QOS-AWARE LINK RATE ADAPTATION IN IEEE 802.16 BROADBAND WIRELESS ACCESS SYSTEMS

Yu-Ting Yu
Department of Computer Science
National Chiao Tung University
Hsinchu, Taiwan

Hsi-Lu Chao
Department of Computer Science
National Chiao Tung University
Hsinchu, Taiwan

ABSTRACT

IEEE 802.16 Broadband Wireless Access system (BWA) is a promising emerging technology. In the IEEE 802.16 standard, multiple data transmission rates are defined by employing different modulation and channel coding schemes. How to select a proper mode affects the system performance significantly. In this paper, an efficient link rate adaptation algorithm, named QoS-aware Link Rate Adaptation (Q-LRA), is proposed. Q-LRA takes both QoS demand and channel condition into consideration to determine the best mode. The QoS demand of a connection is represented as packet error rate (PER). Based on the specified PER, the BS calculates the required signal-to-noise ratio (SNR) threshold of each mode. By comparing the measured SNR and all modes' SNR thresholds, the BS suggests the SS the best mode. The performance of Q-LRA is evaluated by simulations. The simulation results show that Q-LRA improves system throughput and guarantees each connection's QoS demand.

I. INTRODUCTION

The recent explosive growth of the Internet raises the demands for higher capacity, higher data rate, and more advanced multimedia services to customers. The IEEE 802.16 standard is designed to support these demands and specifies the WirelessMAX^{TM} air interface [1], [2]. The IEEE 802.16 BWA systems have many advantages, such as rapid deployment, high speed data rate, high scalability, multimedia services, and lower maintenance, and upgrade costs.

The standard addresses systems that operate from 10 GHz to 66 GHz and the physical layers (PHYs) provide multiple data transmission rates by employing different modulation and channel coding schemes. The mechanism to select one out of multiple available transmission rates is referred to as Link Rate Adaptation (LRA) and the effectiveness of the implemented link rate adaptation scheme can affect the system performance significantly [3]. IEEE 802.16 does define a radio link control (RLC) framework to enable the implementation of PHY layer adaptation schemes. This framework includes the message definitions and signal flow for link adaptation. Unfortunately, it does not define a detailed link rate adaptation algorithm.

The goal of this paper is to propose an efficient link rate adaptation (LRA) algorithm for IEEE 802.16 BWA systems, which is based on the perspectives of PHY and network layers. Specifically, an application is assigned a packet error rate (PER) to indicate its QoS demand. According to the specified PER, adopted channel error model, and currently measured signal-to-noise ratio (SNR), the base station (BS) suggests the subscriber station (SS) the best PHY mode. The objectives of our proposed Q-LRA algorithm include improving system throughput and supporting QoS guarantee.

The rest of this paper is organized as follows. Section II introduces the IEEE 802.16 MAC layer as well as the PHY layer, and literature study. The proposed Q-LRA scheme is described in Section III. Section IV presents and discusses the simulation results. Finally, this paper concludes with Section V.

II. AN OVERVIEW OF THE IEEE 802.16 AND RELATED WORK

A. MAC layer

The IEEE 802.16 MAC layer is similar to the MAC layer specifications in the DOCSIS standards [4, 5]. The MAC layer controls medium access on the uplink channel using a Demand Assigned Multiple Access (DAMA) TDMA system. Each SS is periodically granted transmission opportunities by the BS. The BS accepts bandwidth requests from the SSs and grants them on the service agreements, which are negotiated during connection setup. The BS may also designate certain time slots on the uplink that are available for connections of all SSs. The SSs may use these slots to actually transfer data or to request dedicated transmission opportunities. The uplink channel is divided into a stream of mini-slots. The system divides time into physical slots (PS), each with duration of four modulation symbols. An SS that desires to transmit on the uplink requests transmission opportunities in units of mini-slots. The BS accepts requests over a period of time and compiles an allocation MAP message describing the channel allocation for a certain period into the future called the MAP time. The MAP message is then broadcast on the downlink to all subscriber stations. In addition to dedicated transmission opportunities for individual subscriber stations, a MAP message may allocate a certain number of open slots for contention-based transmission. These transmission opportunities are prone to collisions. Collisions are resolved using the truncated binary exponential algorithm.

B. PHY layer

There are four PHY specifications for IEEE 802.16 BWA systems, including WirelessMAN–SC PHY, WirelessMAN–SCa PHY, WirelessMAN–OFDM PHY (OFDM–PHY), and WirelessMAN–OFDMA PHY [1,2]. In this paper, we focus on WirelessMAN OFDM PHY that is based on Orthogonal Frequency Division Multiplexing (OFDM) modulation and designed for non-line-of-sight (NLOS) operation in the frequency bands below 11 GHz.

To support link rate adaptation, the IEEE 802.16 OFDM–PHY provides seven mandatory PHY modes with

1-4244-1144-0/07/$25.00 ©2007 IEEE.

Table I Seven PHY modes of IEEE 802.16 OFDM PHY

Mode	Data rate (Mbps)	Modulation	Bytes per symbol	Overall code rate	RS code (N,K,T)	CC code rate
1	3.9544	BPSK	12	1/2	(12,12,0)	1/2
2	7.9096	QPSK	24	1/2	(32,24,4)	2/3
3	11.8648	QPSK	36	3/4	(40,36,2)	5/6
4	15.82	16-QAM	48	1/2	(64,48,8)	2/3
5	23.7304	16-QAM	72	3/4	(80,72,4)	5/6
6	31.6408	64-QAM	96	2/3	(108,96,6)	3/4
7	35.596	64-QAM	108	3/4	(120,108,6)	5/6

various modulation schemes and coding rates. Details of these PHY modes are listed in Table I.

In OFDM-PHY, the Forward Error Control (FEC) consists of a Reed-Solomon (RS) outer code and a rate-compatible convolutional inner code. The block diagram of FEC operations is shown in Fig. 1, where input data bits are first coded in sequence by the RS encoder and convolutional-code encoder (CC encoder). After been interleaved, these encoded data frames are transmitted on the radio channel with a bit error probability P_c. At the receiving side, a reverse process (including de-interleaving and decoding) is executed to obtain the original data bits. Since the de-interleaving process only changes the order of received data, the bit error probability is intact. When passing through the CC-decoder and the RS-decoder, some errors may be corrected, and thus results in lower error rates (indicated as P_s and P_{be}, respectively). These measures can be used to estimate the wireless link's PER. Detailed PER calculation will be described in Sec. III.

C. Related Work

In the literature, related work for the IEEE 802.16 LRA algorithms are summarized as follows.

A TCP delay-based LRA algorithm for IEEE 802.16-2004 was proposed in [6]. In [6], the SNR switching thresholds for acceptable end-to-end TCP delay of QPSK, 16-QAM, and 64-QAM modulation schemes are determined, through experiment results. An SS selects the best modulation scheme according to the measured SNR value. The drawback of [6] is that it ignores the effect of FEC mechanism. Upon different RS code and CC code, the selected modulation scheme may be mapped to different PHY mode (see Table I). Besides, the corresponding end-to-end TCP delay for a specific SNR value was obtained via a simple scenario, i.e., only one FTP flow between an SS and a BS. This scenario did not take other flows' impact into consideration. Therefore, the suggested switching thresholds may be with error.

[7, 8] focused on the performance evaluation of an IEEE 802.16-2004 based system in jamming environment. The simulation results showed that under the same jamming power, the system throughput of multitone pilot jamming degrades more seriously than that of partial-band jamming. Besides, a mean carrier-to-interference-noise ratio (CINR)-based link rate adaptation scheme was proposed in [7, 8]. When the updated mean CINR is out of the required range of the current PHY mode, the mode will be upgraded or downgraded accordingly. Since [7, 8] used a mean CINR

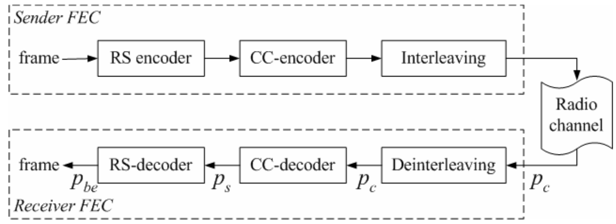


Figure 1 The block diagram of FEC operations

estimator of Exponentially Weighted Moving Average (EWMA) to smoothen the estimated values, the selected and theoretical PHY modes may not be identical (for example, high variance of channel condition).

III. QoS-AWARE LINK RATE ADAPTATION (Q-LRA)

The key design issue of LRA algorithm design is metric determination. The metric is used to decide which PHY mode to switch to and when to do switch. Most of the existing LRA algorithms use the measured SNR value as the metric to select a proper PHY mode. However, SNR parameter is independent of users' QoS requirements. Therefore, our proposed Q-LRA adopts PER, which is specified at the network layer, as the metric to select a PHY mode. Q-LRA consists of two phases: acceptable SNR range derivation and PHY mode selection. Both parts are described as follows.

A. Acceptable SNR range derivation

To derive the SNR thresholds of each PHY mode, we assume fixed packet size and each is with size B. Thus upon a given PER, the corresponding bit error rate P_{be} can be calculated as listed in (1).

$$P_{be} = 1 - \sqrt[B]{(1 - PER)} \tag{1}$$

Through the derived P_{be}, the symbol error rate (i.e., P_s shown in Fig. 1) is further derived as in (2).

$$\sum_{i=T+1}^{n} i \binom{n}{i} P_s^i (1 - P_s)^{n-i} \geq nP_{be}, \tag{2}$$

where T is the maximum number of bits that can be corrected in each RS code block, and n is the number of bits in each block. In addition, the bit error rate (denoted as P_{cb}) before RS-decoding for symbol in GF(2^b) can be derived from P_s by using (3).

$$P_{cb} \geq \frac{1}{b} P_s, \tag{3}$$

where b is a positive integer. In IEEE 802.16 OFDM–PHY, b=8 [1].

To derive the bit error rate (i.e., P_c shown in Fig 1), we need to further calculate the probability that an incorrect path at distance k from the correct path is chosen by the Viterbi decoder, and this probability is denoted as P_k. From [9, 10, 11], P_k is approximated as

$$\sum_{k=d_f}^{d_f+N} (c_k \times P_k) \approx aP_{cb}, \tag{4}$$

where a is the number of bits input into the CC-encoder, d_f is the free distance of the convolutional code in a specific PHY mode, c_k is the number of error bits that occur in all incorrect paths in the trellis that differ from the correct path in exactly k positions.

From [12], the bit error rate p_c can be derived by using (5).

$$p_k = \begin{cases} \sum_{i=(k+1)/2}^{k} \binom{k}{i} p_c^{\,i}(1-p_c)^{k-i}, if\ k\ is\ odd \\ \frac{1}{2}\binom{k}{k/2} P_c^{k/2}(1-P_c)^{k/2} + \sum_{i=k/2+1}^{k} \binom{k}{i} P_c^{i}(1-P_c)^{k-i}, \\ \qquad if\ k\ is\ even \end{cases} \tag{5}$$

Lastly, the P_c can be inputted into the adopted channel error model to obtain the corresponding E_b/N_0 operation threshold of each PHY mode.

In the following, we use Additive White Gaussian Noise (AWGN) channel model as an example to show the obtained operation range of each PHY mode. The settings of N, K, and T values of RS coder are as listed in Table I. We first set PER be 0.1. The required E_b/N_0 thresholds to satisfy PER = 0.1 QoS demand for seven modes are listed in Table II. Thus to have PER=0.1 performance, an SS can operate at mode 2 only when the measured E_b/N_0 is larger than the threshold, i.e., 0.0863 dB. It is interesting that mode 2 has a lower E_b/N_0 threshold than that of mode 1. Similarly, the required E_b/N_0 of mode 4 is smaller than that of mode 3. One possible reason is that we use AWGN model, and this model does not consider some interference and fading phenomenon. Thus the bit error rates of modes 1 and 2 differ slightly. Moreover, the T value of RS code of mode 1 shown in Table I is zero, and this implies that no data byte can be corrected after RS-decoder. Therefore, mode 1 needs better E_b/N_0 to achieve the same PER. Similarly, the CC code rate of mode 3 is higher than that of mode 4, as shown in Table I. That means that mode 4 has better correction rate and require smaller E_b/N_0 to have the same PER performance. Therefore, we need only five PHY modes, i.e., modes 2, 4, 5, 6, and 7, for the case of PER=0.1.

From Table II, we can further adopt 2.4481 dB, 7.0797 dB, 8.9658 dB, and 10.94335 dB as the boundaries to define each mode's acceptable E_b/N_0 range. The obtained acceptable E_b/N_0 ranges are listed in Table III.

The simulated error performances for all PHY modes upon different PER setting are shown in Fig. 2. The x-axis and y-axis are the measured E_b/N_0 and the PER, respectively. Again, modes 1 and 3 need higher Eb/N0 requirements for all PER settings, compared with modes 2 and 4.

B. PHY mode selection

The PHY mode selection has four steps:

(1) An SS informs its BS the required PER of the new service flow i.

(2) Under the adopted channel error model and specified PER requirement, the BS then calculates the corresponding acceptable SNR (denoted as E_b/N_0) ranges of all PHY modes.

Table II E_b/N_0 threshold of each PHY mode upon PER=10^{-1} in AWGN channel.

Mode	1	2	3	4	5	6	7
E_b/N_0 (dB)	0.3535	0.0863	3.8109	2.4481	7.0797	8.9658	10.94335

Table III Acceptable E_b/N_0 range of each reduced mode upon PER=10^{-1} in AWGN channel.

Mode	2	4	5	6	7
E_b/N_0 (dB)	[0, 2.4481)	[2.4481, 7.0797)	[7.0791, 8.9658)	[8.9658, 10.94335)	[10.94335, ∞)

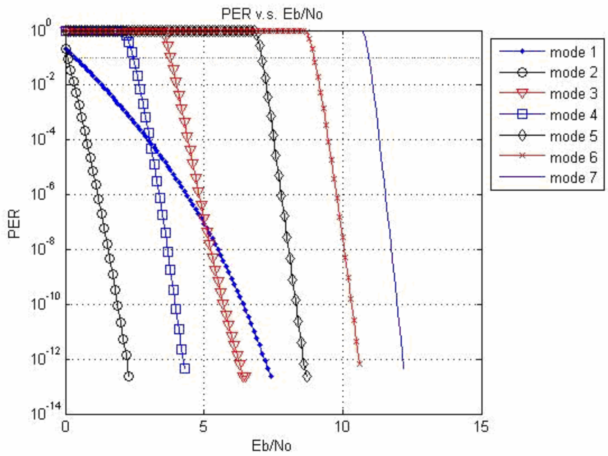


Figure 2 The error performance in the AWGN channel

(3) Comparing the measured E_b/N_0 with the obtained SNR range of each PHY mode, the BS suggests the SS the best one, say mode m.

The BS allocates *Num_slost*[i] slots to the SS according to the supported data rate of PHY mode m (denoted as R_m) and that service flow i's queued data size. *Num_slost*[i] is calculated as in (6).

$$Num\_slot[i] = \frac{data\_queued[i]}{R_m \times T_{slot}}, \tag{6}$$

where T_{slot} is the slot time. Notably that in order to suggest the SS changing the PHY mode timely, the BS must keep monitoring channel condition.

IV. Performance Evaluation

We evaluate our proposed Q-LRA by simulations. We simulate 1000 frames, and frame duration is 10 ms. The control overheads for uplink (UL) and downlink (DL) sub-frames of each mode are based on the suggestions listed in [1, 2], and the data rate of each mode are listed in Table I. Other parameter settings are summarized in Table IV.

There are six scenarios in our simulations:

(1) one BS, five SSs, and 20 connections;

(2) one BS, five SSs, and 25 connections;

Table IV Simulation settings

Parameter	Setting
Channel bandwidth	10 MHz
Packet size	256 bytes
Cyclic prefix size	1/16
Contention slot	10 symbols
Preamble size	2 symbols
FCH size	1 symbol
Viterbi tail	1 symbol

(3) one BS, five SSs, and 30 connections;
(4) one BS, ten SSs, and 20 connections;
(5) one BS, ten SSs, and 30 connections;
(6) one BS, ten SS, and 40 connections.

All SSs has at least one connection and each connection is randomly assigned a PER from [0.05, 0.1, 0.15, 0.2, 0.25, 0.3]. adopt AWGN as the channel model.

The measured channel quality is uniformly distributed within [0, 30 dB]. Again, we adopt AWGN as the channel model.

The performance metrics measured in the simulation include:

(1) system throughput (φ): defined as the ratio of the number of successfully transmitted data bits to the simulation time.

(2) satisfaction ratio (η): the percentage of connections whose QoS demands (i.e., PER) have been satisfied. Indeed, the PER of a connection is the ratio of the number of failed packets to the number of transmitted packets.

The simulation results for system throughput and satisfaction ratio of both scenarios are summarized in Table V, where mode *i* scheme (*i*=1, 2, …) indicates the SS always operates at PHY mode *i*, no matter channel quality. We found that Q-LRA has the largest throughput, followed by modes 7, 6, 5, 4, 3, 2, and 1. For satisfaction ratio, Q-LRA outperforms others (with η=1.0000 for all scenarios). However, modes 1 and 2 have similar satisfaction ratio; modes 3 and 4 have similar satisfaction ratio. It is interesting that mode 6 performs better than mode 7 in satisfaction ratio. To illustrate the reason clearly, we extract the first 70-ms (i.e., short term performance) simulation results of scenario 6 and show the data rates vs. E_b/N_0 values in Figs. 3(a) and 3(b). In Fig. 3(a), the blue curve represents the Q-LRA performance. The key characteristic of Q-LRA is that an SS will update the PHY mode when channel quality changes. Thus at time 20-ms, the channel quality gets worse from 17.4 dB to 2.7 dB (see Fig. 3(b)), and Q-LRA changes operation mode from mode 7 to mode 2. Contrarily, channel quality (2.7 dB) is much below mode 7's operation threshold, operating at mode 7 incurs lots of transmission failures for about 4.5 ms, and thus the average throughput degrades and average satisfaction ratio increases. When channel condition recovers, Q-LRA selects mode 7 again. Thus Q-LRA has more consistent performance compared with mode 7. In other words, the proposed Q-LRA scheme can guarantee connections' QoS demands and improve system throughput simultaneously.

Table V. Simulation results of average system throughput and average satisfaction ratio

Scenario	Scheme	Q-LRA	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
1	φ	25.7633	3.3088	6.5937	8.8000	11.7419	15.1132	17.4832	19.4390
	η	1.0000	0.8125	0.8125	0.7313	0.7313	0.6250	0.5375	0.5375
2	φ	25.7341	2.8865	5.6335	7.3016	10.5336	14.1322	18.8211	19.4952
	η	1.0000	0.6960	0.6960	0.6040	0.6400	0.5880	0.5840	0.5440
3	φ	25.6918	2.6407	5.2158	7.1719	9.7571	13.4516	17.6492	19.5801
	η	1.0000	0.6185	0.6185	0.5852	0.5852	0.5482	0.5444	0.5333
4	φ	24.4660	2.6483	5.2602	7.5760	10.1476	12.7935	16.9060	17.5557
	η	1.0000	0.6313	0.6313	0.6125	0.6125	0.5188	0.5188	0.4688
5	φ	24.2739	2.8629	5.6305	7.8652	10.8012	12.7924	16.3161	18.0436
	η	1.0000	0.6704	0.6704	0.6148	0.6370	0.5037	0.4852	0.4741
6	φ	24.2680	2.9810	6.0126	8.3522	11.6148	15.4952	19.9781	21.4400
	η	1.0000	0.7350	0.7525	0.6900	0.7175	0.6450	0.6150	0.5900

V. CONCLUSIONS

In this paper, we have proposed an efficient link rate adaptation algorithm, i.e., Q-LRA, for a BS to suggest an SS the best PHY mode. Instead of only considering channel quality, Q-LRA takes both QoS demand and channel condition into consideration to determine the best PHY mode. We use PER as the indicator of a connection's QoS demand. Based on the specified PER, the BS calculates the required E_b/N_0 threshold of each mode, and suggests the SS the best mode. The simulation results show that Q-LRA achieves both improving average system throughput and guaranteeing each connection's QoS demand.

VI. ACKNOWLEDGEMENT

This work was supported in part by National Science Council under grant NSC95-2219-E-009-014-, in part by the National Science Council under grant NSC-95-2221-E-009-019, and in part by the Intel Research Council.

REFERENCES

[1] IEEE 802.16-REVd/D5-2004, "IEEE Standard for Local and Metropolitan Area Networks–Part 16: Air Interface for Fixed Broadband Wireless Access Systems," May 13, 2004.

[2] IEEE 802.16e/D5-2004, "IEEE Standard for Local and Metropolitan Area Networks–Part 16: Air Interface for Fixed Broadband Wireless Access Systems–Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands," Sept. 18, 2004.

[3] A. Maharshi, L. Tong, and A. Swami, "Cross-layer design of multichannel reservation MAC under Rayleigh fading," IEEE Transactions on Signal Processing, Vol. 51, No. 8, Aug. 2004, pp. 2054–2067.

[4] http://www.cablemodem.com/specifications/

[5] D. Fellows and D. Jones, "DOCSISTM cable modem technology," IEEE Communication Magazine, Vol. 39, No. 3, Mar. 2001, pp. 202–209.

[6] S. Ramachandran, C. W. Bostian, and S. F. Midkiff, "A Link Adaptation Algorithm for IEEE 802.16," in Proceedings of the IEEE Wireless Communications and Networking Conference, Mar. 2005, pp. 1466–1471.

[7] Nai'an Liu, Dechun Sun, Wuqiang Li, and Changxing Pei, "A link adaptation solution to IEEE 802.16d WMAN," in Proceedings of the

IEEE 7th International Conference on Parallel and Distributed Computing Applications and Technologies, Dec. 2006, pp. 29–32.

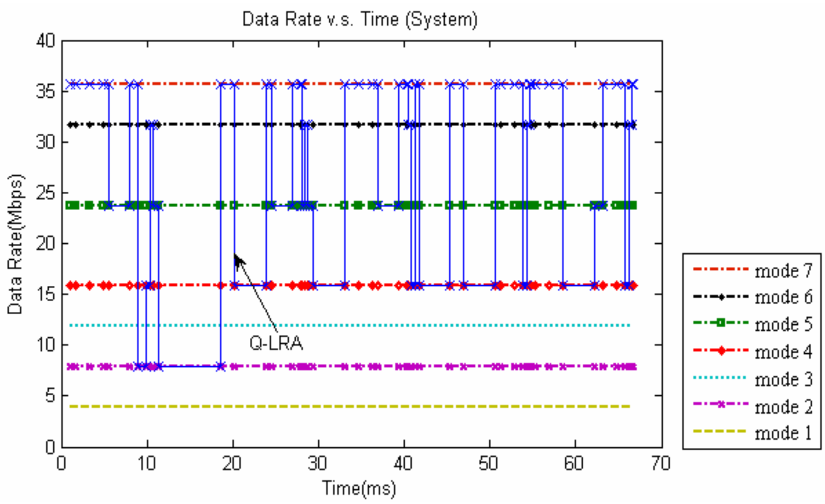
[8] Juan Li and Sven-Gustav Haggman, "Performance of IEEE802.16-2004 based system in jamming environment and its improvement with link adaptation," in Proceedings of the IEEE 17th International Symposium on Personal Indoor and Mobile Radio Communications, Sept. 2006, pp. 1–5.

[9] Daji Qiao, Sunghyun Choi, and K.G. Shin, "Goodput analysis and link adaptation for IEEE 802.11a wireless LANs," IEEE Transactions on Mobile Computing, Vol. 1, No. 4, Oct. –Dec. 2002, pp. 278–292.

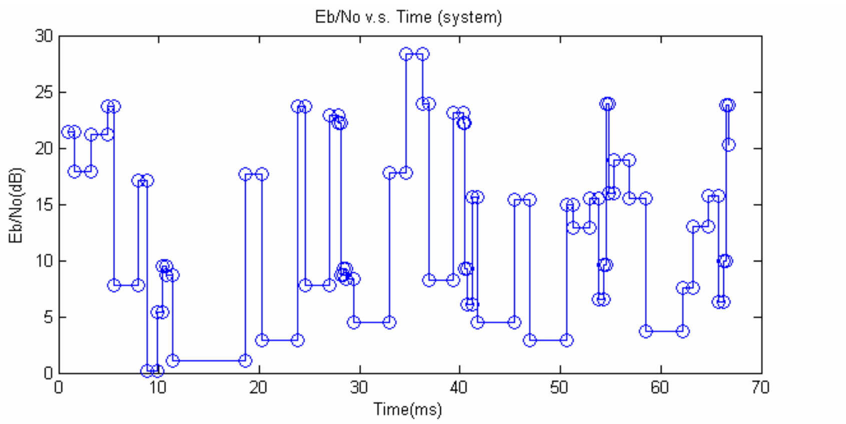
[10] David Haccoun, "High-rate punctured convolutional codes for Viterbi and sequential decoding," IEEE Transactions on Communications, Vol.37, No.11, Nov. 1989, pp. 1113–1125.

[11] P°al Frenger, P°al Orten, and Tony Ottosson, "Convolutional codes with optimum distance spectrum," IEEE Communications Letters, Vol. 3, No. 11, Nov. 1999, pp.317-319.

[12] Greg M. Chiasson and Michael B. Pursley, "Concatenated coding for frequency-hop packet radio," in Proceedings of the IEEE Military Communications Conference, Nov. 1991, pp. 1235–1239.



(a) Adopted data rate for all schemes



(b) Measured E_b/N_0 vs. time

Figure 3 Short-term (the first 70-ms) simulation results