Enhanced Power Efficient Sleep Mode Operation for IEEE 802.16e Based WiMAX

Shengqing Zhu
Department of Electronic and Information
Nanjing University, China

Tianlei Wang
School of Electronic and Information
Engineering South China University of Technology

***Abstract*— To support battery powered mobile broadband wireless access devices efficiently, IEEE 802.16e defines a sleep mode operation for conserving the power of mobile terminals. In this paper we analyze the power consumption and the mean delay of IEEE 802.16e sleep mode operation with a theoretical Markov chain model. The analytical results show that there is a tradeoff between the power consumption and the mean delay, and the key of the tradeoff is the initial sleep window. Then, we present a heuristic algorithm to tune the initial sleep window dynamically according to the traffic load. Extensive simulation results show that the proposed algorithm can improve the power consumption up to 30% compared to the IEEE 802.16e standard. The price is just little increase of the mean delay. Therefore, the proposed algorithm provides a proper tradeoff between the power consumption and the mean delay.**

I. INTRODUCTION

IEEE 802.16e [1] provides enhancements to IEEE Std 802.16-2004 [2] to support subscriber stations moving at vehicular speeds and thereby specifies a system for combined fixed and mobile Broadband Wireless Access (BWA). Taking advantage of the inherent mobility of wireless media, IEEE 802.16e will increase the market for BWA solutions, and it will fill the gap between very high data rate wireless local area networks (WLANs) and very high mobility cellular systems.

In mobile BWA, mobile stations (MS) are usually powered by battery, and therefore power saving is a critical concern in designing the medium access control. In IEEE 802.16e, three power saving classes are defined: type 1 power saving class is recommended for connections of best-effort (BE) and non-real-time variable rate (NRT-VR) traffic; type 2 is recommended for connections of real-time variable rate traffic, and type 3 is recommended for multicast connections as well as for management operations. The basic principle of power saving mechanism is to employ sleep mode operation to minimize MS power usage due to little power consumption in sleep mode. From [1], the sleep mode is characterized by the non-availability of the MS, as observed from the serving BS, to downlink and uplink traffic. When the MS enters into sleep mode, the BS buffers all packets addressed to the MS until it wakes up. From the queueing theory, it is well known that the queueing length in the buffer increases with the sleep interval, and so that packets' end-to-end delay increases with the sleep interval. Therefore, the parameters of sleep mechanism are the keys of tradeoff between power consumption and Quality-of-Service (QoS), which is mainly measured by mean delay.

In the literature, a similar sleep mode operation employed in a cellular digital packet data systems have been investigated in [5] by simulations. For the same system, the authors in [7] developed a queueing model to analyze the packet delay. For the sleep mode operation employed in IEEE 802.16e, there are also some theoretical analysis works [3][4][6]. Among them, [3][4] construct queueing models with multiple vacations to analyze the power consumption and the delay which consists of queueing delay and serving time. Although the queueing models can properly cover all details of the sleep mode operation, they bring costly computation complexity. [6] simplified the calculations for packets' delay by only considering the delay due to the sleep interval but ignoring the queueing delay, but it degrades the accuracy of the model in some degree. Moreover, most research works still stay in the theoretical analysis, but few algorithms for performance improvement are proposed.

In this paper,we develop a simple but precise model, which is capable of obtaining the closed-form expressions of performance measures, to investigate the sleep mode operation of IEEE 802.16e. Furthermore, based on the performance measures, we propose a heuristic algorithm to dynamically tune the parameters of the sleep mechanism to get a proper tradeoff between the power consumption and the mean delay. Extensive simulations are given to evaluate the proposed algorithm.

The rest of this paper is organized as follows. In Section II, we provide a simple description of the considered IEEE 802.16e sleep mode operation. Then, in Section III we present an analytical model to compute the performance metrics of the sleep mode operation. The heuristic algorithm is proposed in Section IV. The performance of the proposed algorithm is validated by extensive simulations in Section V. Finally, the conclusions are drawn in Section VI.

II. SYSTEM DESCRIPTION

In this paper, we address only type 1 power saving class, which is recommended for connections of BE and NRT-VR traffic. Note also that only downlink (from BS to MS) is considered. A typical sleep mode described in IEEE 802.16e [1] is illustrated Fig. 1. Before entering into sleep mode, the MS shall send a MOB-SLP-REQ message to the BS and wait for the approval of BS. The MS comes into the sleep-mode for an interval defined by initial sleep window

1-4244-0957-8/07/$25.00

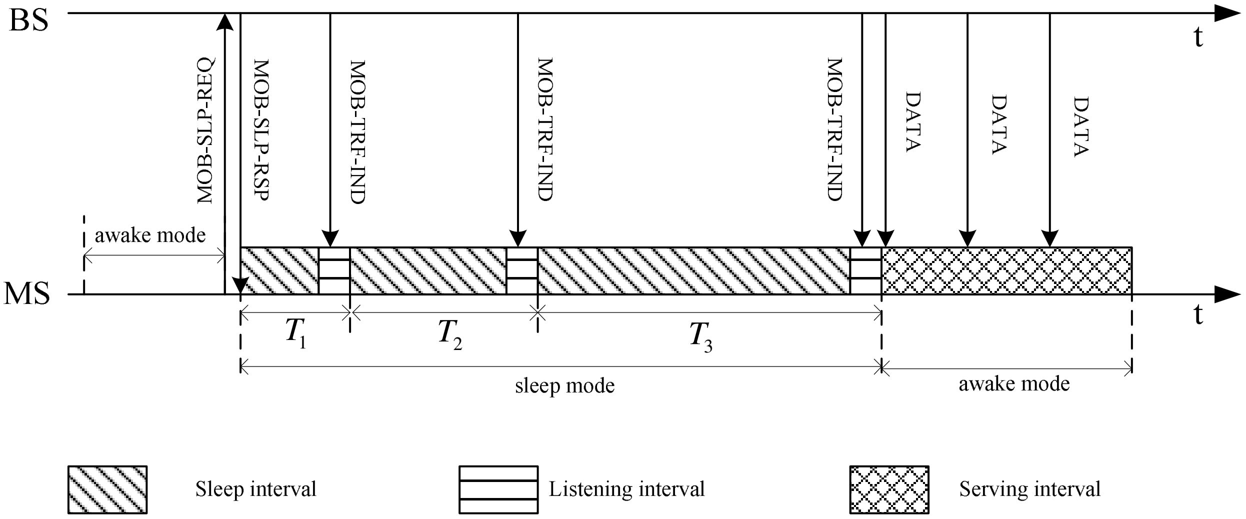

Fig. 1. Illustration of the sleep mode operation in IEEE 802.16e

after receiving an approving MOB-SLP-RSP message, which carries the initial sleep window, listening window, final sleep window exponent, and traffic triggered wakening flag. When sleep interval finishes, the MS wakes up to check whether there are packets for it during the following listen interval. If there are packets addressed to the MS in the buffer of the BS, the MS goes to the awake mode. Otherwise, the MS returns into the sleep-mode again with a new sleep interval, calculated as [1]

$$\begin{aligned}&new\ sleep\ window = \min\{2 \times (previous\ sleep\ window),\\&initial\ sleep\ window \times 2^{(final\ sleep\ window\ exponent)}\}\end{aligned} \tag{1}$$

In the listening interval the BS terminates power saving state of the MS by sending MOB-TRF-IND message in broadcast mode to alert MS of appearance of downlink traffic. When the MS senses a positive MOB-TRF-IND message indication, it stays awake until all packets address to it in the buffer of the BS are received. Herein, an exhaustive access policy [8] is employed, which means that the BS transmits all packets addressed to the MS in its buffer as well as packets arriving to BS during the time the MS receives queued packets.

III. AN ANALYTICAL MODEL

From [3], the listening interval is generally much shorter than the sleep interval, and it is ignored in the analysis. Then, the length of the ith sleep interval, T_i, is given by

$$T_i = 2^i T_b, \qquad 0 \le i \le M. \tag{2}$$

In addition, we assume that the packet arrival process from network to the BS follows a Poisson process with arrival rate λ. The service time of a packet is assumed to be generally distributed with probability density function (pdf) $v(t)$.

The behaviors of an MS working in power saving mode can be described with a bi-dimensional random process $\{s(t), b(t)\}$. Herein, $s(t)$ $(0 \le s(t) \le M)$ represents a stochastic process indicating the sleep stage of the MS at time t ($s(t) = i$ means the MS stays in the ith sleep interval at time t), and $b(t)$ represents the stochastic process indicating the status of the MS at time t ($b(t) = '0'$ means that the MS is sleeping and $b(t) = 's'$ means that the MS is receiving packets from the BS). The state transition diagram of the proposed model is shown in Fig.2.

In Fig.2, β_i represents the transition probability from state $(i, 0)$ to state $(i+1, 0)$ (or from $(M, 0)$ to $(M, 0)$ when $i = M$). Then, we have

$$\beta_i = e^{-\lambda T_i}, \qquad 0 \le i \le M. \tag{3}$$

Correspondingly, the transition probability from $(i, 0)$ to related serving state (i, s) is given by $1 - \beta_i$. Then, we have

$$\begin{cases} p_{i+1,0} = \beta_i p_{i,0}, & 0 \le i \le M-1; \\ p_{M,0} = \dfrac{\beta_{M-1}}{1-\beta_M} p_{M-1,0}; & \\ p_{i,s} = (1-\beta_i) p_{i,0}, & 0 \le i \le M; \\ p_{0,0} = \displaystyle\sum_{i=0}^{M} p_{i,s}. & \end{cases} \tag{4}$$

By means of (4), we obtain

$$\begin{cases} p_{i,0} = p_{0,0} \displaystyle\prod_{m=0}^{i-1} \beta_m, & 1 \le i \le M-1; \\ p_{M,0} = \dfrac{p_{0,0}}{1-\beta_M} \displaystyle\prod_{m=0}^{M-1} \beta_m; & \\ p_{i,s} = (1-\beta_i) p_{0,0} \displaystyle\prod_{m=0}^{i-1} \beta_m, & 0 \le i \le M-1; \\ p_{M,s} = p_{0,0} \displaystyle\prod_{m=0}^{M-1} \beta_m. & \end{cases} \tag{5}$$

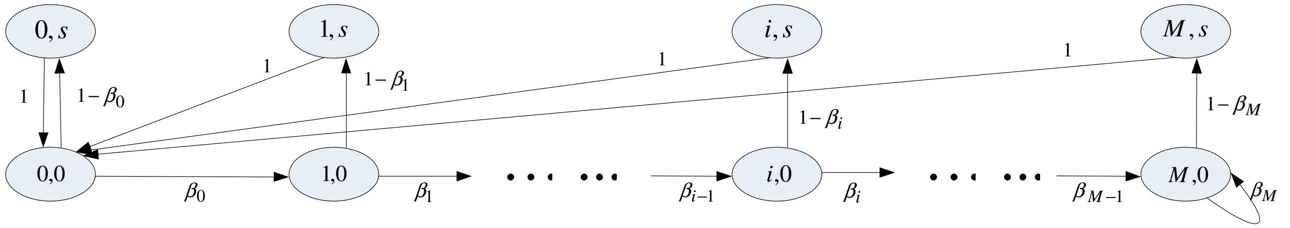

Fig. 2. Markov chain model for the sleep mechanism of IEEE 802.16e

Then, from $1 = \sum_{i=0}^{M}(p_{i,0} + p_{i,s})$, we compute $p_{0,0}$:

$$p_{0,0} = \frac{1}{1+\sum_{i=1}^{M-1}(2-\beta_i)\left(\prod_{m=0}^{i-1}\beta_m\right)+\frac{2-\beta_M}{1-\beta_M}\prod_{m=0}^{M-1}\beta_m} \tag{6}$$

Consequently, the closed-form expressions for all probabilities are calculated from (5).

A. Power Consumption

As mentioned in the introduction, the key purpose of employing sleep mode in IEEE 802.16e is to conserve the power consumption of MS. The power consumption of the MS can be divided into two parts: one is for receiving the expected data packets, and the other is for sleep operation, which consists of sleep, idle listening and switch (from sleep to awake or from awake to sleep). It is worth noting that the first part is decided by the traffic load only and independent of the sleep operation. Let P_s and P_r denote the power consumption for sleep and receiving[1], respectively. Let E_{switch} denote the energy consumption for a pair of switches, which includes a sleep-awake and an awake-sleep. The power consumption for receiving the expected packets is given by ρP_r, where $\rho = \lambda \mathrm{E}[v]$. In addition, the second part of the power consumption can be computed by the probability sum of the power consumption in each state in each state. Based on the analysis above, the total power consumption P_{ps} is given by

$$P_{ps} = \rho P_r + \frac{\sum_{i=0}^{M} p_{i,0}[E_{switch} + P_r T_l + P_s T_i]}{\sum_{i=0}^{M} T_i p_{i,0}} \tag{7}$$

B. Delay

Packets' delay is defined as the time interval from the moment when a packet arrives at the BS till the moment when the packet is successfully received by the related MS. Since packet arrivals follow Poisson distribution, the arrival events are random observers to the sleep intervals. Then, if there are j packets addressed to the MS buffered in the BS after the ith sleep state, the delay averaged over these j packets is given by $\frac{T_i+(j+1)\mathrm{E}[v]}{2}$. During these j packets being served, some new packets may arrive, and during the new arrived packets being served some more packets may arrive, and a such iterative process terminates till no packets arrive during the preceding step. In this way, calculating the mean delay is a complex recursion.

From [9], the energy consumption for the startup procedure (from sleep to awake) is non negligible. Therefore, if the MS works in high traffic load, frequent startups will cost so much energy that such a sleep mode operation is not power efficient[2]. From this standpoint, we only consider the scenario with light traffic load ($\lambda/\mu < 50\%$) where the probability that there are packets available after the first order recursion is very low. To simplify the calculation, we only consider the first order recursion, i.e., all packets except the initial j packets are assumed to arrive during the service time of initial j packets.

From the analysis above, the probability that there are j packets buffered after sleep state $\{i, 0\}$ is given by

$$f_{i,j} = \frac{(\lambda T_i)^j}{j!} e^{-\lambda T_i} \tag{8}$$

If only the first order recursion is considered, the mean number of packets served in the i service state when j packets buffered after $\{i, 0\}$ is given by

$$c_{i,j} = j(1 + \lambda \mathrm{E}[v]) \tag{9}$$

Then, the delay averaged over the packets served in ith service state with j initial packets as

$$d_{i,j} = \frac{1}{c_{i,j}}\left[j\frac{T_i + (j+1)\mathrm{E}[v]}{2} + (c_{i,j} - j)\frac{(c_{i,j} - j + 1)\mathrm{E}[v]}{2}\right] \tag{10}$$

Consequently, the delay averaged over all packets is given by

$$D = \frac{\sum_{i=0}^{M} p_{i,0} \sum_{j=1}^{N} f_{i,j} d_{i,j}}{\sum_{i=0}^{M} p_{i,s}} \tag{11}$$

C. Power Consumption vs. Delay

From (7), given the traffic load, the power consumption varies with the probability that the MS stays in each state, which is determined by the sleep mode parameters T_b and M. With the parameters shown in Table.I, we plot the power consumption versus T_b as Fig.3. It is observed that the power consumption increases with the traffic load, but it decreases with T_b for various traffic loads, which implies increasing T_b is

---

[1] From [9], the power consumptions for idle listening and receiving are nearly the same, and thus we omit the definition of the power consumption for idle listening.

[2] The issue on efficiency of sleep mode operation will be discussed in detail in the next section.

power efficient. However, increasing T_b is not a QoS efficient choice. With the same parameters, we plot the mean delay versus T_b as Fig.4. It is observed that the mean delay decreases with the traffic load but increases with T_b quickly for various traffic load. Therefore, there should be a tradeoff between the power consumption and the mean delay, and the key of the tradeoff is the initial sleep window.

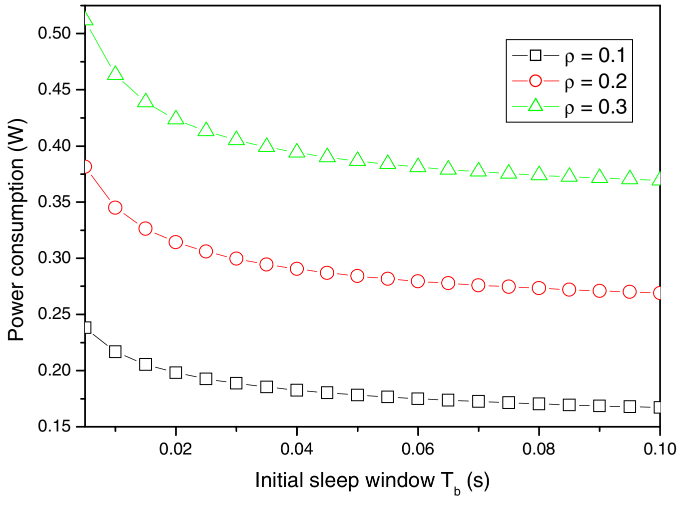

Fig. 3. The power consumption versus initial sleep window

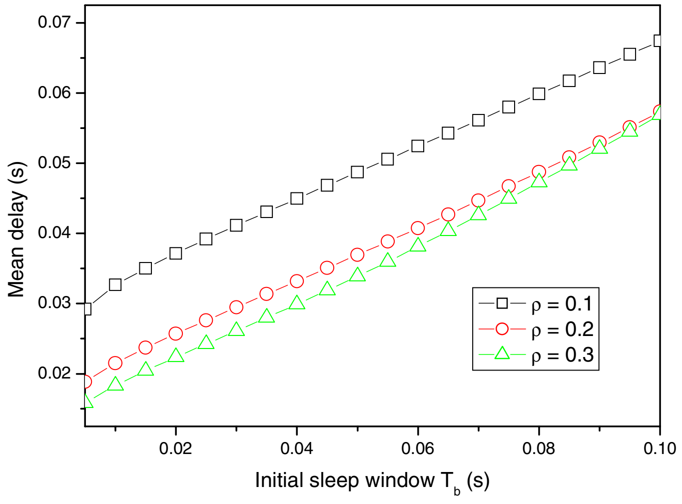

Fig. 4. The mean delay versus initial sleep window

IV. DYNAMIC TUNING OF INITIAL SLEEP WINDOW

In IEEE 802.16e standard, the sleep window reverts to the initial sleep window (T_b) after serving all packets buffered regardless of the traffic load. As shown in Fig.3, a high traffic load leads to high power consumption if the initial sleep window is small. Thus, a traffic-aware initial sleep window tuning should be considered: after serving all packets buffered, the MS revert to an initial sleep window which is dynamically tuned according to the number of packets served. From Fig.4, a high initial sleep window results in high delay, and thus the selection of the initial sleep window should take the effect of delay into account. In addition, the selection set of sleep window is generally fixed in the firmware of the physical layer of IEEE 802.16e devices. Therefore, the initial sleep window selected by the proposed algorithm should also in the feasible set $\{2^i T_b, i = 0, 1, 2, ..., M\}$.

Following the requirement described above, we develop a simple tuning algorithm for the initial sleep window, which is heuristic and tune the initial sleep window according to the traffic load. In this algorithm, after serving all packets in the ith serving state the MS does not enter into the sleep mode with T_b. Instead, the MS employs the initial sleep window T_b^* which depends on the number of packets served in the ith serving state j, i.e.,

$$T_b^* = \begin{cases} T_b, & j \geq 2^i, \\ \dfrac{T_i}{\lfloor \log_2 j \rfloor}, & j < 2^i, \end{cases} \tag{12}$$

where $\lfloor x \rfloor$ represents the maximum integer that is smaller than x.

The update algorithm of the initial sleep window described in (12) is capable of automatically providing a large initial sleep window for high traffic load MS's and a small initial sleep window for low traffic load MS's. With the original standard, high traffic load MS's are power consumption inefficient due to frequently sleep-awake transitions, and a large initial sleep window provided by the proposed algorithm can decrease the power consumption efficiently. Differently, low traffic load MS's suffer from high delay under the original standard, and the proposed algorithm maintains a small initial sleep window so that the delay can be kept within a low level. In a word, the proposed algorithm can achieve a tradeoff between the power consumption and the delay.

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed heuristic algorithm, we implement extensive simulations with the parameters shown in Table.I. The simulation is achieved via discrete event simulation tool NS2 [10]. The simulation time for each scenario is 50 hours, and the results are obtained via averaging values from 10 different runs with different seeds. To the purpose of comparison, the performance of traditional standard is simulated as well, in which the parameters of sleep mode are $T_b = 40ms$ and $M = 5$.

TABLE I

Parameters for Numerical calculation and Simulation

Parameter	**value**
Listening interval T_l (ms)	1
Final sleep window exponent M	5
serving time E$[v]$ (ms)	5
Power consumption for receiving (W)	1
Power consumption for sleeping (W)	0.05
Energy for switching(J)	0.001

We first investigates the performance in power consumption of the proposed algorithm. As shown in Fig.5, the proposed algorithm outperforms the standard in various traffic load. In particular, the performance gain is up to 30% in the region with low traffic load. When the traffic load is high, the performance gain is less than that with low traffic load. This is because that high traffic load makes the MS always stay in the minimum sleep window T_b, which implies the proposed algorithm behaves as the standard.

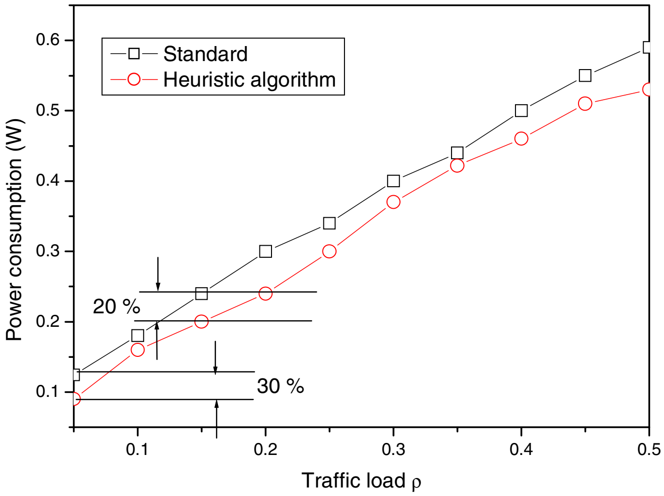

Fig. 5. Power consumption comparison for various traffic load

The performance in mean delay is plotted in Fig.6. It is observed that the mean delay of the proposed algorithm is higher than that of standard for various traffic load, but the gap is very small. The standard enables the MS returns to the minimum sleep window T_b after each serving, and thus it can obtain the minimum mean delay. The proposed algorithm adapts the sleep window to the traffic load, and it is capable of approaching to the mean delay obtained by the standard.

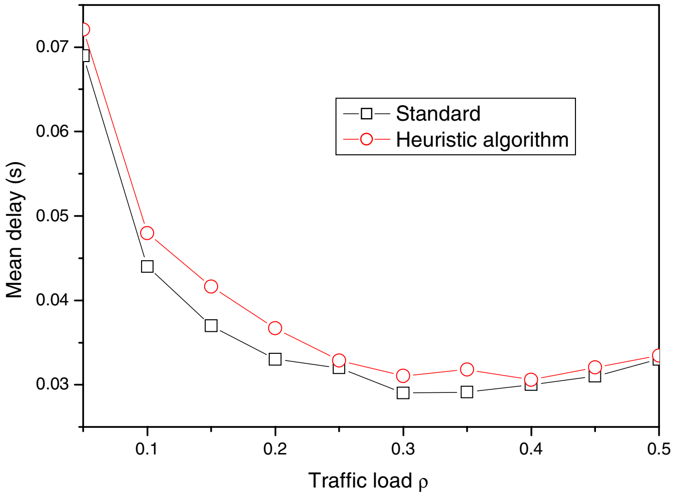

Fig. 6. Meann delay comparison for various traffic load

From Fig.5 and Fig.6, we find that the proposed algorithm can save more power consumption than IEEE 802.16e standard with little increase of mean delay. The proposed algorithm achieves a proper tradeoff between the power consumption and the mean delay.

VI. CONCLUSIONS

In this paper we have presented a simple Markov chain model to investigate the performance of IEEE 802.16e sleep mode operation. This model properly describes the behavior of the MS working in sleep-mode. The analytical results show that the power consumption decreases with the initial sleep window but the mean delay increases with it. Then, a heuristic algorithm, which tunes the initial sleep window dynamically according to the traffic load, was proposed to achieve a tradeoff between the power consumption and the mean delay. Extensive simulation results show that the proposed algorithm can improve the power consumption significantly. The price of the algorithm is just little increase of mean delay.

REFERENCES

[1] IEEE802.16e-2006, IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Broadband Wireless Access Systems C Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, February 2006.
[2] IEEE802.16-2004, IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Broadband Wireless Access Systems, October 1, 2004.
[3] Zhisheng Niu, Yanfeng Zhu, and Vilius Benetis, "A Phase-type Based Markov Chain Model for IEEE 802.16e Sleep Mode and Its Performance Analysis", submitted to INFOCOM 2007, http://network.ee.tsinghua.edu.cn/ zhuyanfeng.
[4] Jun-Bae Seo, Seung-Que Lee, Nam-Hoon Park, Hyong-Woo Lee, and Choong-Ho Cho, "Performance Analysis of Sleep Mode Operation in IEEE 802.16e", VTC2004-Fall, vol. 2, pp. 1169-1173, 26-29 Sept. 2004.
[5] Yi-Bing Lin and Yu-Min Chuang, "Modeling the Sleep Mode for Cellular Digital Packet Data," IEEE Comm. Letters, vol. 3, no. 3, pp. 63- 65, March 1999.
[6] Yang Xiao, "Energy Saving Mechanism in the IEEE 802.16e Wireless MAN," IEEE Communications Letters, vol. 9, no. 7, pp. 595-597, July 2005.
[7] Sun-Jong Kwon, Yun Won Chung, and Dan Keun Sung, "Queueing model of sleep-mode operation in cellular digital packet data", *IEEE Trans. Veh. Tech.*, vol. 52, no. 4, pp. 1158-1162, July 2003.
[8] R. Fantacci and L. Zoppi, "Performance evaluation of polling systems for wireless local communication networks," *IEEE Trans. Veh. Tech.*, vol. 49, no. 6, pp. 2148-2157, November 2000.
[9] Koen Langendoen and Gertjan Halkes, "Energy-Efficient Medium Access Control", Technical report, www.isa.ewi.tudelft.nl/ koen/papers/MAC-chapter.pdf.
[10] K. Fall and K. Varadhan, editors, "ns notes and documentation," The VINT Project, UC BERKELY, LBL, USC/ISI, and Xerox PARC, Nov. 1997.