrtPS (only to meet a minimum reserved bandwidth). Then, if there is a left-over resource,

the algorithm fairly allocates to rtPS, nrtPS, and BE. DL schedule only allocates bandwidth to a connection when it has data to be sent. UL schedule is similar to DL schedule but bandwidth request information is used instead of enqueued packets.

- DL resource allocator: The role of the DL resource allocator is to determine the size and location of each data burst in a frame.
- Packet fragmentation/packing: The allocated data slot may not match exactly the size of packets in queue, fragmentation and packing is needed to better utilize the allocated slot.
- UL ARQ Module: This module manages the packets that are received out of order or partially. The ARQ feedback information is sent back to the transmitter through state information transferred between this module and the DL ARQ module.
- DL Frame Assembler: DL frame assembler combines all packets generated by the scheduler to form a frame and add some additional frame information such as the DL and UL maps.
- Packet Parser: The BS parses packets and classifies incoming packets based on the type in packet headers: data packets or control packets.
- PHY Module: DL PHY module can stamp some PHY information to the packets, such as the transmission time, power, and frequency. UL PHY module calculates the SINR information for all incoming packets and implements the interface to the PHY layer tables which provide block error information when queried with block size and SINR value.

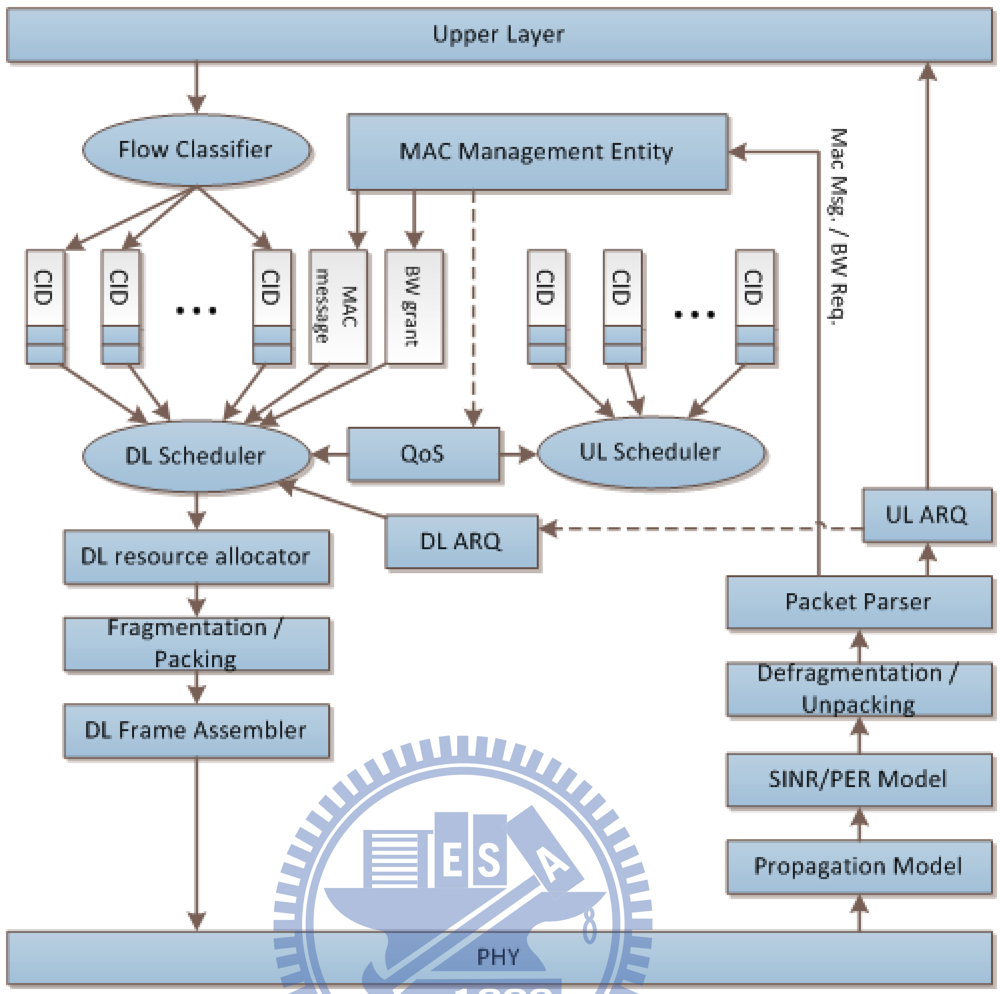

Figure 6: Structure of base station.

Figure 7 presents the framework of mobile station in WiMAX module. The components are described as follows:

- UL Scheduler: The UL scheduler gets the bandwidth grant to the mobile in every frame from the packet parser and then it schedule proper amount of data in the granted UL slots.
- UL Assembler: This module scans the queues at the MSS and generates a burst of data which fits into the granted slots.

The functions of the remainder of the modules are the same as in the case of the BS.

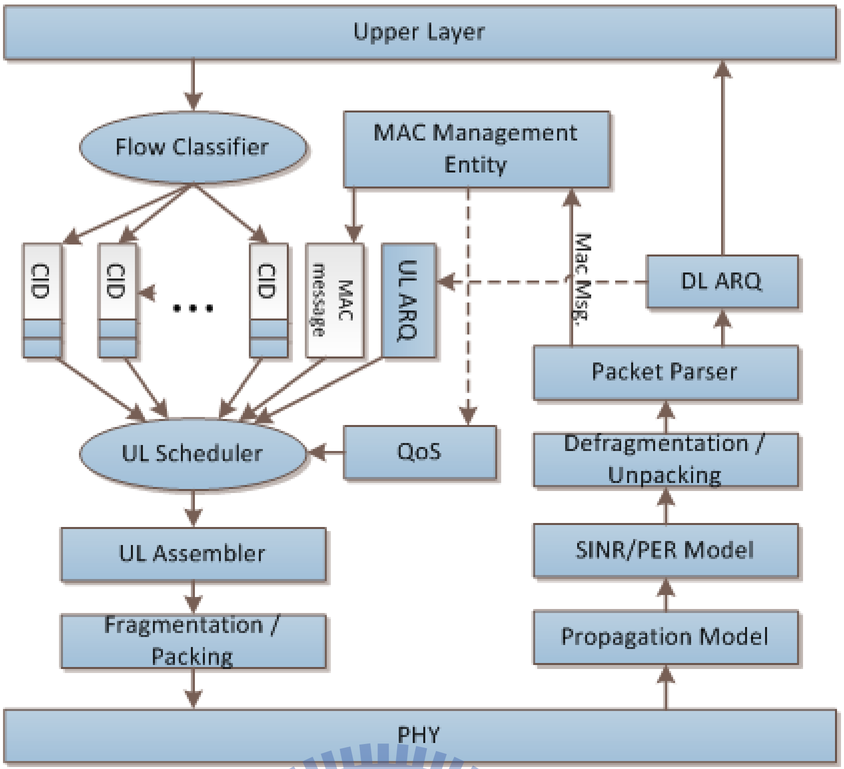

Figure 7: Structure of mobile station.

In addition to BS and MSS support in MAC module, several propagation models are included. The channel model used in this OFDMA module is a Cost231 bulk path loss component. Doppler effects are included to capture mobility effects. The bulk path loss component of the channel is computed during the simulation, because the distance between nodes and current transmit power are necessary parameters. However, the fast fading component of the channel can be computed offline, before the simulation is running.

4.3 WiMAX Module Enhancement

To support sleep mode in NS-2, we add a Power-Saving module in the simulator. This module coordinates with MAC management module to process the sleep mode information, such as MSS requests sleep, MSS terminates sleep, etc. Two sleep mode messages are presented in Table 1. When a MSS initials the sleep mode, MSS sends the MOB_SLP-REQ message including the information of Power Saving Class. The parameters of Power Saving Class are shown in Table 2. The permission of sleep mode is included in MOB_SLP-RSP message which was sent from BS to MSS.

Table 1: Defined management message in power saving module

Category	Message defined
Sleep Mode	MOB_SLP-REQ MOB_SLP-RSP

Table 2: Parameters in power saving module

Parameters	Descriptions
PS_**status_**	Power saving status. This status is used in BS and MSS keeping the current status, such as wake state, sleep state, and listening state.
PSC_type_	The Power Saving Class type that MSS used.
initSleepWin_	Initial sleep window size
finSleepWinBase_	Final sleep window base
listenWin_	Listening window size
finSleepWinExp_	Final sleep window exponent
firstSleepWin_	Final sleep window size
PSC_id_	Power Saving Flow ID

The Power saving module also maintain the time in different power state of a MSS, such as transmission time, receiving time, idle time, and sleep time. These times are calculated to analyze the power consumption of MSS. The information of power consumption is described in section 5.1.

Chapter 5 Evaluation of Energy Efficiency

5.1 Experimental Environment and Measurement Results

In this section, we measure the power consumption behavior of WiMAX to get basic power consumption parameters. The measurements were carried out in M-Taiwan WiMAX Applications Lab (MTWAL) [17], which is the first WiMAX Forum applications lab. MTWAL is a non-commercial proof-of-concept lab established, operated, and owned by Industrial Technology Research Institute (ITRI) [18] in Hsinchu, Taiwan. This lab is deployed WiMAX network dedicated for WiMAX applications tests and demonstrations.

The WiMAX NIC for power measurement is Beceem communication BCS200 with PCMCIA interface. BCS200 implements a full-featured IEEE 802.16e/WiMAX/WiBRO Wave 2 compliant MSS. The BS is deployed on the roof of building, and its location is about 400 meters away from out measurement spot. The experiments were carried out for following conditions.

1. Receiving power: Receiving power is the power consumption when WiMAX NIC is during receiving state.
2. Transmitting power: This is the power consumption that WiMAX NIC is during transmitting state.
3. Idle power: This is the power consumption that WiMAX NIC is in idle state without any traffic.
4. Sleep power: This is the state that WiMAX NIC goes to power saving mode and consume the minimal power in sleep mode.

To get receiving and transmitting power conveniently, we use UDP traffic in our experiments since there is no ACK for UDP. Figure 8 shows our experimental environment.

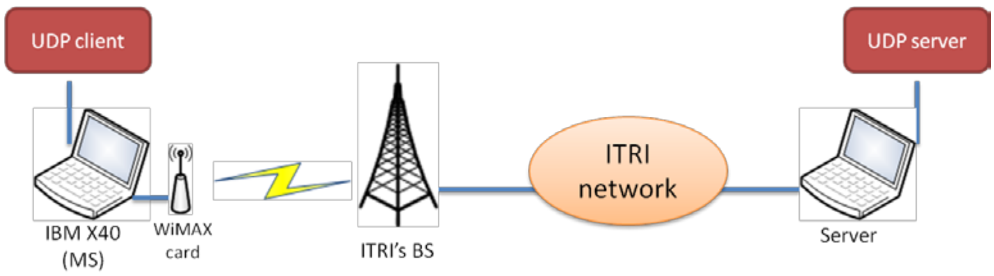

Figure 8: Experimental environment.

Figure 9 shows the current trace of receiving state and idle state. Idle state begins from 4.6 milliseconds to 6.6 milliseconds. During idle state, the current trace is quiet stable since there is no traffic transmitting or receiving.

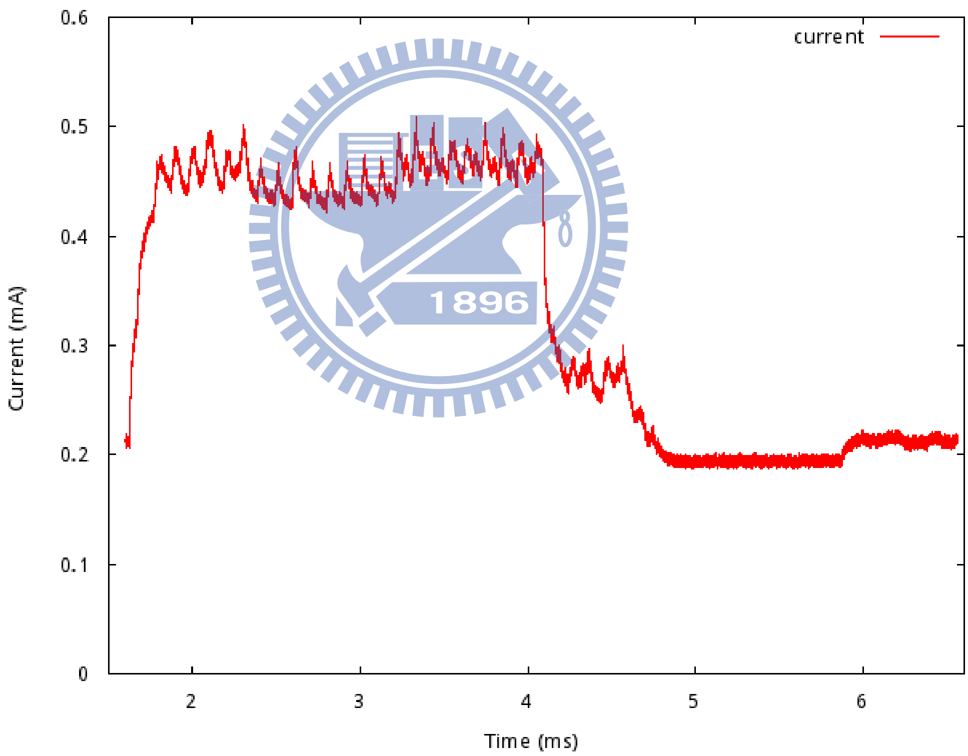

Figure 9: Current trace of WiMAX card in receiving and idle mode.

For measuring the receiving power and transmitting power, the UDP packet with 80 bits payload was generated every 20 millisecond. Receiving state begins from 1.6 milliseconds to 4.0 milliseconds. The current trace of receiving state varied largely when WiMAX NIC is receiving DL/UL map and UDP packets. Figure 10 shows the current trace of receiving state and transmitting state. Transmitting state begins from 3.0 milliseconds to 4.9 milliseconds. The current trace of transmitting state varied significantly when WiMAX NIC is transmitting UDP packets.

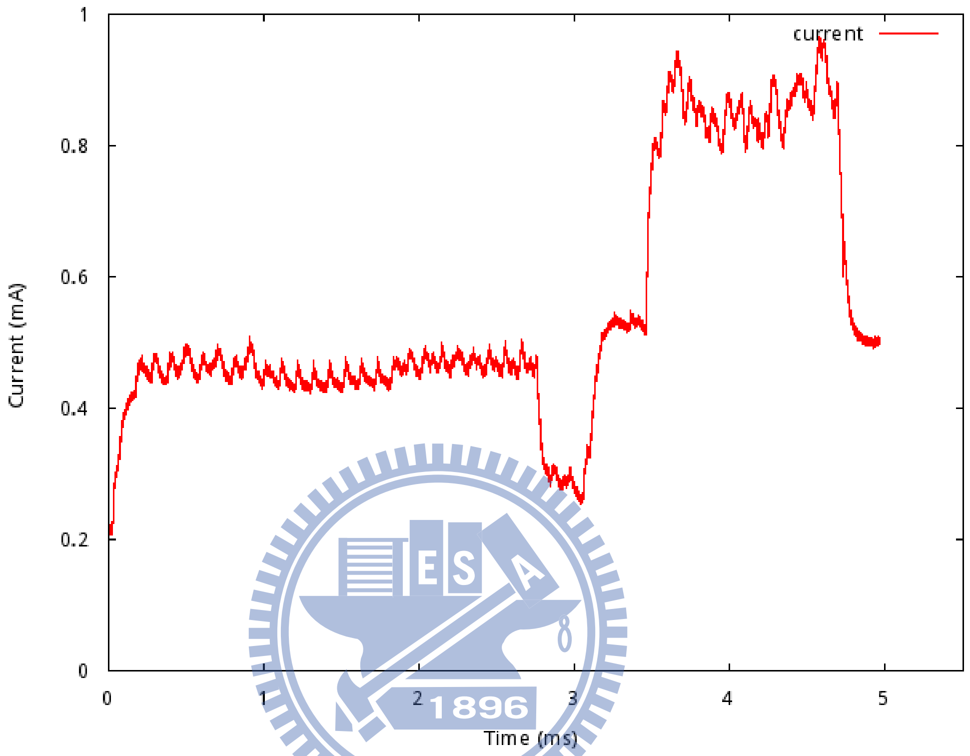

Figure 10: Current trace of WiMAX card in receiving and transmitting mode.

Due to some technology problem, Beceem WiMAX card cannot enter sleep mode. Therefore, we used the power consumption of sleep state from WLAN currently. Table 3 summarizes measurements of power consumption under different mode. The power measurement results are also applied to our simulation to evaluate the energy efficiency of TCP transmission over WiMAX.

Table 3: Power Consumption measurements

Mode	Current (mA)	Voltage (V)	Power (mW)
Idle	200	3.3	660
Receive	450	3.3	1485
Transmit	730	3.3	2409

Sleep	15.2	3.3	50

In the sleep mode, there are more sleep cycles and each sleep cycle includes one sleep interval and one listening interval, show in Figure 11. Since we use Power Saving Class type II in WiMAX, the sleep interval and the listening interval are fixed length during sleep mode operation.

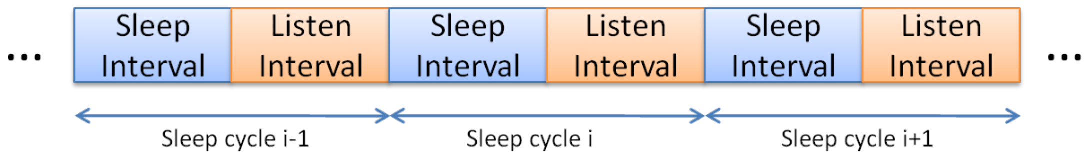

Figure 11: Power Saving Class type II in sleep mode operation.

Let T_{S_i} denote the length of *i*-th sleep interval. Let T_{L_i} denote the length of *i*-th listening interval. The length of *i*-th sleep cycle is $T_{S_i} + T_{L_i}$. Let $\mathrm{T}_{\mathrm{RX}_\mathrm{i}}$ denote the total length of receiving time during *i*-th sleep cycle. Let $\mathrm{T}_{\mathrm{TX}_\mathrm{i}}$ denote the total length of transmitting time during *i*-th sleep cycle. The length of idle time during *i*-th sleep cycle is $\mathrm{T}_{\mathrm{L}_\mathrm{i}} - \mathrm{T}_{\mathrm{RX}_\mathrm{i}} - \mathrm{T}_{\mathrm{TX}_\mathrm{i}}$. Let $\mathrm{P}_{\mathrm{tx}}, \mathrm{P}_{\mathrm{rx}}, \mathrm{P}_{\mathrm{idle}}$ and $\mathrm{P}_{\mathrm{sleep}}$ represents transmitting power, receiving power, idle power and sleep power respectively. Therefore, the power consumption model can be represented by the following equation.

$$\text{Power consumption} = \frac{\sum_{\mathrm{i}=1}^{\infty}\left[\mathrm{T}_{\mathrm{S}_\mathrm{i}}\mathrm{P}_{\mathrm{sleep}} + \mathrm{T}_{\mathrm{RX}_\mathrm{i}}\mathrm{P}_{\mathrm{rx}} + \mathrm{T}_{\mathrm{TX}_\mathrm{i}}\mathrm{P}_{\mathrm{tx}} + \left(\mathrm{T}_{\mathrm{L}_\mathrm{i}} - \mathrm{T}_{\mathrm{RX}_\mathrm{i}} - \mathrm{T}_{\mathrm{TX}_\mathrm{i}}\right)\mathrm{P}_{\mathrm{idle}}\right]}{\sum_{\mathrm{i}=1}^{\infty}\left(\mathrm{T}_{\mathrm{S}_\mathrm{i}} + \mathrm{T}_{\mathrm{L}_\mathrm{i}}\right)}$$

By applying the power consumption model, the energy evaluation in NS2 simulator is obtained.

5.2 Simulation Environment

In this section, we explain the traffic model in detail and then define the evaluation metrics to evaluate energy efficiency. For a long session transmission, FTP traffic is used in the simulation scenarios. FTP agent in NS-2 simulates bulk data packets which were sent by TCP agent and were controlled by TCP flow and congestion control algorithm. To evaluate the energy efficiency of TCP transmission, we specify several metrics to access the performance of WiMAX. The following metrics are defined:

1. Throughput: the overall amount of user data, which purged from MAC header and physical preamble overhead, carried out by simulator in a unit of time.
2. End-to-end delay (or delay for short): the time taken for a packet to be transmitted across a network from source to destination.
3. Sleep interval: the interval from the entrance into the sleep-mode to the exit (measured in frames).
4. Interleaving interval: Assigned duration of MSS listening interval (measured in frames).
5. Number of MSSs: the number of MSSs which are serving by the BS.

5.3 Simulation Parameters

The WiMAX simulation scenarios are written in TCL scripts to descript network environment and corresponding parameters. The TCL command shall be proper defined to configure the parameters for WiMAX PHY and MAC layer. For example, to create an OFDMA PHY object for ns nodes, we use:

$ns node-config -phyType Phy/WirelessPhy/OFDMA

This command makes simulator instance $ns to configure its nodes which use OFDMA PHY in the simulation. Table 4 shows parameters we used in scenarios.

Table 4: Simulation parameters

Simulation parameters	Value(s)
PHY	OFDMA
System **bandwidth**	10 MHz
FFT size	1024

Cyclic prefix **ratio**	1/8
Frame duration	5 ms
Modulation	QPSK, 16-QAM, 64-QAM
Power saving mo**de**	Power Saving Class II
Sleep intervals	0, 1, 4, 8
Interleaving intervals	0, 1
Scheduling class	UGS, nrtPS, BE

5.4 Results and Discussion

In this section, we report the simulation results and evaluate the energy efficiency for TCP transmission over WiMAX. We discuss the relative effectiveness of TCP mechanisms with WiMAX behavior by two conditions. First, we analyze the TCP throughput under different system parameters values, i.e., TCP throughput varied with numbers of MSSs which contend the bandwidth resource. Second, to evaluate how TCP affects the energy consumption of WiMAX, we use Powe Saving Class II in WiMAX to transmit the TCP packets under different network delay. Finally, we access the energy efficiency of TCP transmission over WiMAX with TCP throughput and energy consumption of WiMAX.

In the first scenario, we investigate the effects of bandwidth contention with TCP throughput and with energy consumption of WiMAX. Figure 12 shows the network environment that multiple MSSs connect to the BS. In this scenario, TCP connection with BE scheduling service is used. Since an MSS request bandwidth request form BS by sending bandwidth requests, we also analyze the energy consumption on MAC message.

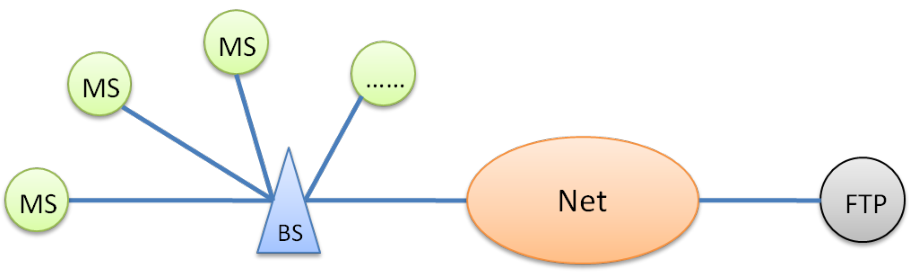

Figure 12: Contention environment.

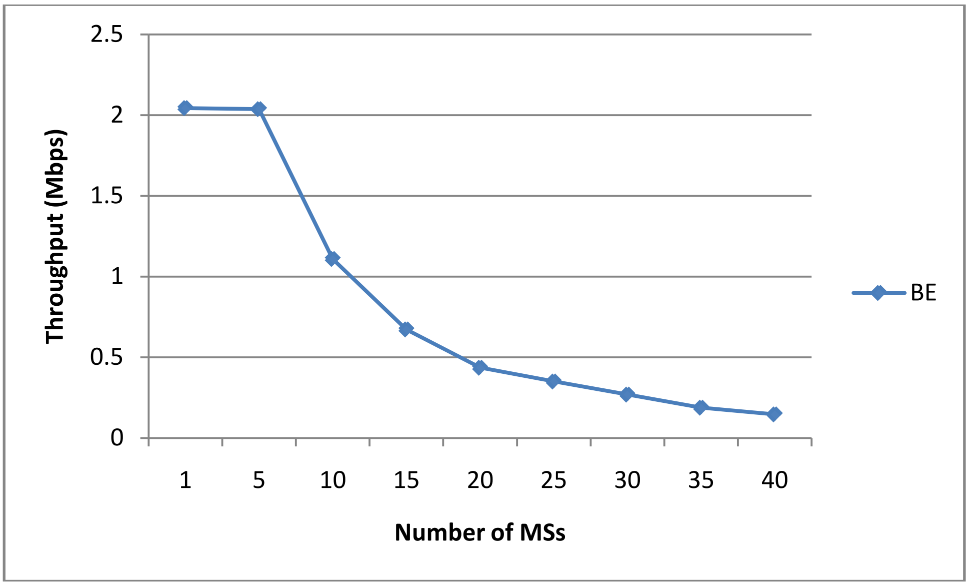

Figure 13: Throughput versus number of MSSs

Figure 13 shows the average TCP throughput versus number of MSSs. The throughput is downgraded when system loading is increased since the bandwidth resources are shared by MSSs. Next, we evaluate the energy that an MSS consumed to carry out such TCP throughput. As we know, the energy consumption is relative to TCP throughput if there is no packet error or packet lost. However, energy consumption in WiMAX network is much difference.

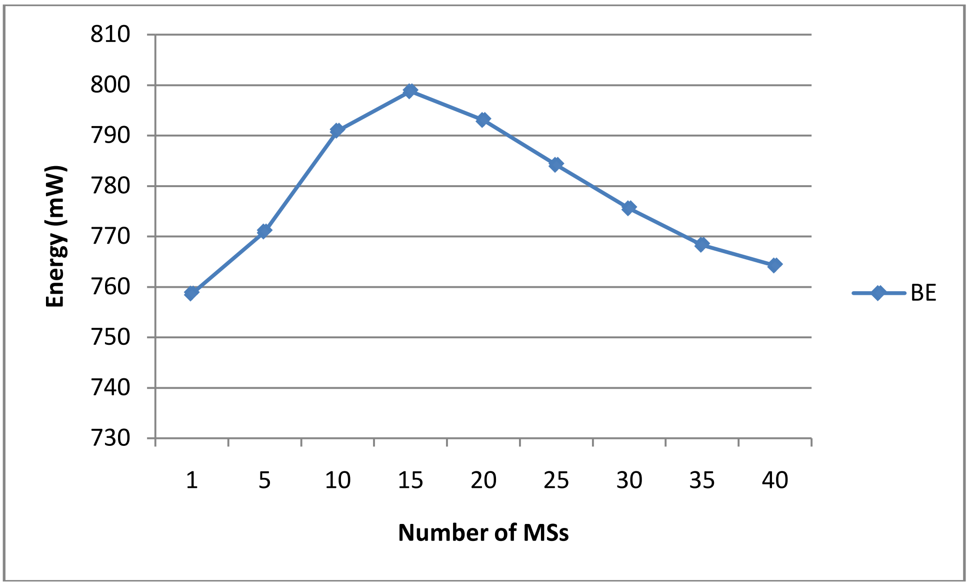

Figure 14: Energy consumption of the MSS.

Figure 14 shows that the energy consumption is highest in 15 MSSs. When the number of MSSs is less than 15, the resource contention is less and the MAC message is not often sent. In this condition, the energy consumption is correlated with the number of MAC messages (i.e., DL-MAP and bandwidth request) when the number of MSSs increases. Therefore, the less energy on MAC message is required in low contention environment. However, when system is overloaded (i.e., the number of MSSs > 15), the bandwidth resources are shared by each MSS and the throughput of TCP slows down. In this case, less energy is used to send TCP packets since TCP throughput is decreased.

Next, we use different types of scheduling service in WiMAX to transmit TCP packets. Through this scenario, the energy efficiency with scheduling services is compared. Figure 15 shows the throughput results for UGS, nrtPS, and BE scheduling classes. Due to the management of UGS in WiMAX, UGS scheduling has the character of contention-free. Hence, we use UGS service as a taget to compare nrtPS service and BE service if there is a well-design and optimized UGS management mechanism in BS which always can predict and offer the bandwidth need to MSSs. If there is such mechanism, it will have average 13 percent higher than nrtPS service and BE service in terms of throughput. NrtPS service also has higher throughput than BE service because nrtPS service has more polling slot than BE service.

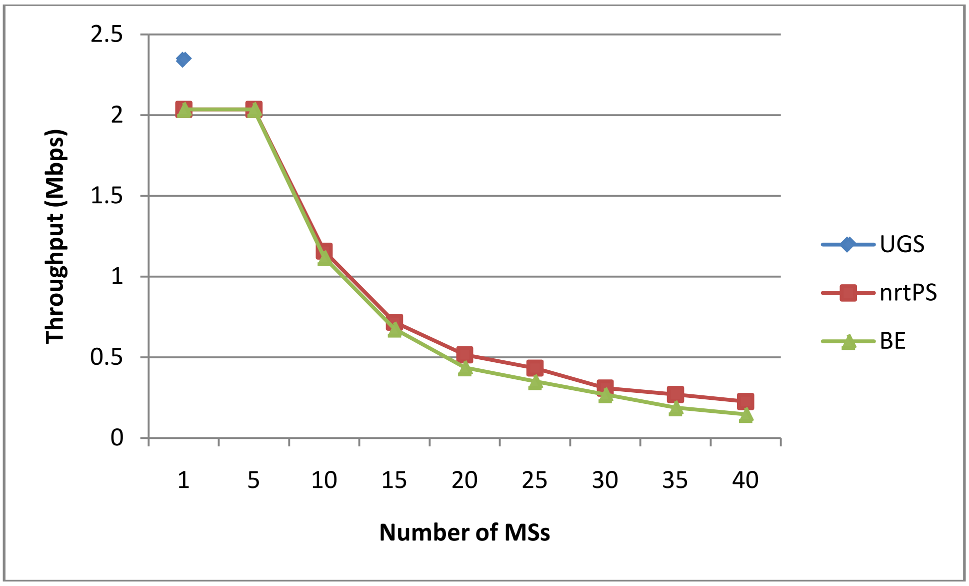

Figure 15: Throughput for different scheduling classes.

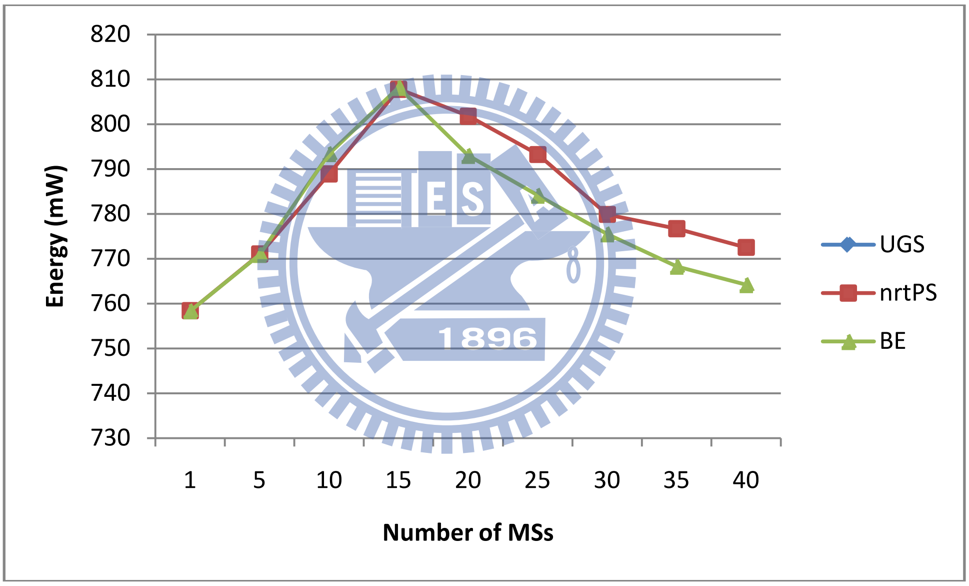

Figure 16: Energy consumption for different scheduling classes.

Figure 16 shows the energy consumption corresponds to throughput in different types of scheduling classes. When there is only one MSS, the energy consumption with UGS service is almost equal to nrtPS service and BE service. On the other hand, nrtPS service has higher energy consumption than BE service. The explanation is that using UGS service has higher throughput than nrtPS service and using nrtPS service also has higher throughput than BE service. Therefore, the higher throughput archived consumed more energy in transmitting.

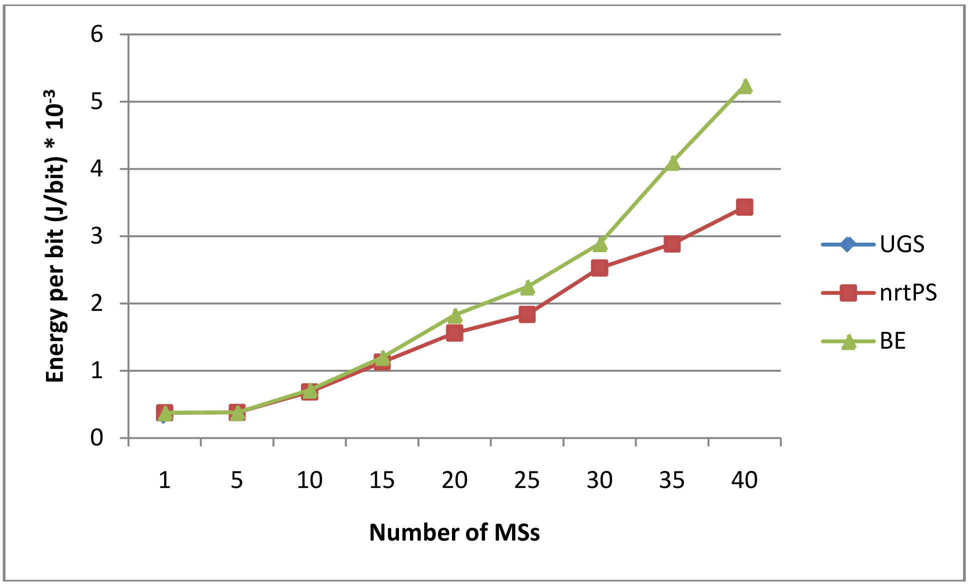

Figure 17: Energy efficiency for different scheduling classes.

To analyze the energy efficiency of scheduling classes in WiMAX, we use throughput and energy consumption to compare the efficiency. Figure 17 presents the energy efficiency for different types of scheduling classes in WiMAX. In this case, energy-per-bit means the energy that WiMAX takes to transmit a bit. Thus the lower value represents the lower energy consumed. The result shows that nrtPS service has 35 percent less than BE service in energy consumption when system is overloaded (the number of MSS equals to 40). Besides, UGS service has 13 percent less than nrtPS service in energy consumption.

In second scenario, we consider how upper layer (TCP layer) affects down layer (WiMAX layer) in energy consumption. Due to the TCP mechanism, the performance of TCP may be varied because of different bandwidth, transmission delay, etc. We analyze the impacts in two scenarios: network delay scenario and contention scenario. For network delay scenario, Figure 18 presents a common network environment that end-to-end delay may increase when packets are routed by multiple hops. In this scenario, long delay affects TCP performance, especially during the startup period. Poor TCP performance makes WiMAX interface idle to waits for incoming packets and causes extra energy consumption. Therefore, we consider setting WiMAX into sleep class II and dynamically adjusting the sleep and interleaving intervals for TCP transmission over WiMAX. We also identify the number of key factors that might impact the performance and energy consumption: sleep interval, interleaving interval and delay. To evaluate how the transmission delay affects the performance, we ran all simulations with one MSS, using BE service, and receiving data from FTP server.

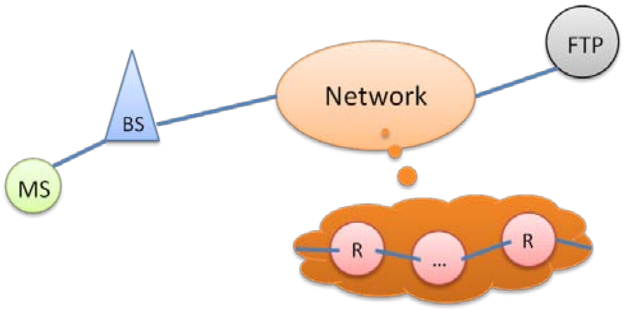

Figure 18: Network environment

Figure 19 shows the average transfer delay versus throughput in different ratio of sleep and interleaving intervals. We adjust the sleep intervals as 0 frame, 1 frame, 2 frames, 4 frames, and 8 frames. As expected, the average throughput decreases in high transfer delay. In fact, MSS in always-on (sleep interval = 0 and interleaving interval = 0) has highest throughput in short delay and high delay. This is obviously because packets can transfer without waiting to MSS awakes. But, MSS in always-on also means it wastes more energy during idle state for coming packets. Moreover, the result shows that the length of sleep interval affects TCP throughput. It is reasonable since MSS in sleep mode cannot transmit packets and makes TCP throughput downgrading.

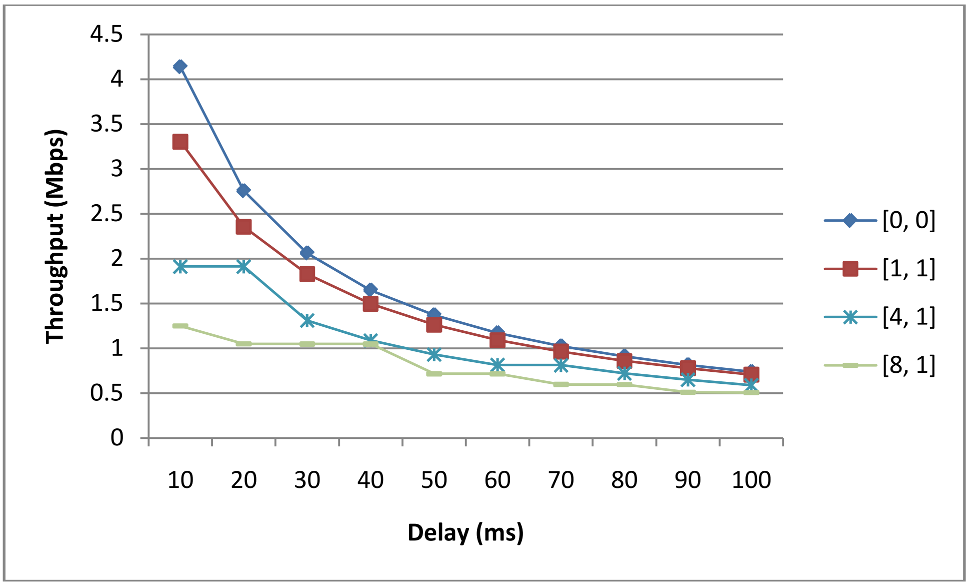

Figure 19: Throughput versus delay

The energy consumption of WiMAX versus transfer delay is shown in Figure 20. MSS with longer sleep intervals saves much energy. Therefore, we analyze the energy efficiency is to identify the energy-per-bit results.

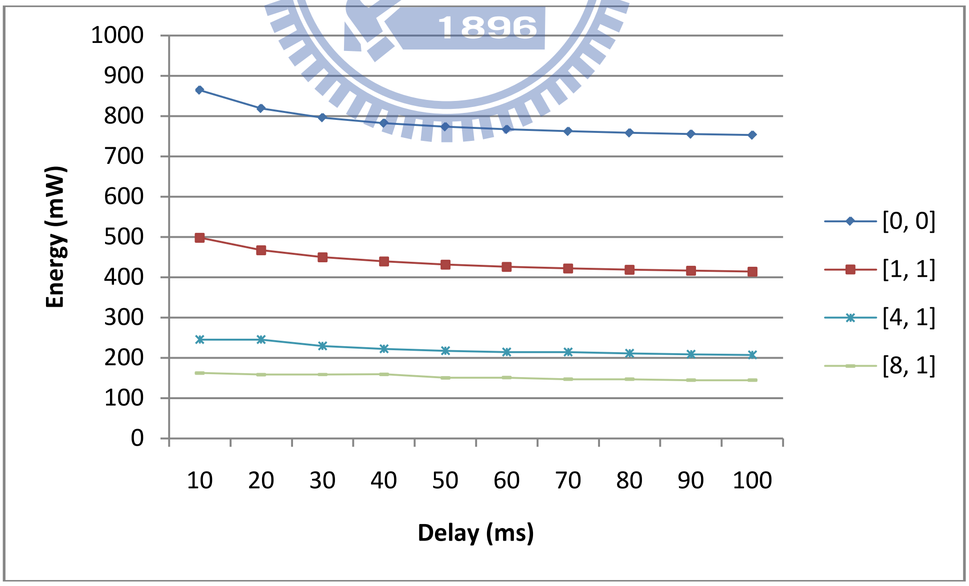

Figure 20: Energy consumption versus delay

Figure 21 presents the energy-per-bit versus transfer delay. The result shows that longer sleep intervals applies much energy efficiency. However, long sleep intervals also means low TCP throughput. Therefore, sleep interval is a trade-off between throughput and energy consumption.

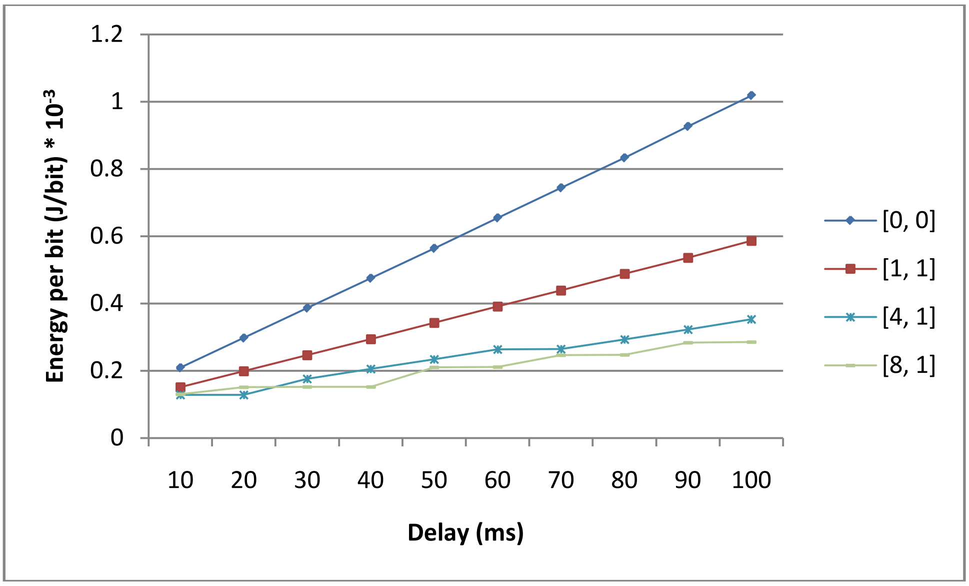

Figure 21: Energy efficiency versus delay

This result also shows that energy efficiency of TCP transmission over WiMAX is associated with delay and sleep intervals. MSS with long sleep intervals also increases the delay to process the coming packets. Our purpose is that an MSS doing sleep operation in MAC layer does not increase the transfer delay in TCP layer. To eliminate the extra delay caused by MSS in sleep operation, we use a conventional proxy-based solution, like I-TCP. Figure 22 presents the scenario; a proxy server is added on BS and split TCP connections to both wireless and wired links. The proxy server relays the packets between the FTP server and MSS. Therefore, when the MSS is unavailable in sleep operation, TCP performance does not slow down. All buffered packets can be sent to the MSS when the MSS is in interleaving intervals. Then, we re-run all the scenarios and analyze the results.

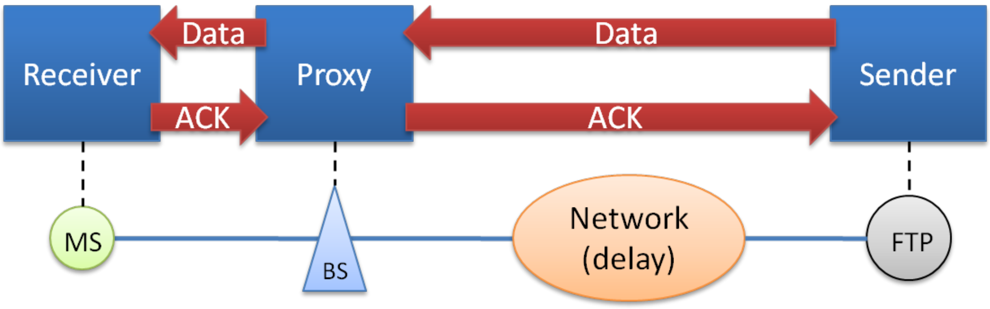

Figure 22: Proxy server in BS.

Figure 23 shows TCP throughput versus transfer delay under different sleep intervals. After adding the proxy server in the BS, the throughput under different sleep intervals downgrades and merges together when delay increases. This is because that when there is enough bandwidth resource for MSSs transmitting packets, the length of sleep intervals does not affect the transfer delay and TCP performance. TCP performance is only affected by transfer delay. Hence, using proxy server in BS resolves the impact of TCP performance which caused by sleep operation.

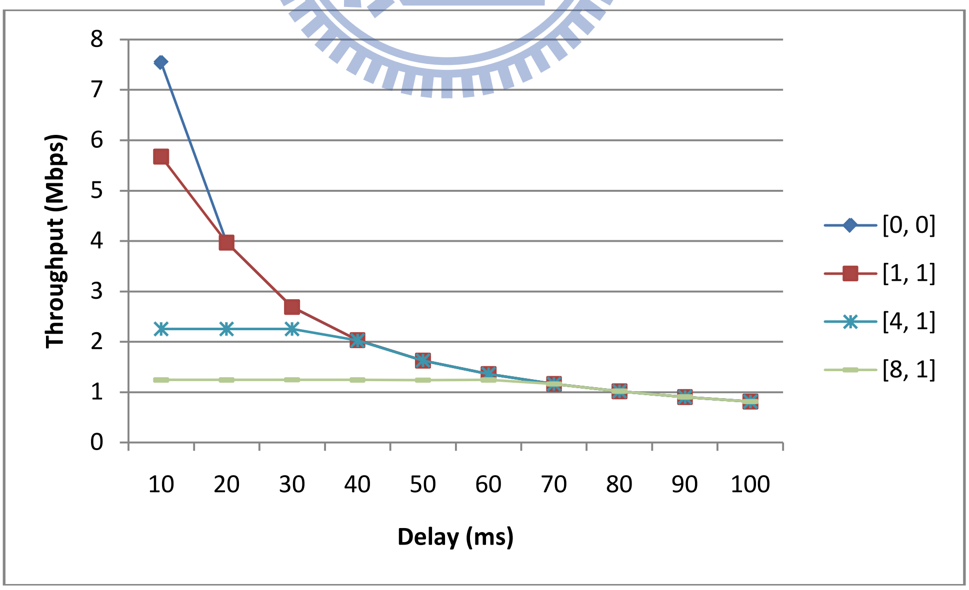

Figure 23: Throughput versus delay.

Figure 24 presents the energy consumption of WiMAX with different length of sleep intervals. As expected, the energy consumption is related to TCP performance and is downgrading in high transfer delay.

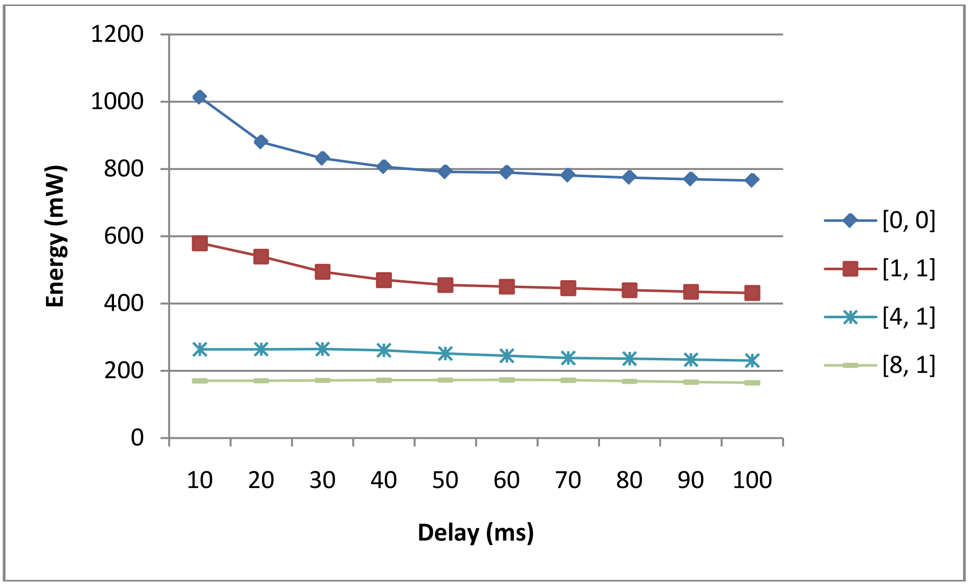

Figure 24: Energy consumption versus delay

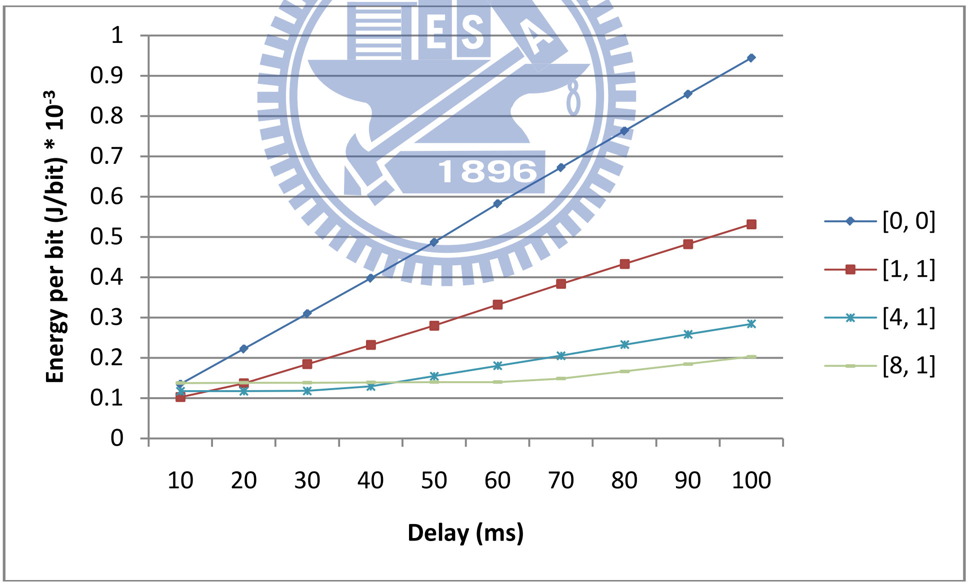

Figure 25: Energy efficiency versus delay

Figure 25 presents the energy efficiency versus delay with different length of sleep intervals. The result implies that the proxy-based model we used can eliminate the side-effect of sleep operation of WiMAX. The TCP throughput varied when transfer delay increases. Therefore, we should determine the length of sleep and interleaving intervals under different delay to benefit the best energy efficiency gain. Thus, when transfer delay is 30 milliseconds, we shall set sleep interval as one frame and interleaving interval as one frame. When transfer delay is 30 milliseconds and 50 milliseconds, we shall set sleep intervals as four frames, and eight frames respectively.

In third scenario, we change the number of MSSs from one to five MSSs connecting to the BS. Only one MSS is set to power saving mode and the others stay always-on. The proxy server is also added in BS in this scenario. We evaluate the energy efficiency of TCP transmission in a contending environment. Throughput result is shown in Figure 26. MSS with power saving reaches the top of throughput at 40 milliseconds transfer delay. This is because that an MSS has to contend the resource with others by sending bandwidth request messages. When transfer delay is short, TCP throughput is high and MSSs have to contend the resource aggressively. In this condition, if an MSS sets to sleep mode, it is harder for this MSS to contend the resource. Thus, the performance of the sleeping MSS has lower throughput at beginning. With the delay increases (i.e. around 30 to 40 milliseconds), other MSSs' TCP throughput decreases and bandwidth request messages become less. It is easier for the sleeping MSS to contend the bandwidth resource. Therefore, the throughput of the sleeping MSS has increases until 40 milliseconds delay.

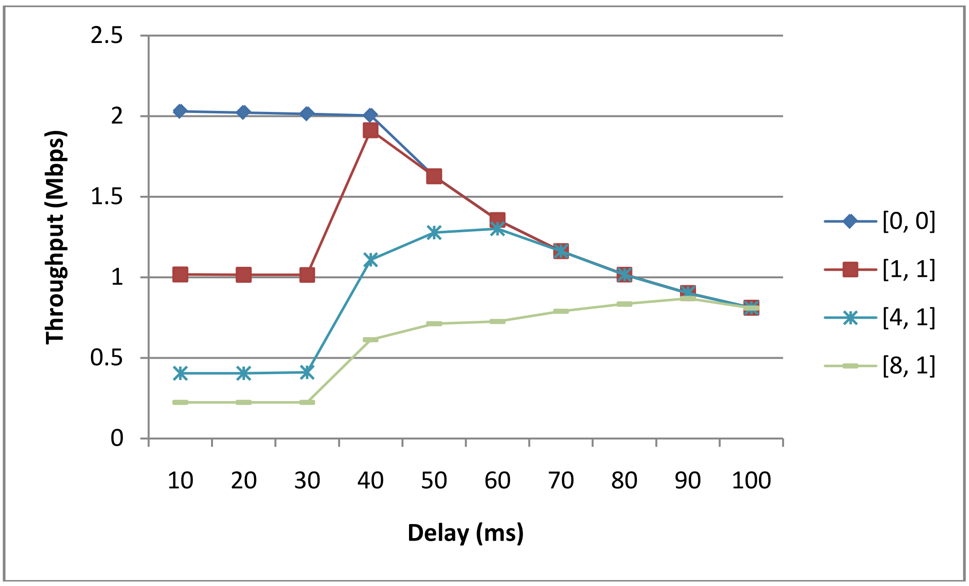

Figure 26: Throughput versus delay

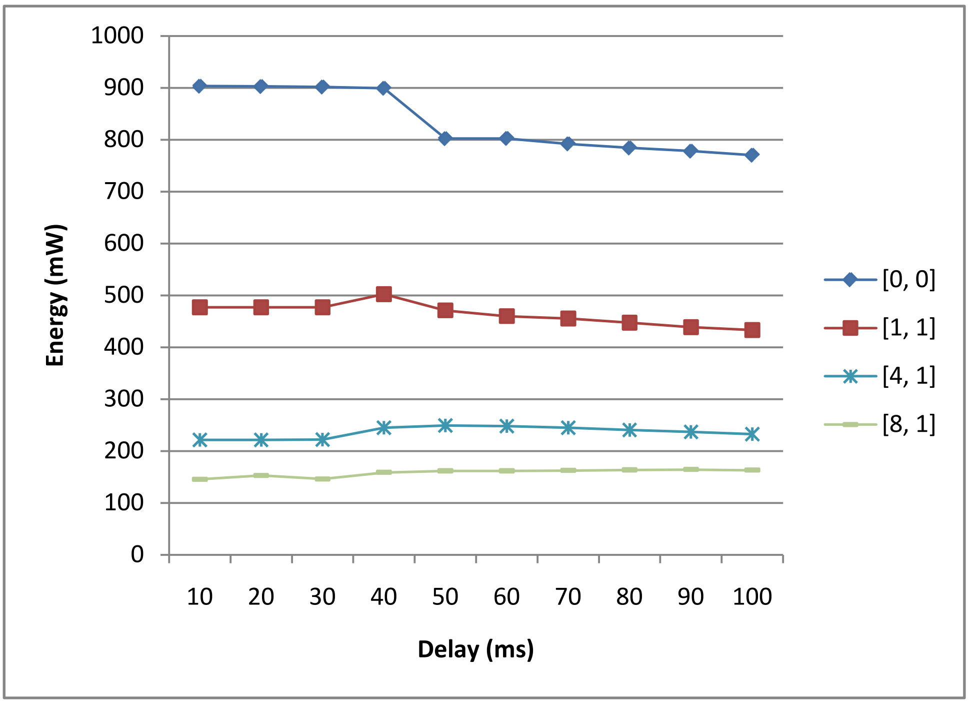

Figure 27: Energy consumption versus delay

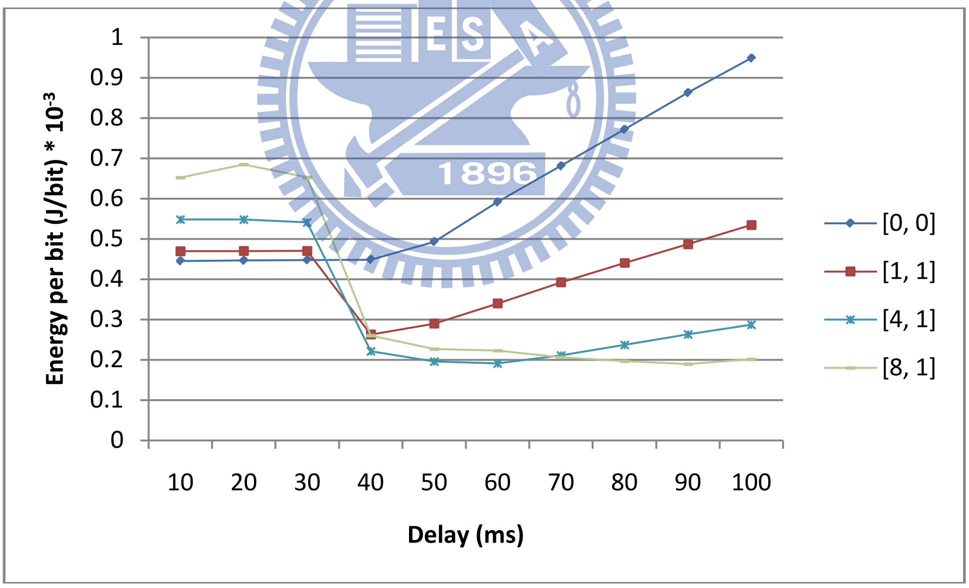

Figure 28: Energy efficiency versus delay

Figure 27 shows the energy consumption of WiMAX versus transfer delay. It is obviously that the energy consumption is related to TCP throughput and sleep intervals. Longer the sleep interval is, less energy consumption uses. Figure 28 presents the energy efficiency versus delay in different length of sleep intervals. We compare the result to previous condition that is only one MSS transmitting. When there is only one MSS connecting to BS, the MSS in interleaving interval always has bandwidth to transfer packets since it is a contention-free environment. That means energy efficiency is only related to transfer delay. However, when there are more MSSs contending the resource and transfer delay is short, it is harder for the MSS contending the resource during interleaving interval. This makes the MSS with sleep mode having less TCP throughput when delay is short (i.e., delay < 40). Therefore, the energy efficiency is not only related to transfer delay but also to number of MSS. To benefit the best energy efficiency gain for TCP transmission over WiMAX, Power Saving Class type II and proxy server are used. Besides, when delay is short, we should set MSS not into sleep mode. When delay is 40 milliseconds, we should set sleep intervals as four frames. When delay is 70 milliseconds, we should set sleep intervals as eight frames. In fact, when transfer delay is long, our proposed approach will outperform traditional always-on approach by 50 percent in terms of energy efficiency.

Chapter 6 Conclusions

In this paper, we establish a simulation environment to evaluate the power consumption of WiMAX interface. Our simulator based on NS2 extends the WiMAX module to support sleep mode and power consumption. Besides, a real WiMAX test-bed is used to obtain the power consumption parameters and models of a WiMAX interface. Then, we investigate the energy consumption of TCP transmission over WiMAX. First, we evaluate the cross layer effects for TCP transmission over WiMAX. Second, the extra energy consumption introduced by WiMAX MAC in transmitting TCP packets also been analyzed. Finally, we evaluate the energy efficiency in different schedule classes for TCP over WiMAX.

Based on simulation results, we observe that When WiMAX is under heavy workload, 18% extra energy is consumed for contending resources for TCP transmission under BE service. TCP transmission with nrtSP service reduces 35% energy consumption comparing with that with BE service when WiMAX is under heavy workload. UGS service achieves the best energy efficiency in transmitting TCP over WiMAX if parameters could be set properly. We apply sleep class II and proxy to TCP transmission over WiMAX could reduce 50% energy consumption that conventional non-sleep approach when network delay is large. To achieve the best energy efficiency by applying sleep class II and proxy, we should depend on the factors of TCP delay and contention.

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