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Abstract

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Performance Improvement for Multichannel HARQ Protocol in Next Generation WiMAX System

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***Abstract*—Hybrid automatic repeat-request (HARQ) is critical to an IEEE 802.16e OFDMA network, as it can significantly improve the reliability of wireless link. However, as revealed by our simulation, the maximum number of parallel HARQ channels defined in the current system will render a potential bottleneck and preponderantly limit the overall system capacity of next generation WiMAX network, wherein the wireless link is anticipated to support much higher data rate. Moreover, the current IEEE 802.16 standard fails to tap into the considerable synergy inherent in HARQ and MAC layer fragmentation, as these two schemes have been designed separately. In order to enhance the throughput performance and improve the preparedness of multichannel HARQ protocol for adoption by future 802.16j and 802.16m system, we then propose two remedies, namely expansion of ACID field and an adaptive fragmentation scheme[1]. The performance evaluation results further confirm that the ACID expansion readily *doubles* the link level throughput, while the adaptive fragmentation can effectively stave off the dismal degradation that plagues the IEEE 802.16e HARQ protocol in high bit error rate regime[2]. Equally importantly, the two proposed schemes substantially reuse the existing mechanisms in the current 802.16 standard and only incur diminutive additional complexity, thereby speeding up the possible acceptance and implementation of the technology.**

***Index Terms*—Multichannel hybrid ARQ, fragmentation, IEEE 802.16, WiMAX, cross-layer design**

I. INTRODUCTION

IEEE 802.16 [2] [3] recently has gained tremendous momentum in industry as a primary technology for broadband wireless access (BWA). In the year of 2006 alone, the commitment to WiMAX [4] deployment pledged by service providers within United States has already totaled 4 billion USD [5] [6].

In order to provide reliable high-speed broadband wireless services, IEEE 802.16 has resorted to a large number of advanced technologies in both physical (PHY) and medium access control (MAC) layer. Amongst them, hybrid automatic repeat-request (HARQ) [7] [8] is an error control mechanism that combines MAC layer automatic repeat-request (ARQ) with PHY layer forward error correction (FEC) coding to improve the reliability of packet transmission. Albeit only an optional feature in the OFDMA-based IEEE 802.16e PHY, HARQ has been mandated by WiMAX profile [9], given the critical role it plays in ensuring robust transmission over unpredictable wireless channel. Another important feature specified in the IEEE 802.16 standard is fragmentation, which is a well-known technique conventionally used at the MAC layer to help adapt to the changing link condition and utilize the wireless channel resource in a more efficient manner.

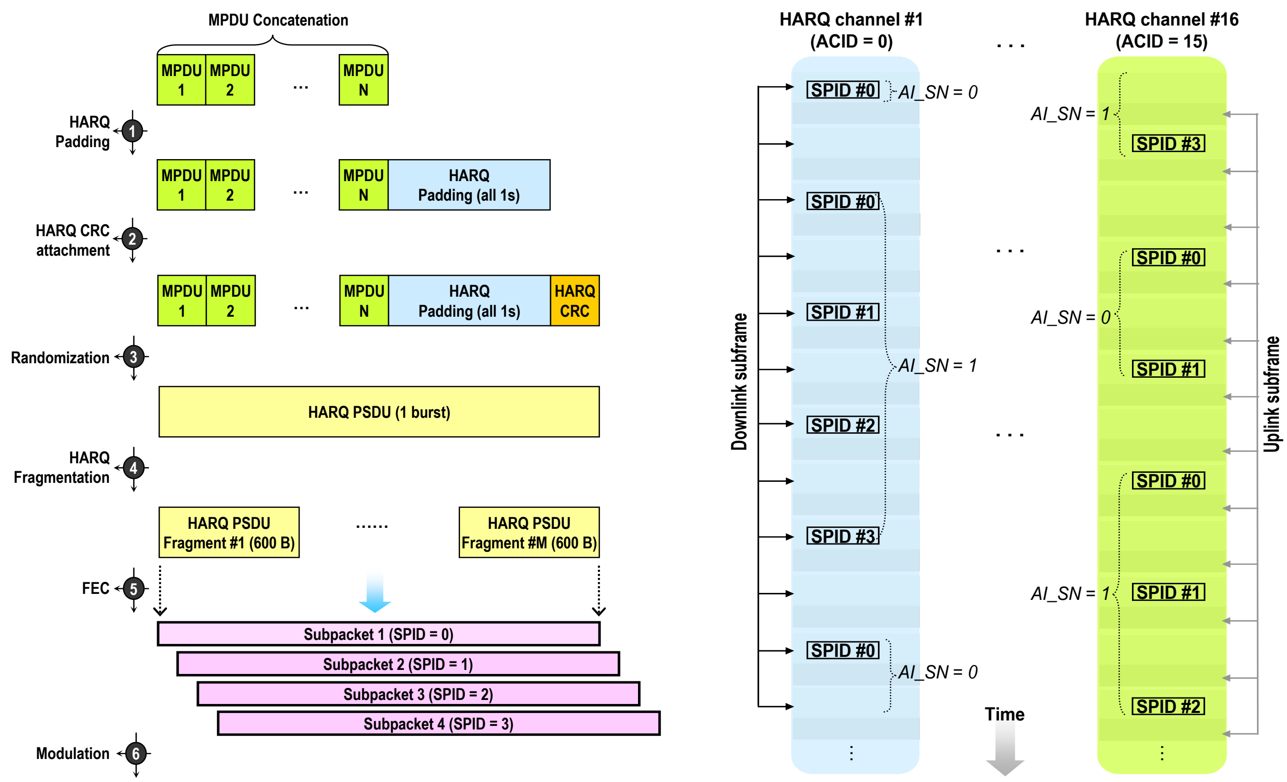
Since HARQ in the current IEEE 802.16e [3] standard was initially devised to meet the need of a single hop network with an approximate link capacity of 46Mbps [10], it is far from optimal for the next generation 802.16 system, wherein wireless link is anticipated to enjoy a much higher transmission rate. In IEEE 802.16j [11] system, for instance, the *relay* link that connects two relay stations (RSs) or an RS and a base station (BS) is expected to experience a better channel quality than the *access* link between a mobile station (MS) and the BS, and thus can sustain a higher data rate. Meanwhile, the future IEEE 802.16m network has been required to deliver a substantially more throughput (e.g., 100Mbps) as compared to the legacy 802.16e from day one [12]. Moreover, the current IEEE 802.16 standard also fails to tap into the considerable synergy inherent in HARQ and MAC layer fragmentation, as these two schemes have been designed separately.

In this paper, we first evaluate the current HARQ protocol, and identify potential bottleneck in the context of next generation 802.16 network. Based upon this study, we propose a simple yet efficient remedy to ameliorate the performance bottleneck, and enable HARQ to deliver the throughput demanded by future system. Furthermore, we follow a cross-layer approach and design an adaptive fragmentation scheme for HARQ, which, by leveraging the synergy between the MAC and HARQ fragmentation, can further improve the performance. Since this new adaptive fragmentation scheme substantially reuses the channel measurement and reporting, HARQ and MAC level fragmentation function already provided by the current IEEE 802.16 standard, it only incurs diminutive additional complexity in implementation.

The rest of the paper is organized as follows. To supply the necessary background, Section II first briefly describes the HARQ protocol and MAC level fragmentation specified in the OFDMA-based IEEE 802.16e standard [3]. In Section III, the current HARQ protocol is evaluated, and potential performance bottlenecks identified. Based upon the observation made therein, we further propose and evaluate two remedies, namely expansion of ACID field and an adaptive fragmentation

[1] Some concepts and results contained herein have been previously presented at IEEE 802.16 standard meeting in January 2007 as a part of Mitsubishi Electric's proposal for IEEE 802.16j [1].

[2] Anfei Li worked on this study while visiting Mitsubishi Electric Research Lab, Cambridge, MA.



(a) HARQ process defined in 802.16e [3].

(b) Multichannel HARQ.

Fig. 1: Illustration of HARQ operation defined in OFDMA-based IEEE 802.16e.

scheme for HARQ in Section III-A and III-B, respectively. Finally, the conclusion is provided and future work discussed in Section IV.

II. Background and Motivation

A. HARQ in IEEE 802.16e

At the physical layer of IEEE 802.16e [3], two distinct modes, namely chase combining (CC) and incremental redundancy (IR), have been defined for HARQ, aiming to achieve simple redundancy and additional coding gain, respectively. Meanwhile, a *multichannel* stop-and-wait mechanism is used by HARQ at the MAC layer to provide automatic repeat-request (ARQ) capability.

As shown in Figure 1(a), the MAC protocol data unit (MPDU) [13] or a concatenation of multiple MPDUs handed down to the HARQ layer is first padded, if necessary, so that the resultant MPDU or MPDU concatenation falls into the permissible set {4, 10, 16, 22, 34, 46, 58, 118, 238, 358, 598, 1198, 1798, 2398, 2998} bytes (i.e., step 1). A two-byte cyclic redundancy check (CRC-16) field is then appended at the end, yielding a data unit of length in the set {6, 12, 18, 24, 36, 48, 60, 120, 240, 360, 600, 1200, 1800, 2400, 3000} bytes (i.e., step 2). After randomization (i.e., step 3), the HARQ physical service data unit (PSDU) is generated, which then is divided into one or multiple of 600-byte long fragments before the FEC coding is applied on each individual HARQ fragment. This HARQ fragmentation is needed, since the maximum data unit the FEC coding can handle at one time is of 600 bytes. Regardless of whether HARQ fragmentation occurs or not, four subpackets are created for each HARQ PSDU in the end, which are modulated and transmitted to receiver.

For the sake of clarity, we will call the HARQ PSDU *encoder packet* in the ensuing discussion, which includes the original MPDU or concatenated MPDUs, appended HARQ CRC-16 field and optional padding bits. A subpacket identifier (SPID) is used to uniquely identify four subpackets generated by the incremental redundancy HARQ mode. No such identification is needed for chase combining, as all the subpackets associated with one encoder packet are the same in CC mode.

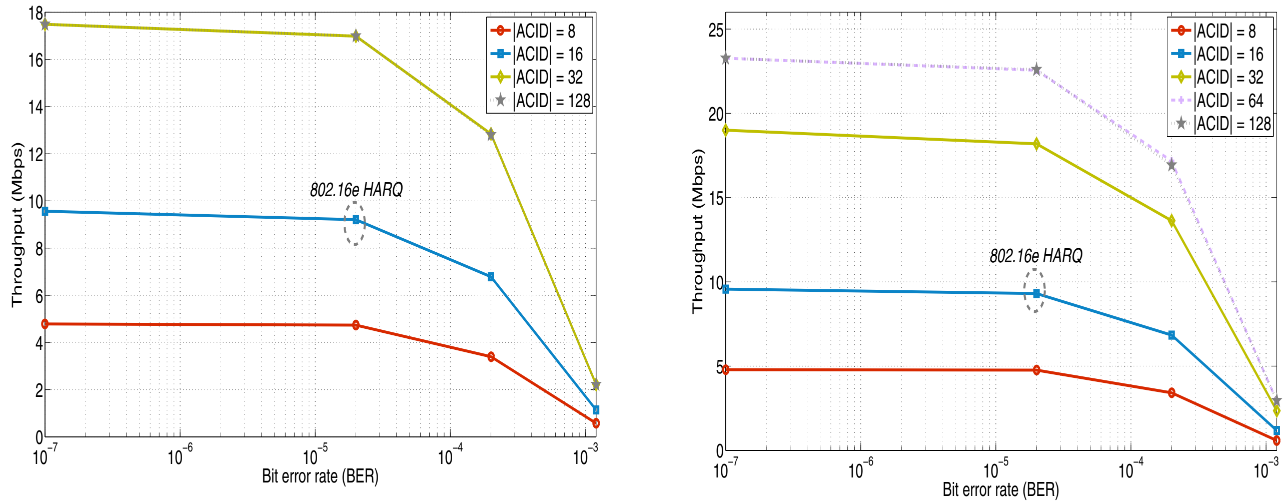
When the receiver cannot decode the first subpacket, it indicates the failure to the transmitter by sending a negative acknowledgment (NAK) in the subsequent subframe. Consequently, the transmitter selects another subpacket out of the four subpackets and transmits it to the receiver. The retransmission continues until either the receiver decodes the encoder packet correctly, or the transmission of all four subpackets fails, which in either way completes one HARQ process for the encoder packet.

If the encoder packet is not successfully delivered to the receiver after one HARQ process, it is up to the higher layer protocol (e.g., ARQ at MAC) whether or not to initiate a retransmission of the lost data at the respective layer.

As demonstrated in Figure 1(b), the multichannel stop-and-wait ARQ adopted by IEEE 802.16e HARQ enables it

TABLE I: Key PHY and MAC parameters

DL/UL Permutation	FFT size	Channel bandwidth	MCS (MAP and preamble)	Cyclic prefix
PUSC	1024	20 MHz	QPSK 1/2	1/32
Sampling factor (n)	Period for UCD/DCD	Frame duration	RTG	TTG
28/25	every 10 frames	20 ms	10 μs	10 μs



(a) IEEE 802.16j link

(b) IEEE 802.16m link

Fig. 2: Impact of ACID on HARQ performance (ARQ window size = 1024)

to transport consecutive MPDUs or concatenated MPDUs belonging to the same MAC connection over a wireless link in a parallel manner by using multiple HARQ *channels*. Each such channel is essentially a stop-and-wait HARQ instance, and can be uniquely identified by an ARQ channel identifier (ACID). Since ACID in current IEEE 802.16e only has *four* bits, it can at most support *16* parallel HARQ channels. In addition, an ARQ identifier sequence number (AI_SN) is associated with each encoder packet within the same HARQ channel, and shall toggle between zero and one for consecutive encoder packets.

B. MAC Fragmentation in IEEE 802.16

In order to achieve efficient use of available bandwidth relative to the QoS requirements of a connection's service flow, a MAC service data unit (MSDU) [13] can be fragmented and consequently produce multiple MPDUs in IEEE 802.16e [3]. Note that whether or not to fragment the traffic belonging to a particular connection is negotiated during the connection establishment process, although capabilities of fragmentation and reassembly are mandatory at each station.

III. HARQ Performance and Improvement

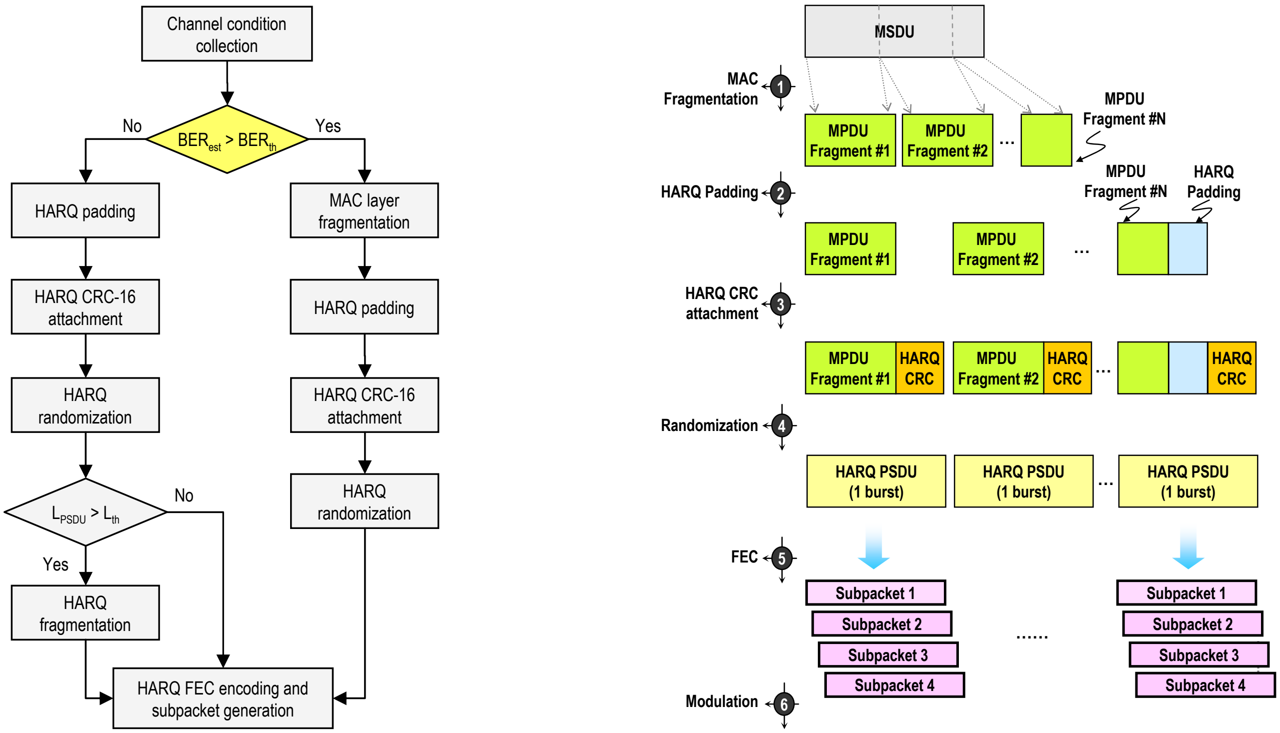
Extensive simulations have been conducted to evaluate the performance of the IEEE 802.16e HARQ protocol. To concentrate on the HARQ protocol itself, perfect scheduling and link adaptation [14] [15] are assumed. Moreover, suppose each MS has only *one* transport connection, which has infinite traffic supply and thus always has packets with length of 1500 bytes to transmit during the OFDMA resource blocks assigned to it. Other key PHY and MAC parameters used in evaluation are summarized in Table I.

A. HARQ ACID Expansion

The performance of the multichannel HARQ protocol on an 802.16j and 802.16m link is presented in Figure 2(a) and 2(b), respectively. The 64 QAM modulation with 3/4 coding rate is used on 802.16j relay link, while 100Mbps link rate has been assumed for an 802.16m system.

Use $|ACID|$ to denote the maximum number of parallel transmissions supported in the system, which is essentially equal to the maximum ACID value plus one. Figure 2(a) and 2(b) clearly indicate that the throughput of multichannel HARQ continues increasing as $|ACID|$ grows, and becomes saturated when $|ACID|$ reaches 32 and 64 for 802.16j and 802.16m link, respectively. This evidently suggests that the multichannel HARQ protocol with a 4-bit long ACID field will fail to fully leverage the abundant capacity provided by the underlying wireless link in 802.16j and 802.16m network, as it severely limits the possible parallel HARQ transmissions. In order to further confirm our findings, we have simulated the current HARQ protocol with a large number of other protocol parameters (e.g., various ARQ window size), and obtained similar observation. Due to the space limitation, however, these simulation results will not be presented here.

In order to remedy its inability to tap into the bandwidth



(a) Flowchart.

(b) Protocol illustration.

Fig. 3: Proposed adaptive fragmentation for HARQ.

available in the next generation WiMAX system, it is imperative to expand the ACID field. Figure 2 readily confirms that the HARQ throughput can be easily *doubled*, if the maximum number of HARQ channels is increased to 128. On the other hand, when $|ACID|$ grows above 128, only diminishing throughput gain can be reaped, which cannot justify the additional buffer needed to support this further parallization of HARQ operation. Based upon this study, we recommend to expand the ACID field to *6* bits for both 802.16j and 802.16m system in order to support at most *128* parallel HARQ transmissions.

B. Adaptive Fragmentation

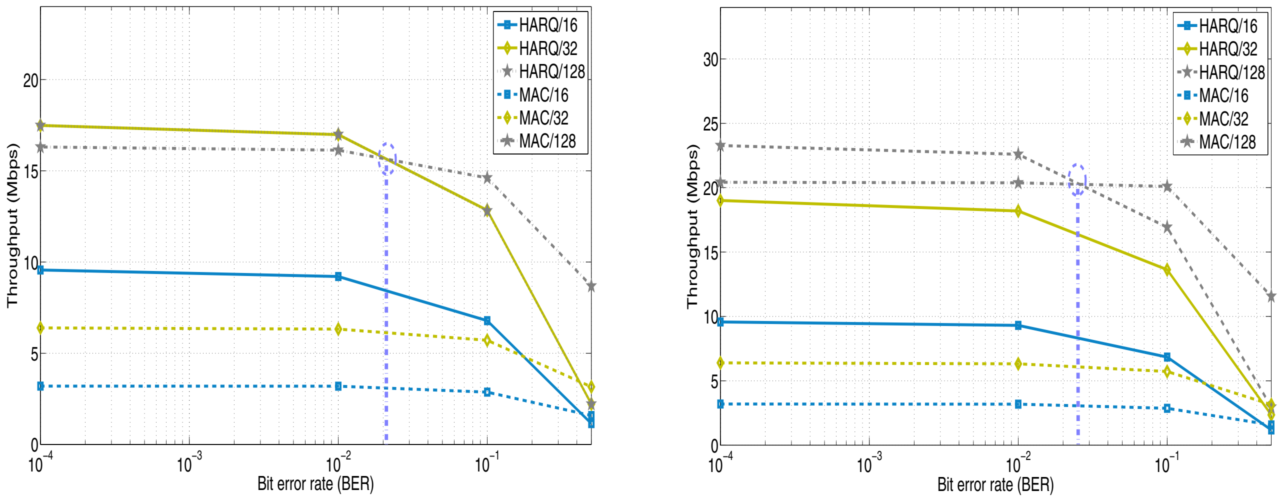
As described in Section II-A and II-B, fragmentation may occur both at MAC layer and during the HARQ process, thereby potentially causing unnecessary duplicate processing and resulting in additional overhead. In order to further streamline the HARQ operation, we propose an adaptive fragmentation scheme in this section. By leveraging the considerable synergy inherent in HARQ and MAC layer fragmentation, the proposed adaptive fragmentation scheme can significantly improve the performance of the HARQ protocol in the context of next generation WiMAX network.

For the sake of simplicity, the description of the adaptive fragmentation for HARQ will focus on MPDU without concatenation. Nevertheless, as it will become apparent later on, the proposed scheme can be applied on concatenated MPDUs directly.

1) Basic Operation: In our proposed adaptive fragmentation scheme, station continuously monitors the channel quality. As shown in flowchart 3(a), if it experiences a grave channel condition, the station shall apply fragmentation on an MSDU at MAC layer. Otherwise, the station shall simply attach a generic MAC header (GMH) [3] in the front and an optional MAC layer CRC-32 at the end of the MSDU, respectively, and pass the constructed MPDU to the legacy HARQ process, wherein HARQ PSDU may be fragmented before FEC encoding. The decision of whether the fragmentation shall be performed at MAC layer or not can be made based upon the physical layer channel state information (e.g., bit error rate) or history of HARQ transmissions (e.g., packet error rate), which anyway has to be collected in the legacy IEEE 802.16e.

As illustrated in Figure 3(b), each resultant MPDU fragment except the last one shall be of the size of 598 bytes, if fragmentation occurs at MAC layer. Once entering the HARQ process, the last fragment may need to be padded so that the resultant MPDU fragment has a length in the allowable set {4, 10, 16, 22, 34, 46, 58, 118, 238, 358, 598} bytes. Thus, all the MPDU fragments will automatically become 600 bytes long, after the HARQ CRC is attached, thereby obliviating the need to fragment them in HARQ. Subsequently, each resultant HARQ PSDU is randomized and FEC encoded, generating four subpackets in the end.

2) Performance Evaluation: Figure 4(a) and 4(b) compare the performance of MAC layer fragmentation and HARQ fragmentation, when channel error rate increases on an 802.16j



(a) IEEE 802.16j link

(b) IEEE 802.16m link

Fig. 4: Performance of adaptive fragmentation for HARQ (ARQ window size = 1024)

link and 802.16m link, respectively. The label "X/Y" for each curve in the figures represents that the fragmentation is performed at "X" (i.e., MAC or HARQ) level, and the $|ACID|$ permitted in the system is Y.

For a given $|ACID|$ value Y, it is evident in Figure 4(a) that the throughput of HARQ fragmentation is always higher than that of MAC level fragmentation, when channel bit error rate is lower than a certain threshold $BER_{th}(Y)$. Meanwhile, once the channel quality deteriorates below $BER_{th}(Y)$, MAC level approach then outperforms the HARQ fragmentation.

For small $|ACID|$, the throughput curves for MAC and HARQ fragmentation intersect only when bit error probability drops to a dismal level. However, once the channel quality witnesses such a grave degradation, link adaptation [15] [14] normally will start to lower the modulation and coding scheme accordingly, thereby rendering it highly unlikely for a system to operate in such a high bit error rate regime.

Nevertheless, this observation by no means declares that the proposed adaptive fragmentation cannot find its application in a real network. On the contrary, for the optimal $|ACID|$ for next generation WiMAX network (i.e.,128) suggested in Section III-A, Figure 4(a) clearly reveals that an adaptive fragmentation can stave off a substantial throughput deterioration and help system deliver a steady high performance over a wider range of bit error rate. Simulation has also been performed for other ARQ window size (e.g., 2048) and similar throughput improvement has been observed. Moreover, it has been found via simulation that the threshold value $BER_{th}(128)$ for the optimal $|ACID|$ remains approximately the same for different ARQ window sizes.

The throughput results for an IEEE 802.16m link are depicted in Figure 4(b), wherein the performance gain of adaptive fragmentation for corresponding $|ACID|$ is also evidently demonstrated. On an 802.16m link, moreover, our simulation again shows that the threshold $BER_{th}(128)$ for adaptive fragmentation is insensitive to ARQ window size.

For 802.16j and 802.16m system, therefore, a corresponding threshold $BER_{th}(128)$ can be stored at a station and used to determine at which layer shall a packet be fragmented. The agnosticity to other system parameters is a highly desirable feature of this proposed adaptive fragmentation scheme, and can further corroborate its feasibility of implementation.

IV. Conclusion and Future Work

In this paper, we have simulated the multichannel HARQ protocol defined in 802.16e standard and discovered that the maximum number of parallel HARQ channels (i.e., $|ACID|$) supported by the current system will render a potential bottleneck and preponderantly limit the overall system capacity of the next generation WiMAX network, given the wireless link therein is anticipated to support a much higher data rate. Moreover, the current IEEE 802.16 standard fails to tap into the considerable synergy inherent in HARQ and MAC layer fragmentation, as it has designed these two schemes separately.

In order to enhance the throughput performance and improve the preparedness of multichannel HARQ protocol for its adoption by the future 802.16j and 802.16m network, we then propose two remedies, namely expansion of ACID field and an adaptive fragmentation scheme. The performance evaluation results further confirm that the ACID expansion can readily *double* the link level throughput, while the adaptive fragmentation can effectively stave off the dismal degradation that plagues the IEEE 802.16e HARQ protocol. In addition, the two proposed schemes substantially reuse the existing mechanisms in current 802.16 standard, and thus would incur only diminutive additional complexity for implementation.

Regarding the future work, it is worthwhile to evaluate the impact of link adaptation mechanism on the proposed adaptive fragmentation protocol. Also, ACID expansion would require additional buffer capacity at both transmitter and receiver, whose impact on product cost deserves a more detailed examination.

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