Is Random Network Coding Helpful in WiMAX?

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***Abstract*—The IEEE 802.16 standard, or WiMAX, has emerged to facilitate high-bandwidth wireless access in real-world metropolitan areas, commonly referred to as 4G. In WiMAX, Hybrid Automatic Repeat reQuest (HARQ) is adopted to transmit data packets reliably. However, it sacrifices resilience in time varying channels, and it may under-utilize the wireless medium in the cases of multi-path and multi-hop transmissions. On the other hand, random network coding has been shown to be effective towards improving throughput in multi-hop wireless networks, when deployed above the physical and MAC layers. It would be encouraging to observe that network coding is also helpful at the MAC layer in practice, especially within the emerging WiMAX standard.**

Is random network coding beneficial in WiMAX at the MAC layer? In this paper, we seek to answer this question by evaluating network coding in three cases: single-hop transmissions, handovers, and multi-hop transmissions. We show that random network coding has indeed offered important advantages as compared to traditional HARQ. Our observations may lead to the use of random network coding at the MAC layer in practical WiMAX systems.

I. Introduction

The IEEE 802.16 family of standards, or *WiMAX* [1], has been designed to facilitate high data rate communication in metropolitan-area wireless networks, and has been commonly referred to as 4G. In WiMAX, physical layer and MAC layer standards are specified. Many advanced communication and networking techniques are adopted in the standards in order to improve the performance, such as OFDM/OFDMA, MIMO and AMC [1]. Supported by these techniques, WiMAX is able to provide better performance than traditional wireless communication standards, especially for applications requiring high and resilient throughput.

Specifically at the physical layer of WiMAX, Hybrid Automatic Retransmission reQuest (HARQ) has been used to provide reliable data transmission [2]. It is a variation of the ARQ error control protocol, and combines ARQ and Forward Error Correction. Its performance, especially in the context of WiMAX, has been thoroughly investigated in an information-theoretic fashion [3]. In Type-II HARQ, its performance can be further improved by packet soft combining, including Chase Combining and Incremental Redundancy, both of which help to increase the probability of successful decoding [4], [5].

However, HARQ incurs some overhead in terms of the redundant traffic, with its retransmissions and ACK/NACK packets. The build-in reliability in HARQ sacrifices some degree of *resilience* in realistic channels with varying qualities over time. Most existing literature on the performance of HARQ [6], [7] has not taken such an issue into consideration. In addition, in handover and multi-hop transmission modes in WiMAX, a mobile station is able to establish connections with two or more uplink nodes through different sub-channels. In these cases, HARQ may not be able to fully utilize the wireless medium, as it is designed for a point-to-point channel. As HARQ is performed on all the links, it may incur additional overhead and delays.

On the other hand, *network coding* has been originally proposed in information theory [8], and has since emerged as one of the most promising information theoretic approaches to improve network performance. The upshot of network coding is to allow coding at intermediate nodes in information flows. It has been shown that *random linear codes* using a Galois field of a limited size are sufficient to implement network coding in a practical network setting [9]. It has recently been shown that network coding on GF(2) (*i.e.,* XOR-only coding) is able to significantly improve end-to-end unicast throughput in multi-hop wireless networks, when implemented above the MAC layer of IEEE 802.11 [10], [11]. While the benefits of network coding in 802.11-based wireless networks have been explored, it is encouraging to observe that network coding is also helpful in WiMAX.

Is random network coding beneficial in WiMAX? In this paper, we seek to answer this question by evaluating the use of network coding in three different cases within the context of WiMAX: single-hop transmissions, handovers, and multi-hop transmissions. We show that random network coding has indeed offered important advantages when implemented in WiMAX MAC layer, by replacing the traditional HARQ at the physical layer. With random network coding, we show that performance can be improved significantly in WiMAX. Our observations may lead to the use of random network coding at the MAC layer in practical WiMAX systems. To our knowledge, there has not been existing work that evaluates the advantages (and drawbacks) of network coding at the MAC layer of WiMAX, as compared to HARQ, which has been offering very satisfactory performance in WiMAX.

The remainder of this paper is organized as follows. In Sec. II, we present a simple MAC-layer protocol — called MAC-layer Random Network Coding (MRNC) — to take advantage of network coding in WiMAX. In Sec. III, we

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intuitively show the advantages of MRNC in three different WiMAX scenarios. The performance evaluation of MRNC and HARQ based on simulations in all three scenarios is presented in Sec. IV. Finally, we conclude the paper in Sec. V.

II. How Can Network Coding be Used in WiMAX?

In order to observe how helpful random network coding may be at the MAC layer of WiMAX, we first need to propose a detailed protocol to use random network coding at the MAC layer of WiMAX. Such a MAC layer Random Network Coding protocol, henceforth referred to as MRNC for brevity, is designed to fairly evaluate the usefulness of random network coding in WiMAX.

In random network coding [12], a data segment (also referred to as a *generation* or a *group* in the literature) is divided into n blocks, denoted as $[b_1, b_2, \cdots, b_n]$, each of which has a fixed number of bytes, referred to as the block size. If the segment size is pre-determined, the block size k can be directly computed from n. When the segment is to be transmitted, the sender randomly chooses a set of coding coefficients $[c_1, c_2, \cdots, c_n]$ in the Galois field GF(2^8), and then produces one coded block x of k bytes:

$$x = \sum_{i=1}^{n} c_i b_i \tag{1}$$

Thus, each coded block is a linear combination of all or a subset of the original data blocks. The n coding coefficients used to encode *original blocks* are typically embedded in the header of each coded block [12], leading to a total overhead of n bytes per coded block. In MRNC, however, since the sender has the entire original segment when producing coded blocks, we just need to embed the random seed used to produce the series of coefficients with a known pseudo-random number generator. This effectively reduces the overhead to just 4 bytes for the random seed.

In MRNC, the sender keeps transmitting coded blocks from the current segment, until an ACK is received from the receiver. Upon receiving the ACK, the sender proceeds to process the next segment. A coded block can be sent in a MAC packet (*i.e.*, the MAC-layer Protocol Data Unit (MPDU) in WiMAX). In WiMAX downlink communication, for example, the base station or relay station serves as the sender.

For each packet it receives, the receiver uses a *progressive decoding* [13] process using Gauss-Jordan elimination. Progressive decoding has the favorable property that decoding occurs as coded blocks are being received, which implies that the decoding time overlaps with the time required to receive the blocks, and is hidden from the tally of overhead caused by the decoding complexity. Gauss-Jordan elimination is also able to immediately discard linearly dependent blocks that are not useful for decoding, as they will lead to a row of all zeros. Immediately after n linearly independent coded blocks have been received for a segment, the receiver is able to recover the entire original segment, and sends an ACK back to the sender. In WiMAX downlink communication, for example, the receiver is typically the mobile station or the relay station.

We heuristically set the MRNC block size to be identical to the size of MPDU. There are a total of $n = 128$ equal-size coded blocks within a data segment in our experiments, offering a satisfactory encoding and decoding performance with our implementation of random network coding.

III. Is Network Coding Helpful in WiMAX?

Random network coding serves as the cornerstone in the design of MRNC, and is instrumental towards most of its advantages over HARQ. In this section, we present intuitive justifications with respect to how network coding is used in MRNC. We show that random network coding is indeed helpful in practical WiMAX systems in the context of three different scenarios: single-hop transmissions, handovers, and multi-hop transmissions.

A. Single-hop Transmissions

In HARQ Incremental Redundancy, information is first coded and punctured according to a specified puncturing scheme. The sender transmits only the systematic bits at first, and transmits one redundancy packet when it receives negative feedback from the receiver. Packet soft combining is performed upon receiving redundancy packets at the receiver side. This procedure will be continued until the packet is correctly decoded or the maximum number of retransmissions is reached.

As described above, HARQ incurs some overhead in terms of the redundant traffic, with its retransmissions and ACK/NACK packets. In WiMAX, the mobile station (MS) may have high degrees of mobility, leading to a fluctuating channel quality over time. ACK/NACK packets may also incur errors and delays due to poor channel conditions. Such errors and losses in acknowledgment packets may lead to additional redundant packet transmissions that may be unnecessary, triggered by the ARQ timeout. In addition to the overhead, the build-in reliability in HARQ sacrifices some degree of *resilience* in realistic channels with varying qualities over time.

In contrast, random network coding offers an elegant and simple solution to these challenges. With the rateless property of random linear codes, MRNC is able to adapt the rate of data transmission to coincide with the available bandwidth in time-varying wireless channel conditions. With MRNC, the sender keeps on transmitting coded blocks, and the receiver only needs to “hold a bucket” to “collect” n linearly independent blocks, such that it is able to recover the original data segment. It is not necessary for the receiver to transmit ACK/NACK packets with *each individual* coded block, and for the sender to transmit redundant packets when errors occur. Intuitively, MRNC is able to offer resilient transmissions, due to the inherent resilience to errors with random linear codes. Should a particular coded block be lost, subsequent coded blocks received are equally innovative and useful.

B. Handovers

Handover is an essential functionality in WiMAX for dealing with user mobility, which is a process where a MS migrates from the air-interface of one base station (BS) to the air-interface provided by another BS. Recently, IEEE P802.16e/D4 [1] adopts soft handover schemes, such as Macro Diversity Handover (MDHO).

For MSs that support MDHO, they maintain an active set of BSs that are involved in MDHO. When the signal strength from a certain BS is above a particular threshold (H_Add), this BS will be added into the active set of the MS. On the other hand, a BS will be removed from the active set if the power is below the drop threshold (H_Delete). With this mechanism, a MS updates the active set periodically using the signal strength as the metric. In the handover region, the MS associates to all BSs in the active set, and establishes downlink connections with these BSs through separate downlink sub-channels supported by OFDM/OFDMA in WiMAX physical layer. Uplink communications are established through the same uplink sub-channel to all BSs that are associated to the MS. Such uplink data from the MS will simultaneously be relayed by the BSs to a Radio Network Controller (RNC), which connects to all BSs as a cross router.

In WiMAX soft handover, HARQ may not be able to fully utilize the wireless medium, as it is designed for a point-to-point channel. The transmissions have to be synchronized by having all BSs sending the same MAC/PHY PDUs to the MS in the same time epoch. Moreover, the HARQ performed in all links will generate additional overhead. Intuitively, random network coding is helpful to take full advantage of the available bandwidth from each BS, and to improve downlink transmission rates. With random network coding, the synchronization efforts can be avoided, since all coded blocks are considered equally innovative. Taking advantage of the properties of OFDM/OFDMA in WiMAX, each sub-channel can be used separately for transmitting different coded blocks simultaneously without collision. In this case, all sub-channel resources can be fully utilized, which coincides with the advantage of network coding in typical cases of multi-path communication.

We show the intuition behind the advantage of random network coding in a two-way handover procedure with an example, shown in Fig. 1. After the MS enters the handover region, it connects to both BSs, each through a unique sub-channel scheduled by each BS. Encoding is implemented at RNC, and different linearly independent coded blocks are issued to the two BSs simultaneously. The BSs then relay these coded blocks to the MS concurrently. The MS collects these coded blocks from both BSs, and responds with an ACK through the common uplink channel once it has received a sufficient number of linearly independent coded blocks. In this fashion, random network coding helps to fully utilize the downlink channels from both BSs.

C. *Multi-hop Transmissions*

In the scope of the IEEE 802.16j standard of WiMAX, the concept of relay station (RS) is introduced, with a mandatory two-hop transmission mode and an optional multi-hop mode. Similar to the case of handovers, when the MS moves into

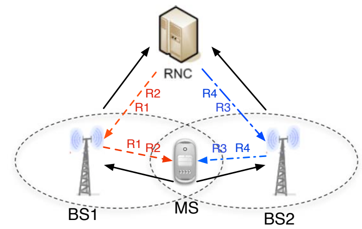


Fig. 1. The advantage of random network coding in a WiMAX two-way handover procedure.

the overlap region of both BS and RS, the MS is able to communicate directly with BS, indirectly with BS via RS, or with both.

In the HARQ scheme that is proposed specifically for the multi-hop mode in WiMAX, HARQ will be performed in the links between BS and RS, BS and MS, and RS and MS. We may observe that the transmissions performed on all the links may cause additional overhead, and the available resources in these channels are not fully utilized. In comparison, the multi-path advantage of random network coding is also beneficial in this scenario. Extended from the handover case, all BSs and RSs with a signal strength above H_Add are maintained in the active set of the MS, with weaker stations eliminated from the set periodically. With random network coding, the MS is able to receive coded blocks from different paths establishing connections with all BSs and RSs with acceptable signal strengths, through which different coded blocks are transmitted concurrently. All transmission sub-channels can be fully utilized to increase the throughput, as all received coded blocks are equally useful. Neither synchronization nor retransmission is required. The example shown in Fig. 2 explains the intuition behind such an advantage of random network coding.

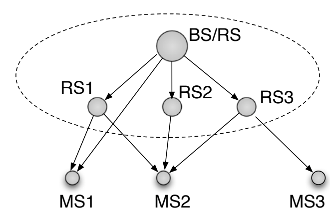


Fig. 2. The advantage of random network coding in WiMAX multi-hop transmissions.

IV. Performance Evaluation

We are now ready to resort to extensive simulations to study the performance of MRNC, as compared to HARQ. For this purpose, we use Matlab and ns-2 WiMAX simulator which is the only simulator for WiMAX that is available to be used in both academia and industry. The packet error rates in the additive white gaussian noise (AWGN) model are obtained through extensive simulations based on the technical specification document [1]. For HARQ, we only focus on Incremental Redundancy which is shown to achieve better performance than Chase Combining [14]. We set the maximum number of retransmissions to be 4, and the corresponding optimal size of redundancy packets based on the results in [14].

A. Single-hop transmissions

We first focus on the throughput performance in single-hop transmissions. Both protocols are used to transfer a large file in downlink between the same sender and receiver pair. For the sake of a fair comparison, the transmission rate is set to be 25 Mbps for both MRNC and HARQ.

We believe that realistic channel conditions vary over time, sometimes quite significantly. In such time-varying channel conditions, a superior protocol needs to be resilient to channel condition fluctuations, and deliver not only a high average throughput, but also small variance in throughput over time (referred to as *variance*). To evaluate MRNC and HARQ in time-varying channel conditions, we utilize Jakes channel files with a velocity of 40 km/h so that the received per-packet SNR values may vary over time. We perform the simulation over 1000 seconds. The results have clearly shown that MRNC delivers 50% less variance in throughput over time than HARQ, which is desirable in WiMAX with realistic channel conditions. We have also calculated the average throughput, with the verdict that MRNC enjoys a 10% gain over HARQ. These results verify the advantages of random network coding in single-hop transmissions.

B. Handovers

We next try to identify the performance gain offered by random network coding in the handover case in WiMAX, as compared to HARQ. Our evaluation is performed under the following realistic scenarios. A total of 19 BSs are deployed in the service area. The cell sites are layout as shown in Fig. 3. A constant downlink channel rate (25 Mbps) is allocated to the MS for each sub-channel from the BSs it attaches.

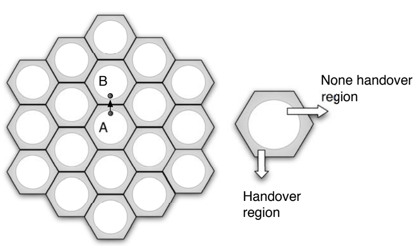


Fig. 3. The scenario being used for simulating a WiMAX handover event.

In the simulation, the MS is allowed to move around in the service area. Its initial speeds (in km/h) and directions (in degrees) are generated with a uniform distribution of $U[10, 50]$ and $U[0, 360]$, respectively. The MS will change its speed and direction after a certain amount of time with an exponentially distribution, with a mean value of 1 minute. The new speed is uniformly generated with $U[10, 50]$ if the current speed is below 10 km/h; otherwise, it is obtained using $U[v - 10, v + 10]$, where v is the current speed. The new direction is obtained from a Gaussian distribution with the mean as the current direction, and a standard deviation of 40. The initial location of the mobile station is randomly chosen in the handover region.

Fig. 4 shows the downlink throughput of both protocols on the MS through a 2000-second simulation. The improvement

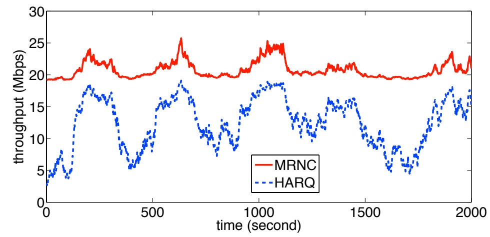
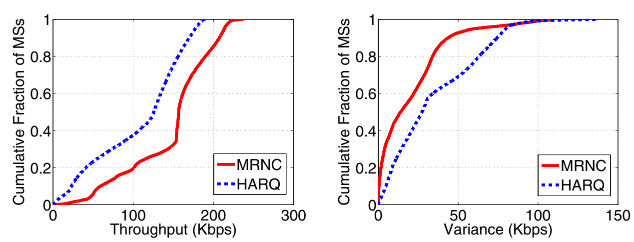


Fig. 4. MRNC vs. HARQ: throughput in a realistic handover case.

of the average throughput with MRNC is proximately 65%. MRNC also outperforms HARQ with respect to the throughput variance over time with 67% gain. These improvements are more substantial than those in the single-hop case, which coincides with our intuition that network coding fits naturally in the handover case.

With the objective of becoming even more realistic, we seek to extend our performance evaluation to a large scale scenario. In the cellular system described previously, we set a large number of MSs active in the service region concurrently. The arrival process of new MS connections in each cell is assumed to be a Poisson process with a mean of 5 connections/cell/second. The MS active time duration is exponentially distributed with a mean of 100 seconds. Every active MS is moving around the service area using the same way as the previous simulation. We run the simulation for 1000 seconds, and the downlink throughput at the MS is examined. From the results, there are a total of 94880 MSs that have ever been active in the service area during the simulation time, with 450 MSs active simultaneously in each cell on average. Fig. 5 plots the CDF of the average throughput and its variance, considering all active MSs in the simulation. Not surprisingly, MRNC outperforms HARQ by 40% with respect to both average throughput and variance, due to its effective use of bandwidth and the inherent resilience of random network coding.



(a) (b)

Fig. 5. MRNC vs. HARQ in a large-scale handover scenario: (a) CDF of throughput. (b) CDF of variance.

C. Multi-hop Transmissions

Finally, we illustrate the synergy between network coding and the WiMAX multi-hop mode. We evaluate the performance in a practical setting of the multi-hop case, by considering the benefit of multi-path transmissions. Our simulation scenario is shown in Fig. 6. In order to extend the coverage area of the cell, the RSs are placed within the border of the radio ranges of BSs.

The MS in the simulation receives downlink data either directly from RS or BS, or from both. A similar evaluation

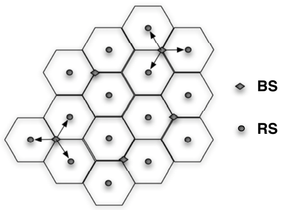


Fig. 6. Practical setting of the multi-hop scenario.

is performed with the same setting as our simulation in the first handover case. We observe from the results that MRNC gains a 36% throughput improvement and a 70% variance improvement, as shown in Fig. 7. This coincides with our intuition and is not a surprise: it shows the ability of random network coding to fully utilize available wireless spectrum in the multi-hop case.

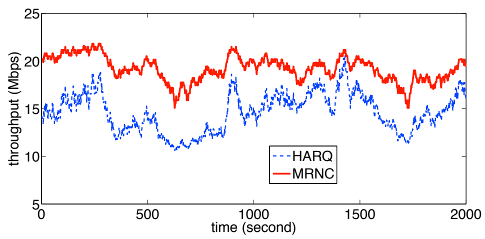


Fig. 7. MRNC vs. HARQ: throughput in a realistic multi-hop scenario.

Finally, we consider the case of a large-scale multi-hop network, with the same simulation setup as in the large-scale handover scenario. Fig. 8 presents the CDF of the throughput and variance from a 1000-second simulation. As expected, MRNC outperforms HARQ in both average throughput and variance. In particular, MRNC achieves a 60% higher throughput on average, as well as a 40% gain with respect to variance over HARQ. This confirms and highlights the benefits achieved by MRNC in the WiMAX multi-hop mode.

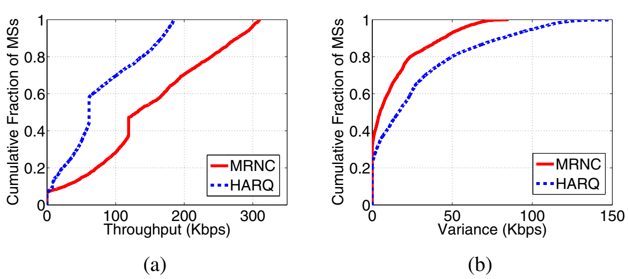


Fig. 8. MRNC vs. HARQ in a large-scale multi-hop scenario. (a) CDF of throughput. (b) CDF of variance.

In closing, we would like to study the overhead of MRNC. As neither BSs nor RSs have constraints with respect to memory and computational power, we are only concerned with the overhead at MSs. With respect to the overhead caused by *coding*, we have already employed Gauss-Jordan elimination to perform progressive decoding in MRNC, which maximizes the timing overlap between coding and network transmission. With respect to the overhead from *packet headers*, as compared to HARQ, MRNC only adds 4 bytes to carry the random seed.

V. Concluding Remarks

WiMAX employs a state-of-the-art design using HARQ Incremental Redundancy. In comparison, the recent advances in the literature on network coding have clearly shown the advantages that simple random linear codes may be able to bring to wireless networks. Is random network coding helpful at the MAC layer of WiMAX, when used instead of traditional HARQ? In this paper, we have designed a protocol, referred to as MAC-layer Random Network Coding (MRNC), with the intention of taking full advantage of the rateless property of random linear codes in WiMAX. With extensive studies, we have observed that random network coding has indeed offered salient advantages over HARQ, especially in cases where the channel condition varies over time, during the handover procedure, and in the multi-hop mode of WiMAX. These observations may lead to the future use of random network coding at the MAC layer in practical WiMAX systems.

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