Application of Network Coding to IEEE 802.16j Mobile Multi-hop Relay (MMR) Network for Throughput Enhancement

Kyungjun Lee, Wonjin Sung, Ju Wook Jang

Abstract: **We observe simultaneous transmission of relay stations allowed in current IEEE 802.16j draft standard for multi-hop relay networks may involve severe interference among the relay stations, hence leading to throughput degradation. Allowing only 1/3 of the relay stations to simultaneously transmit instead of 1/2 relay stations as in the current draft standard reduces the interference but results in reduced throughput. To remedy this problem, we devise schemes to incorporate network coding at link-layer level (decode-and-forward) into the simultaneous transmission of relay stations. Data movement is rearranged to maximize coding gain. Formula is derived to dictate exact movement of packets traveling between base station and mobile stations via intermediate relay stations. The frame structure in the current IEEE 802.16j draft standard does not allow broadcast needed for network coding. We devise a new frame structure which supports the broadcast. A new R-MAP (pointers to the burst data) is introduced to implement the broadcast. Since our new frame structure is used only for base station to relay station or relay station to relay station communication, our schemes retain backward compatibility with legacy mobile stations based on IEEE 802.16e standard. Simulation based on simple configuration of RSs shows considerable improvement in terms of system throughput and round trip delay. For a 4-hop relay network with 1 base station and 4 relay stations with symmetric traffic in uplink and downlink, throughput is improved by 49% in downlink and by 84% in uplink traffic compared with IEEE 802.16j draft standard under the assumption that omni-directional antennae are used in BS and RSs.**

Index Terms: **IEEE802.16j, interference, mobile WiMAX, Network Coding**

I. INTRODUCTION

The 4th generation (4G) systems require system throughput of up to 1 Gbps for nomadic users and 100Mbps for fast moving mobile station (MS)s [1]. Users expect very high throughput to enjoy high bandwidth multimedia applications regardless of their locations and mobility. However, unfairness in throughput which depends on the location of each MS due to path loss makes this goal hard to achieve in an efficient way. Much more resource should be allocated to MSs near the cell boundary to achieve throughput comparable with that of MSs near the base station (BS). Placing relay station (RS)s between BS and MSs at the cell boundary is an attractive approach to solve this problem in a competitive way.

IEEE 802.16j is an amendment to the IEEE 802.16 broadband wireless access standard to enable the operation of multi-hop relay station (RS)s. It aims to enhance the coverage and system throughput. Deployment of more RSs will shorten average distance between neighboring RSs, resulting in reduced path loss over each hop.

Multi-hop networks have been suggested for rural area sparsely populated since base station is very expensive to establish. It is feasible to deploy relay stations along the street in a linear fashion. Multi-hop networks whose number of hops is greater than 2 have been considered in [2], [3], [4], [5], and [6]. In [4], 4 relays are considered and [5] assumes 6 relays. In [6], a 6 hop relay network which consists of 1 BS and 5 RSs located in a linear fashion is described.

However, increase in the number of RSs managed by one BS will suffer latency and system throughput degradation if only one serving station (BS or RS) is allowed to transmit at a time in a relay zone. To avoid this problem, current IEEE 802.16j draft standard [2], [3] for multi-hop relay networks allows simultaneous transmission of every 2nd RS. Specifically, odd hop RSs transmit in the downlink relay zone of odd number frames and the BS and even hop RSs transmit in the downlink relay zone of even number frames. The interference might be severe if the RSs do not use directional antennae. As a result, the scheme may suffer degradation in network throughput.

Z. Tao, A. Li, K.H. Teo, and J. Zhang [4] solved the interference problem without using directional antennae by simultaneous transmission of every 3rd RS. However, the number of stations allowed to transmit simultaneously will be reduced by a factor of 1.5. Hence the resulting throughput will be decreased.

We propose new schemes for simultaneous transmission which incorporate network coding at link-layer level (decode-and-forward). Our schemes achieve higher throughput than the scheme in current IEEE 802.16j draft standard with omni-directional antennae or with directional antennae. Our schemes keep the power level of the interfering signal as low as the scheme by Tao *et al*. [4]. Our scheme helps in preventing throughput degradation when relays of more than two hops are employed, which in turn encourage the use of multi-hop relays.

Network coding has opened a new research area that may have interesting applications in practical networks. It has received much attention since the seminal work of R. Ahlswede, N. Cai, SYR. Li, and RW. Yeung [7]. Recently, much research work [8]- [12] has focused on bitwise XOR operation in MAC-layer for data exchange in wireless networks. In [13]- [15], applying network coding at physical-layer is considered for higher coding gain.

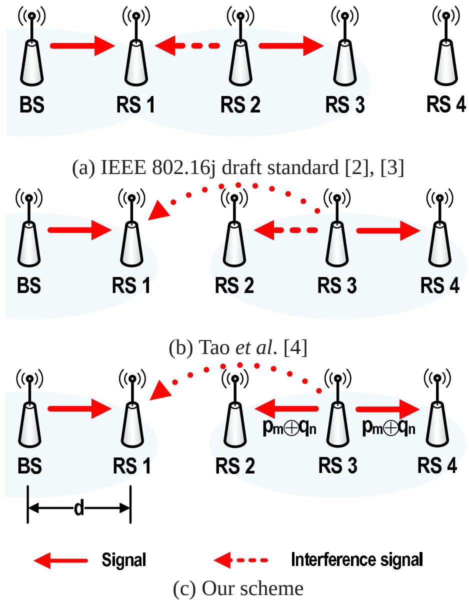
To incorporate network coding in an efficient way, our scheme

Manuscript received July 31, 2008.

The authors are with the Department of Electronic Engineering, Sogang University, 1 Shinsu-dong, Mapo-gu, South Korea (e-mail: ghost@eeca1.sogang.ac.kr, wsung@sogang.ac.kr, jjang@sogang.ac.kr).

Table 1. Path loss exponents for different environments

Environment	Path Loss Exponent, γ
Free space	2
Urban cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building with line of sight	1.6 to 1.8
Obstructed in building	4 to 6



(a) IEEE 802.16j draft standard [2], [3]

(b) Tao *et al.* [4]

(c) Our scheme

Fig. 1. Simplified diagrams of transmission schemes
(d : the distance between adjacent stations, p_m, q_n : packet)

rearranges movement of packets in such a way to maximize the coding gain. Formula is derived to dictate the movement of individual packets at packet level. The frame structure in the current IEEE 802.16j draft standard does not allow broadcast operations needed for network coding. We devise a new frame structure in which we introduce new R-MAP (mapping pointers to bursts) for broadcast operation. Our new frame structure is used for BS/RS communication or RS/RS communication, hence does not lose compatibility with legacy MS (mobile station)s based on IEEE 802.16e standard [16]. The simulation results show that our scheme excels other schemes in terms of throughput and round trip delay (RTD).

The rest of the paper is organized as follows. Section II briefly describes the previous transmission schemes for IEEE 802.16j multi-hop relay networks along with background. The problems with simultaneous transmission allowed in current IEEE 802.16j draft standard are also discussed in detail. Our schemes to incorporate network coding and a new frame structure design to implement the schemes are elaborated in Section III. Performance evaluation is summarized in Section IV and Section V concludes our work.

II. BACKGROUND AND PREVIOUS TRANSMISSION SCHEMES

A. IEEE 802.16e

The IEEE 802.16e [16], [17] system consists of BS and MS and the BS controls all MSs in its coverage. The OFDMA frame structure is divided into two portions in time domain, one is for downlink (DL) and the other is for uplink (UL) data transmission. In a DL sub-frame, BS transmits data to MSs, on the other hand, in a UL sub-frame, the MSs transmits data to BS. The BS schedules transmissions of MSs in time and frequency domain to make no collision during the UL sub-frame, as transmitting UL-MAP in the DL sub-frame.

B. IEEE 802.16j

IEEE 802.16j [2] aims for throughput enhancement, extending coverage by deploying RSs [18], [19] in the 802.16e network and is now in progress for standardization. The frame structure is modified as a result of deploying RS. In the frame structure, each DL sub-frame and UL sub-frame is divided into two portions, which are an access zone for communication between BS/RS and MS, and a relay zone for communication between BS/RS and RS.

Two different types of RS are defined in IEEE 802.16j draft standard, namely transparent and non-transparent. The transparent RS does not transmit DL frame-start preamble, FCH, MAP message(s) or channel descriptor (DCD/UCD) messages whereas the non-transparent RS transmits them. Each type has its own advantages and corresponding usage cases. For MS within BS coverage, it is better to use transparent relay and for the purpose of coverage extension, non-transparent RS works better.

In the IEEE 802.16j draft standard, an increase in the number of RSs managed by one BS will lead to latency and performance degradation in the network if only one BS or RS transmits data at a time in a relay zone. Therefore, simultaneous transmission scheme of BS and RSs is included.

C. Previous Transmission Schemes and Frame Structures

Simultaneous transmission of the RSs may involve interference. For an RS which is to receive signal from intended adjacent RS, signals from all the other RSs serve as interference. The interference is inversely proportional to a power of the distance from an interfering RS to the RS receiving signal. We use Erceg path loss model [20] shown in equation (1) for estimation of the power of interfering signal where γ is the path loss exponent.

$$PL = A + 10 \cdot \gamma \cdot \log_{10}(\frac{d}{d_0}) + \Delta PL_f + \Delta PL_h \qquad (1)$$

The γ depends on propagation environment as shown in Table 1 [21]. Ignoring other constant terms for brevity, we assume signal power attenuates as c/(distance)$^{\gamma}$ where c is a constant. Assuming γ is 4, the power of interfering signal is expected to be reduced by a factor of 16 as the distance is increased by the factor of 2.

Current IEEE 802.16j draft standard [2], [3] for multi-hop relay networks allows simultaneous transmission of every 2nd RS

Table 2. Comparison of previous schemes

Schemes	Simultaneous Transmission	Power of Interference signal from the nearest transmitting stations (intuitive rough estimate)
IEEE802.16j draft standard [2], [3]	Every 2nd RS	$c \cdot \left(\frac{1}{d}\right)^4$
Tao *et al*. [4]	Every 3rd RS	$\frac{c}{16} \cdot \left(\frac{1}{d}\right)^4$

Assuming the path loss exponent is 4
Assuming log-normal shadow fading model
Standard deviation of log-normal shadowing : 8dB
c : constant
d : the distance between adjacent stations

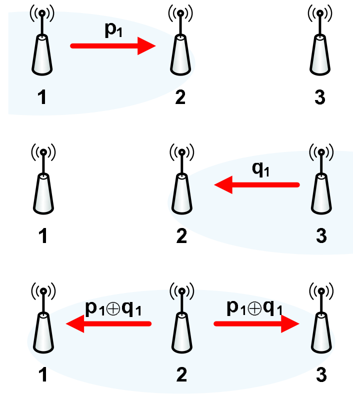


Fig. 2. XOR network coding
(p_1, q_1 : packet)

as shown in Fig. 1 (a) for throughput enhancement. Odd (even) hop RSs transmit while even (odd) hop RSs receive. We observe that, if the RSs do not use directional antennae, the interference among RSs would be too severe to achieve the intended throughput enhancement by allowing simultaneous transmission. Referring to Fig. 1 (a) the solid arrows denote the intended transmission of signals while the broken arrow denote interference signal. Note that the signal from RS 2 intended for RS 3 (solid arrow from RS 2 to RS 3) serves as interference signal to RS 1 (broken arrow from RS 2 to RS 1). For RS 1 the interference is severe since its power level is same as that of the intended signal from BS. Therefore, the received SINR (Signal to Interference plus Noise Ratio) at RS 1 will be under 0dB. It means that QPSK, 1/6 can be used based on Table 5, if AMC (Adaptive Modulation and Coding) is used. The throughput will be decreased by the factor of 15 compared with maximum modulation and coding scheme (64QAM 5/6). If it is set the higher modulation and coding rather than proper modulation and coding according to corresponding SINR, the BER (Bit Error Rate) will be increased. As a result, the scheme may suffer degradation in network throughput unless all RSs use directional antennae.

The transmission scheme by Tao *et al*. [4] circumvents this problem without using directional antennae by allowing simultaneous transmission of every 3rd RS as shown in Fig. 1 (b). BS and RS 3 are allowed to transmit while RS 2 remains idle and RS 1 and RS 4 receive. Uplink transmission is similar except that the direction of arrows is reversed. The basic idea of this scheme is to separate transmitting stations far enough to avoid interference. Assuming γ is 4 in equation (1), the power of interfering signal from RS 3 to RS 1 is 1/16th of the signal from BS to RS 1 since the distance from RS 3 to RS 1 is twice the distance from BS to RS 1.

Table 2 summarizes the above discussion. The scheme in current IEEE 802.16j draft standard [2], [3] for multi-hop relay networks allows 1/2 of the total RSs in a linear array example to simultaneously transmit for possible throughput enhancement. However the scheme, if used without directional antennae, involves considerable interference, which prevents the scheme from achieving intended throughput enhancement. The scheme by Tao *et al*. [4] reduces the power level of interference signal by the factor of 16 by separating transmitting RSs, but the expected throughput will be lower since only 1/3 of the total RSs in a linear array example is allowed to simultaneously transmit.

In the next section, we present our schemes which incorporate network coding at link-layer (decode-and-forward) to achieve higher throughput than the scheme in current IEEE 802.16j draft standard with omni-directional antennae or with directional antennae. Our scheme keeps the power level of the interfering signal as low as the scheme by Tao *et al*. [4]. Movement of packets is rearranged to maximize the coding gain. Formula is derived to dictate the movement of individual packets. The frame structure in the current IEEE 802.16j draft standard does not allow broadcast operations needed for network coding. We devise a new frame structure which implements the network coding in efficient way without losing compatibility with legacy MS (mobile station)s.

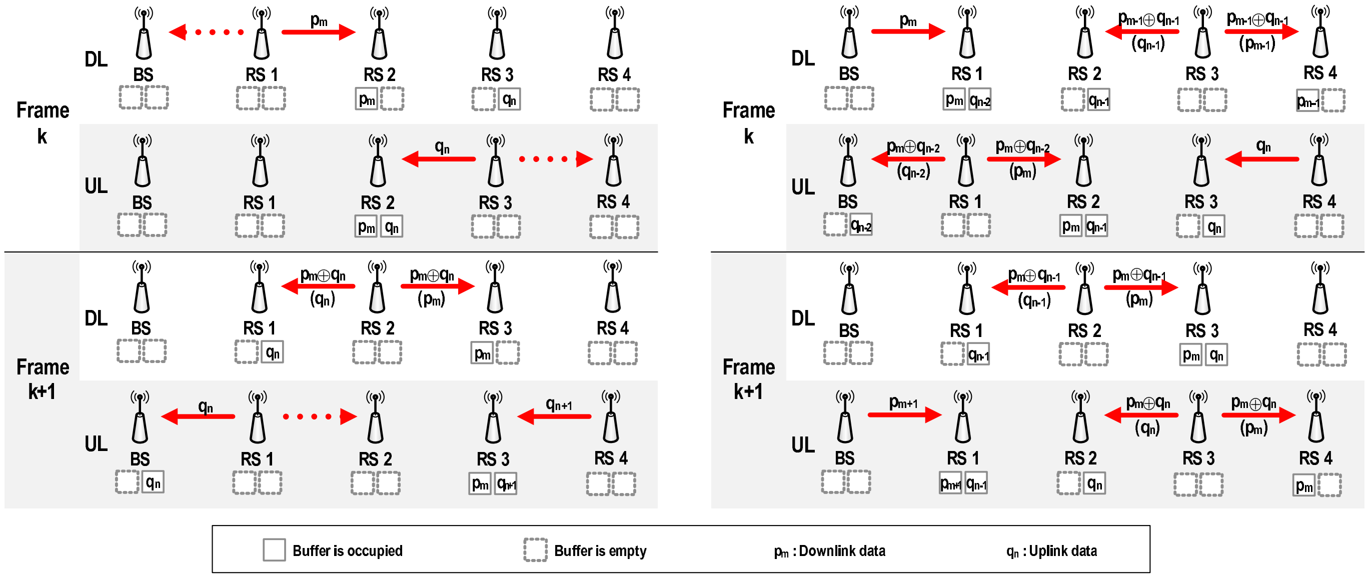
III. THE PROPOSED SCHEME AND FRAME STRUCTURE

A. Proposed Schemes for MMR networks

In this section we present our scheme to incorporate network coding in IEEE 802.16j multi-hop relay networks for throughput enhancement while keeping the interference low. We also show our design of new frame structure to implement the scheme.

Fig. 2 illustrates a network coding applied at link-layer [8]. Station 2 receives p_1 first and then q_1 from stations 1 and 3, respectively and then broadcasts the $p_1 \oplus q_1$ to stations 1 and 3. Station 1 retrieves q_1 by performing XOR operation, $\{p_1 \oplus q_1\} \oplus p_1 = q_1$. Similarly, station 3 retrieves p_1. As a result, four transmissions can be reduced to three transmissions, resulting in coding gain of 4/3.

First we combine the above network coding technique with the scheme by Tao *et al*. [4] in Fig. 1 (b). The result is shown as proposed scheme I in Fig. 3 (a). The $p_m(q_n)$ denotes a packet traveling left to right (right to left). In Fig. 3 (a), RS 2 receives p_m in DL sub-frame of frame k. One buffer in RS 2 is occupied by p_m (shown as a solid box holding p_m). Next RS 2 receives q_n in UL sub-frame of frame k. Now two buffers in RS 2 are occupied by p_m and q_n (shown as two solid boxes each holding p_m or q_n). In DL sub-frame of frame k+1, RS 2 broadcasts $p_m \oplus q_n$. RS 1 retrieves q_n by performing XOR operation, $p_m \oplus q_n \oplus p_m = q_n$. As a result, q_n is stored in a buffer of



(a) Proposed Scheme I (b) Proposed Scheme II

Fig. 3. Detailed description of transmission schemes
(Symbols in the racket, (p_m), (q_n) denote the packets to be retrieved)

RS 1. Similarly, RS 3 retrieves p_m to store it into its buffer. In this way, our scheme I reduces four transmissions to be performed over four sub-frames to three transmissions over three sub-frames. One out of four sub-frames is saved, resulting in asymptotic throughput gain of 4/3 if we assume the linear array of RSs is long enough.

In proposed scheme II, we show, by rearranging movement of packets traveling right to left $(\{q_n\})$ from proposed scheme I, that the throughput gain can be further improved. Fig. 3 (b) shows the movement of packets in detail. Packets traveling right to left $(\{q_n\})$ stay at each RS in two sub-frames while packets traveling left to right $(\{p_m\})$ stay at each RS in one sub-frame. For example, q_{n-1} stays at RS 2 in the duration of two sub-frames (DL sub-frame and UL sub-frame of frame k) while p_m stays only one sub-frame (UL sub-frame of frame k). In other words, q_{n-1} waits at RS 2 one more sub-frame to encounter p_m. The purpose of this rearranged packet movement is to enable the XOR operation of $p_m \oplus q_{n-1}$ which will be broadcast during the next sub-frame (DL sub-frame of frame k+1).

Table 3 shows a snapshot which shows in what sub-frame which packets are stored at which RS. For example during DL of frame k+1, both p_m and q_n stay at RS 3. Assume packets $\{p_m\}, m = 1, 2, 3...$ start their travel from BS to RS 4 at c sub-frames after packets $\{q_n\}, n = 1, 2, 3...$ start their travel from RS 4 to BS. Then the number of subframes needed for p_m and q_{n-2} to meet at RS 1 (as illustrated in Fig. 3 (b), during DL of frame k) can be derived as equation (2).

$$3(m-1) + 1 + c = 3(n-3) + 6 \tag{2}$$

The left hand side represents the number of subframes for p_m to arrive at RS 1 while right hand side denotes the number of subframes for q_{n-2} to arrive at RS 1 plus one subframe for waiting. Assuming c is 2, we have $m = n - 1$.

This equation dictates the packet movement for efficient network coding gain assuming constant flow of packets in both directions. For example, we know in advance p_{100} will meet q_{99} for XOR at RS 1 during $\{3 \times (101-3)+6\}$-th subframe or 300th subframe if we start sending $\{p_m\}$, $m = 1, 2, 3...$ at c sub-frames after sending packets $\{q_n\}$, $n = 1, 2, 3....$

The above can be generalized to any number of hops as equation (3) where s denotes the total number of stations including BS and r denotes the number of hops by which RS is apart from BS.

$$3(m-1) + r + c = 3(n-3) + 2(s-r) - 2 \tag{3}$$

Equation (3) represents the number of subframes needed for p_m to meet q_n for XOR at RS r where s is the total number of stations (total number of hops plus one). It is also assumed that packets $\{p_m\}, m = 1, 2, 3...$ start their travel from BS at c sub-frames after packets $\{q_n\}, n = 1, 2, 3...$ start their travel. Note that equation (2) is specific case of equation (3) where $r = 1$ and $s = 5$.

Table 3. A snapshot of proposed scheme II

	p_{m+2}	p_{m+1}	p_m	q_{n-2}	q_{n-1}	q_n	q_{n+1}
UL (Frame k-1)			BS	RS 1	RS 3		
DL (Frame k)			RS 1	RS 1	RS 2	RS 4	
UL (Frame k)			RS 2	BS	RS 2	RS 3	
DL (Frame k+1)		BS	RS 3		RS 1	RS 3	
UL (Frame k+1)		RS 1	RS 4		RS 1	RS 2	RS 4
DL (Frame k+2)		RS 2			BS	RS 2	RS 3
UL (Frame k+2)	BS	RS 3				RS 1	RS 3
DL (Frame k+3)	RS 1	RS 4				RS 1	RS 2
UL (Frame k+3)	RS 2					BS	RS 2

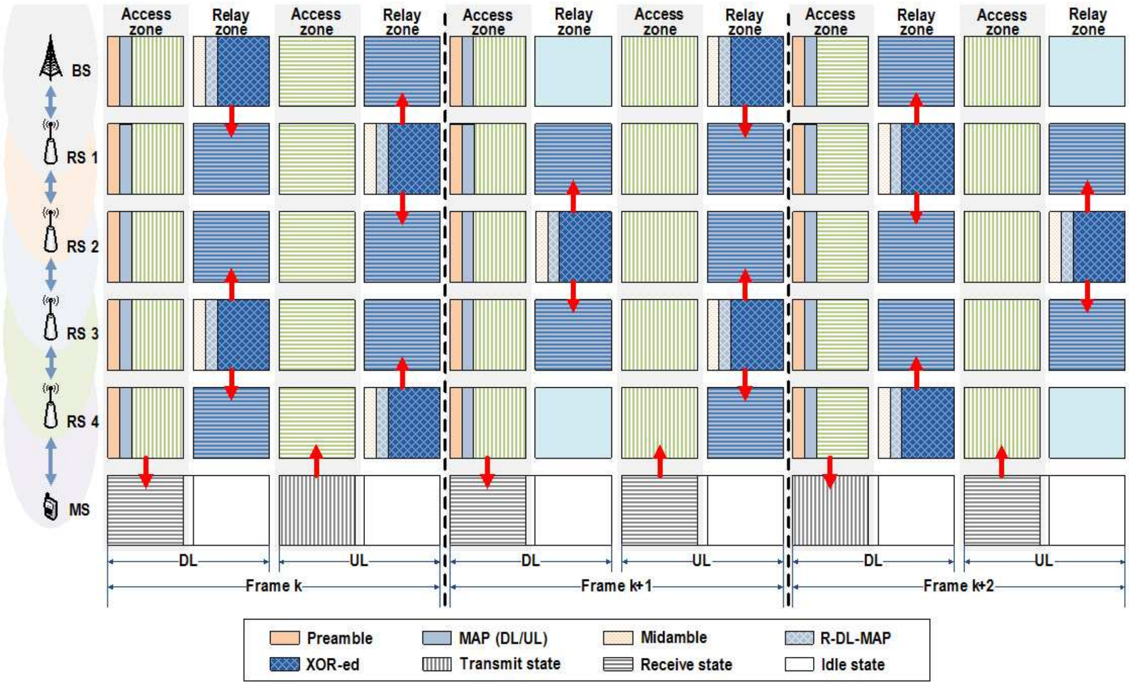


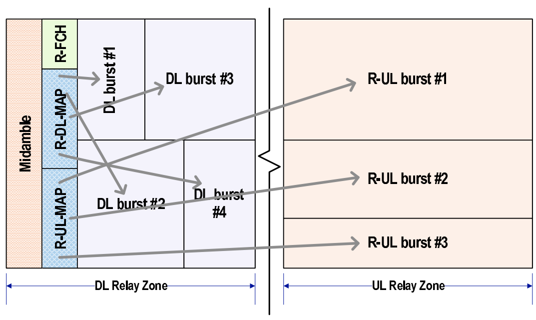
Fig. 4. A new frame structure design for proposed scheme II

B. *Frame Structure for Proposed Scheme*

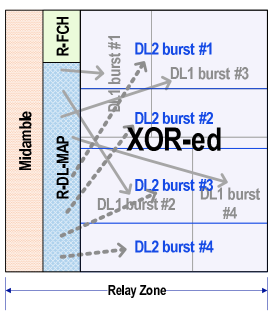
In Fig. 4, we show a new frame structure design which implements the proposed scheme II described in the above. An example relay network involving four relay stations and end-to-end communications occurring therein are shown along with the corresponding frame structure.

Similar to the legacy design, the new frame structure for proposed scheme II is also composed of DL sub-frame and UL sub-frame. Each DL or UL sub-frame is further divided into access zone and relay zone. Access zone is used for BS and RSs to communicate with MSs. Access zone in our new frame structure remains the same as the legacy design to provide backward compatibility to the legacy MSs (IEEE 802.16e MSs). The arrows represent the data flow. For example, the arrow from RS 4 in access zone of DL in the frame k denotes the downlink transmission from RS 4 to its subordinate MSs. During this access zone, BS and other RSs also perform downlink transmission to their corresponding subordinate MSs. We omitted this in Fig. 4 for brevity of graphical representation. Our new frame structure for proposed scheme II differs from the legacy design in relay zones. Relay zone is used for transmission between BS and RSs. In order to incorporate network coding, it is necessary to enable RSs in the middle to perform broadcast transmission in relay zones. However, the current frame structure of IEEE 802.16j draft standard does not allow this.

Fig. 5 (a) shows an example of relay zone frame structure of current IEEE 802.16j draft standard. In the DL relay zone, BS or RS j transmit its own midamble, R-MAP (R-DL-MAP, R-UL-MAP) to its neighboring RS 1 or RS j+1. The midamble is used by the RS 1 or RS j+1 to synchronize with the BS or the RS j. R-DL-MAP and R-UL-MAP are used as pointers to which resources are allocated to which bursts in downlink and uplink transmission, respectively. Using these maps the neighboring RS 1 or RS j+1 can determine when (i.e., time) and where (i.e., frequency) should it receive from and transmit to the BS or RS j. The gray arrows illustrate the pointers in R-DL-MAP and R-UL-MAP.



(a) Current frame structure



(b) Proposed frame structure

Fig. 5. Comparison of frame structure in relay zone

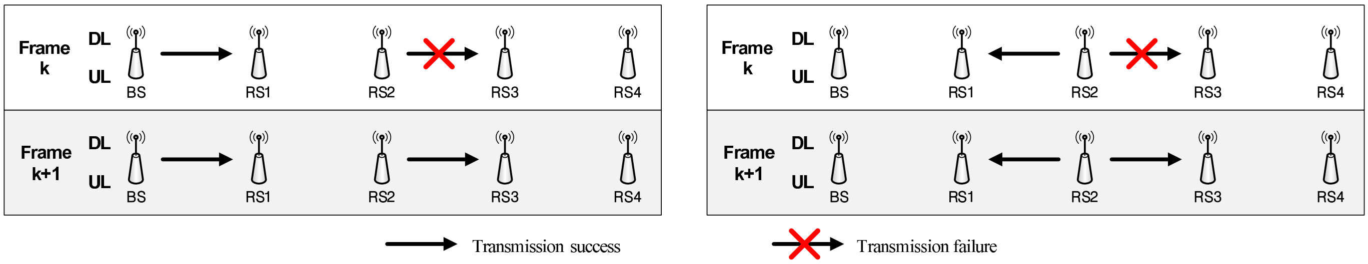


Fig. 6. Effect of packet loss

We propose a new R-MAP which consists of only R-DL-MAPs. Refer to Fig. 3 (b) where we illustrate our scheme with packet by packet level for simplicity. Now we show how we translate this to frame by frame level minding compatibility with existing frame structure. RS j receives two frames from RS j-1(or BS if j=1) and RS j+1 and performs XOR operation to obtain the frame for broadcast. XOR is performed only on the burst data part. The upper half of the R-MAP is used to store pointers to burst data for RS j+1 while the lower half of the R-MAP is used to store pointers to burst data for RS j-1 or BS if j=1. The basic idea behind our scheme is to make XOR operations transparent to pointers in the proposed new R-MAP. RS j-1(or BS if j=1) or RS j+1 performs XOR first to retrieve the intended burst data as a whole and then use the pointers in the lower half of the R-MAP or the upper half of the R-MAP to identify individual bursts. The solid arrows in Fig. 5 (b) originating from the upper half of the R-MAP illustrate the pointers to individual bursts for RS j+1, while the broken arrows illustrate the pointers to individual bursts for RS j-1 (or BS if j=1). In this way there is no increase in the bandwidth overhead for our new frame structure to incorporate the network coding. We expect that our R-MAP is applicable to IEEE 802.16j without hardware modification. R-MAP is a control signal used in transmission between BS and RS. Therefore, we expect that small amendment of standard draft is necessary in BS and RSs, but not for MSs. Thus our scheme maintains backward compatibility with the IEEE 802.16e MSs.

C. Effect of Packet Loss

Throughput degradation due to packet loss may be more severe for our scheme than for the simultaneous transmission scheme based on the IEEE 802.16j draft standard [2]. The draft standard does not define what to do when packet loss happens in any link during simultaneous transmission which involves about half of the wireless links.

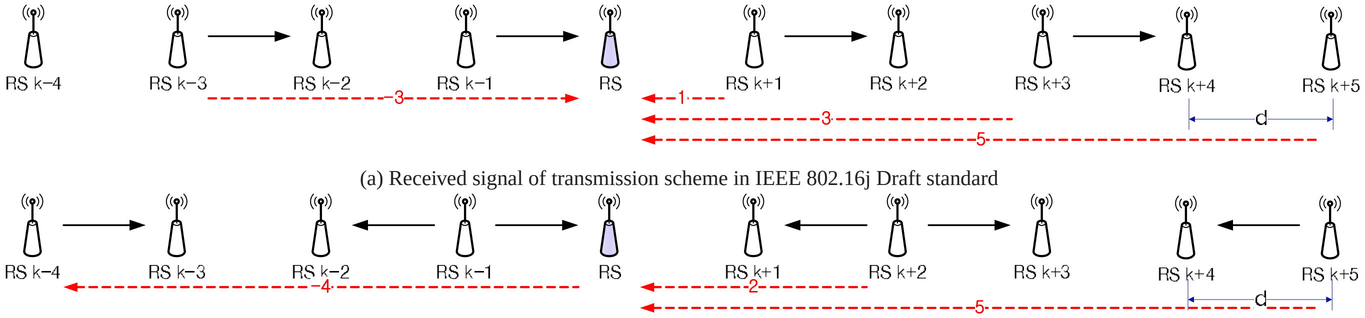
We may consider two cases. One with additional buffer space for the packets to be retransmitted and one with no such space available. We consider the latter case first. The left diagram in Fig. 6 shows what may happen on packet loss during simultaneous transmission based on [2]. Since simultaneous transmission of every 2nd RS proceeds in a pipelined fashion, we may envision that each packet loss stalls the imaginary pipeline, which is equivalent to losing one frame for each transmitting BS or RS. In Frame k, the packet from RS 2 to RS 3 is lost. RS 3 is supposed to send the packet to RS 4 in Frame k+1, but can't due to the loss.

A simple solution is to repeat the Frame k which is equivalent to stalling the pipeline for the duration of one frame. If we assume for brevity that the loss probability is p for all the wireless links and independent then the pipeline stalls with average probability of $1-(1-p)^{k/2}$ for k-hop relay networks (assume for simplicity k is even). The right diagram in Fig. 6 shows what may happen on packet loss in our proposed scheme II. The same packet is broadcast from RS 2 to RS 1 and RS 3. If either RS 1 or RS 3 fails to receive the packet, we stall the pipeline. The pipeline stalls with average probability of $1-(1-p)^{2k/3}$ for k-hop relay networks (assume for simplicity k is divisible by 3). Therefore, the probability of stalling the pipeline or missing a frame for our scheme is larger than the IEEE draft standard by $(1-p)^{k/2}-(1-p)^{2k/3}$. This in general implies that as packet loss rate increases the throughput degradation of our scheme may be more severe than the draft standard.

Let $N0$ denote the number of frames needed to finish a certain exchange of files when there is no packet loss. Assume $P1 = 1-(1-p)^{k/2}$ and $P2 = 1-(1-p)^{2k/3}$. Then the scheme by IEEE 802.16j draft standard needs $N0(1+P1+P1^2+P1^3+\cdots) = N0/(1-p)^{k/2}$ while our scheme needs $N0/(1-p)^{2k/3}$. If $k=6$ and $p=0.1$, the throughput degradation of our scheme would be 0.9^4 while throughput degradation of the scheme by IEEE draft standard would be 0.9^3. Our scheme is affected more by the packet loss since our scheme uses more wireless links than the draft standard.

However, we observe that p seldom goes higher than 0.01 since the MCS level is chosen in such a way packet loss would be smaller than 0.01 [22]. The throughput degradation of our scheme would be smaller than 0.99^4 while throughput degradation of the scheme by IEEE draft standard would be smaller than 0.99^3. The throughput degradation would be very small as shown in Table 7 for p = 0.01 and 0.001.

The above simple solution which repeats previous frame on any packet loss would seem wasteful considering stations other than the station who failed in sending in previous frame would waste their frame time. If we allow additional buffer space, those stations can reduce the waste by sending new frames instead of unnecessary retransmission. Trade-off analysis for buffer space and throughput improvement can be performed by developing probability models. Based on the analysis, we may develop a new transmission scheduling which may be more complex. However, for packet loss rate as low as 0.01, the small gain in throughput can hardly justify the complexity.



(a) Received signal of transmission scheme in IEEE 802.16j Draft standard

(b) Received signal of proposed scheme II

Fig. 7. Received signal of each transmission scheme

D. Interference Analysis

For simplicity, let's assume the distance between neighboring stations is fixed as d and the received signal power for RS k from a neighboring station RS k-1 (as shown in Fig. 7) is $P(k-1,k)$. The received power for RS k from station RS k-j is $P(k-j,k)$. We also assume the receiving RS is in the center of a relay which grows infinitely on the left and on the right. As the interfering RS is away farther, the inference will grow much weaker. We assume no stations other than the relay itself. We employ intuitive rough estimate shown in Table 2. Since we assume identical wireless environment for comparison, only the relative signal strength matters. We expect the rough estimate serves the purpose. We have equations (4)-(8). Clearly our scheme has higher CINR than the draft standard as equation (7) and (8) indicate.

$$P_s = P(k-1,k) \tag{4}$$

$$P_I = \sum_{j=3,5,7,\cdots}^{N} P(k-j,k), \quad where\ N = \left\lceil \frac{number\ of\ hops}{2} \right\rceil \tag{5}$$

$$P(k \pm j, k) = \frac{P(k \pm 1, k)}{j^4} \tag{6}$$

$$\begin{aligned} &CINR_{IEEE802.16j(Omni-directional\ antenna)} \\ &= 10\log \frac{P_s}{P_I + N_0 \times NF} \\ &\cong 10\log \frac{P(k-1,k)}{\sum\limits_{j=-7,-5,-3,1,3,5,7,\cdots}^{N} P(k-j,k)} \\ &= 10\log \frac{P(k-1,k)}{P(k-1,k) \times \sum\limits_{j=-7,-5,-3,1,3,5,7,\cdots}^{N} \frac{1}{j^4}} \\ &= 10\log \frac{1}{1 + 2 \times (\frac{1}{3^4} + \frac{1}{5^4} + \frac{1}{7^4} + \frac{1}{9^4} + \cdots)} \cong -0.124dB \end{aligned} \tag{7}$$

$$\begin{aligned} &CINR_{Proposed\ Scheme\ II} \\ &\cong 10\log \frac{P(k-1,k)}{\sum\limits_{j=2,-4,5,-7,8,-10,11,\cdots}^{N} P(k-j,k)} \\ &= 10\log \frac{P(k-1,k)}{P(k-1,k) \times \sum\limits_{j=2,-4,5,-7,8,-10,11,\cdots}^{N} \frac{1}{j^4}} \\ &= 10\log \frac{1}{\frac{1}{2^4} + \frac{1}{4^4} + \frac{1}{5^4} + \frac{1}{7^4} + \frac{1}{8^4} + \frac{1}{10^4} + \frac{1}{11^4} + \cdots} \cong 11.62dB \end{aligned} \tag{8}$$

IV. PERFORMANCE EVALUATION

Simulation has been performed to evaluate the performance of the proposed schemes. The key parameters of the simulation are set according to IEEE 802.16 Standard [2], [16], which are summarized in Table 4 [17], [23], and [24]. To model MMR networks, we consider a relay network with 1 BS and 4 non-transparent RSs located in a linear fashion as shown in the left of Fig. 4. We assume serving stations (BS/RSs) use omni-directional antennae and transmit with the frequency reuse factor of 1 for high capacity, namely sharing the same frequency bandwidth [25]. For IEEE 802.16j draft standard scheme, we also consider the cases where BS uses a directional antenna to RSs/MS to reduce interference for comparison with our schemes. Table 6 compares our proposed schemes against the scheme in IEEE 802.16j draft standard [2], [3] with omni-directional antennae, with directional antennae and the scheme

Table 4. The Parameters used the simulation

Parameters	Value
System Bandwidth	10 MHz
FFT Size	1024
Null Sub-Carriers	184
Pilot Sub-Carriers (DL/UL)	120 / 280
Data Sub-Carriers (DL/UL)	720 / 560
Sub-Channels (DL/UL)	30 / 35
Symbol Period	102.9μs
Frame Duration	5 ms
Permutation (DL/UL)	PUSC / PUSC
Sampling factor (n)	28 / 25
Number of symbols in a frame (DL : UL)	47 (26 : 21)
TTG	121.2μs
RTG	40.4μs

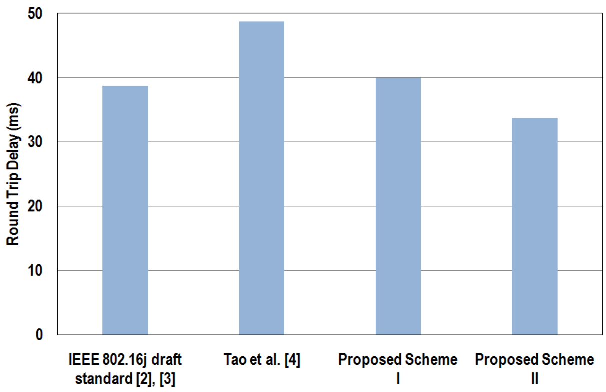


Fig. 8. Comparison of round trip delay (RTD)

by Tao *et al*. in terms of round trip delay and throughput. The numbers in (%) are obtained by comparing the performance of a scheme against the scheme in IEEE 820.16j draft standard with omni-directional antennae as shown in equation (9).

$$Relative\ Performance(\%) = \frac{R_{a\ scheme}}{R_{IEEE802.16j(Omni-directional)}} \times 100 \quad (9)$$

Additionally, we evaluate the performance when packet losses occur in downlink. We consider packet loss probability is 1% and 0.1%.

A. Round Trip Delay

Round trip delay (RTD) [2], [18], [26] is the end-to-end latency of round trip travel of a packet from BS to MSs served by the last RS via intermediate RSs on the path. We estimate how many sub-frames are needed for an MS to transmit a packet to BS and then receive an immediate response from the BS. The duration of each sub-frame is about 2.5ms. Fig. 8 shows that the RTD of our proposed scheme II excels other schemes. Compared with the schemes based on IEEE 802.16j draft standard [2], [3], RTD is reduced by 13%. Compared with the scheme by Tao *et al*. [4], RTD is reduced by 30%.

B. Throughput

Throughput of our schemes which exploit network coding depends on whether uplink traffic and downlink traffic are balanced or not. We expect the greater throughput gain for more balanced traffic. A recent trend in the use of the Internet exhibits that data traffic from user created content (UCC) is rapidly growing with a potential to create a huge amount of uplink (UL) traffic. Therefore, we consider two cases that ratios of uplink traffic to downlink traffic are 1:1 and 2:1, respectively. If the ratio is 2:1, mismatch in downlink traffic and uplink traffic may result in waste of resource in the uplink transmission if we assign the same amount of time slots as the downlink transmission. We assume a log-normal fading environment for our simulation. AMC (adaptive Modulation and Coding) is used between serving station (BS or RS) and MS. MCS levels used for estimated SINR are summarized in Table 5 [22].

Table 5. Modulation and coding schemes (MCS)

MCS Level	Coding Rate	SINR (dB)
QPSK	1/12	-3.95
QPSK	1/6	-1.65
QPSK	1/3	1.5
QPSK	1/2	4.3
QPSK	2/3	7.95
16QAM	1/2	9.3
16QAM	2/3	13.1
16QAM	3/4	15.8
64QAM	2/3	18.45
64QAM	5/6	24.8

Packet Error Rate < 1%
AMC with Diversity Channel
Ped-A 3km/h

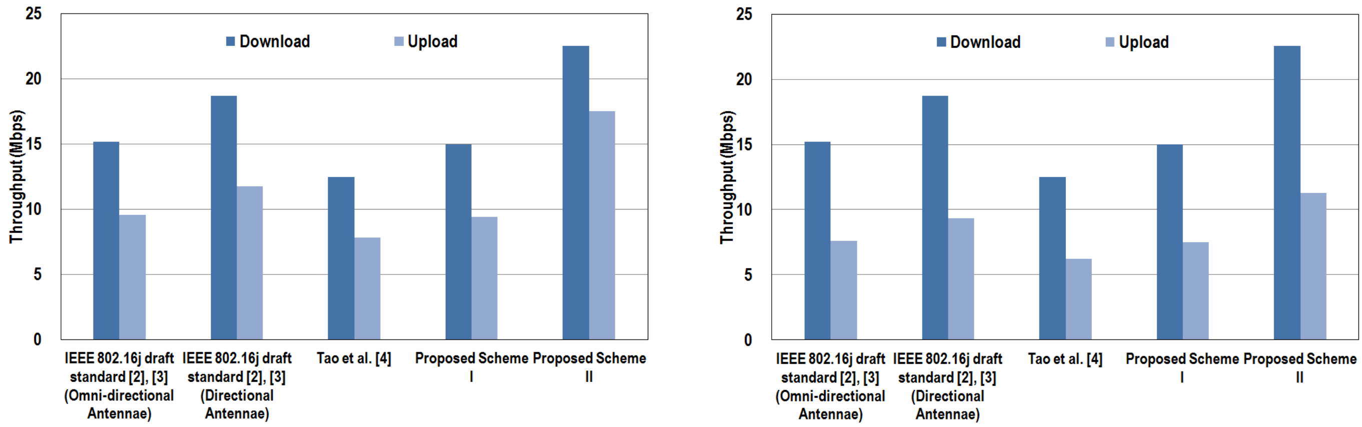
Each MS is assumed to have only one transport connection which has infinite traffic supply. Also, the ratio of the relay zone to the access zone is assumed to be one to one. Fig. 9 compares the throughput of our schemes against previous schemes assuming symmetric traffic supply as in Fig. 9 (a) and assuming asymmetric traffic supply as in Fig. 9 (b). In the asymmetric case, the ratio of downlink traffic and uplink traffic is assumed to be 2:1.

Table 6 summarizes the performance evaluation and relative performance of each scheme compared against that of improvement of each scheme compared with the scheme in IEEE 802.16j draft standard assuming omni-directional antennae. Proposed scheme II excels all other schemes also in terms of the throughput. It shows 49% and 84% more in downlink and uplink, respectively when traffic is symmetric and 49% and 48% for when traffic is asymmetric (2:1). Employing directional antennae turns out to be 23% more throughput. The scheme by Tao *et al*. [4] shows 18% less throughput. When traffic is asymmetric by 2:1, the improvement of proposed scheme II is decreased to about 35% in uplink.

Table 7 shows effect of packet loss rate on the throughput for our proposed scheme II compared with the IEEE draft standard. Since the MCS levels are chosen in such a way as the packet loss rate is kept below 0.1%, we show simulation when packet loss rate is 1% and 0.1% respectively. The throughput degradation for our scheme is greater than the IEEE draft standard. However the difference is negligible as shown in Table 7.

V. CONCLUSION

Attempt is made to incorporate the network coding for IEEE 802.16j Mobile Multi-hop Relay networks. Based our observation that current simultaneous transmission scheme for multi-hop relays in IEEE 802.16 draft standard may involve interference among relays themselves, we devise schemes to avoid the interference while improving throughput via network coding. A new formula for scheduling packet movement is derived to improve the throughput. Since current frame structure is not compatible with broadcast operations required by network coding we propose a new frame structure to incorporate the network coding without losing compatibility with legacy MS(mobile sta-



(a) Symmetric traffic supply (Down : Up = 1 : 1)

(b) Asymmetric traffic supply (Down : Up = 2 : 1)

Fig. 9. Throughput of our scheme compared against previous schemes

Table 6. The result of performance evaluation

	End-to-End Latency (ms)	Throughput(Mbps)			
		Symmetric Down:Up(1:1)		Asymmetric Down:Up(2:1)	
		Down	Up	Down	Up
IEEE 802.16j draft standard (Omni-directional Antenae) ([2], [3])	38.75 **(100%)**	15.19 **(100%)**	9.54 **(100%)**	15.19 **(100%)**	7.60 **(100%)**
IEEE 802.16j draft standard (Directional Antennae) ([2], [3])	38.75 (100%)	18.72 (123%)	11.76 (123%)	18.72 (123%)	9.36 (123%)
Z. Tao, A. Li, K.H. Teo, and J. Zhang ([4])	48.75 (126%)	12.48 (82%)	7.84 (82%)	12.48 (82%)	6.24 (82%)
Proposed Scheme I	40.00 (103%)	14.98 (99%)	9.41 (99%)	14.98 (99%)	7.49 (99%)
Proposed Scheme II	33.75 (87%)	22.56 (149%)	17.55 (184%)	22.56 (149%)	11.28 (148%)

Table 7. Throughput degradation when packet loss rate is not zero

	Throughput degradation	
	(P=1%)	(P=0.1%)
IEEE 802.16j draft standard ([2], [3])	-2.00%	-0.20%
Proposed Scheme II	-2.70%	-0.27%

tion)s.

ACKNOWLEDGMENTS

This study was supported by the Seoul Research and Business Development Program, Seoul, Korea.

REFERENCES

[1] ITU-R, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000," Rec. M. 1645, 2003.

[2] IEEE Std 802.16j Draft, "Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems - Multi-hop Relay Specification," Dec. 2007.

[3] W. C. Wong, J. Sydir, H. H. Lee, K. Johnsson, R. Peterson, and E. Visotsky *et al.*, "Frame Structure to Support Multi-hop Relay Operation," Jan. 2007.

[4] Z. Tao, A. Li, K. H. Teo, and J. Zhang, "Frame Structure Design for IEEE 802.16j Mobile Multi-hop Relay (MMR) Networks," in *Proc. GLOBECOM*, pp. 4301–4306, Nov. 2007.

[5] K. H. Teo, Z. Tao, J. Zhang, A. Li, "Adaptive Frame structure for Mobile Multihop Relay (MMR) Networks," in *Proc. ICICS*, pp. 1–5, Dec. 2007.

[6] D. M. Shrestha, S. H. Lee, S. C. Kim and Y. B. Ko, "New Approaches for Relay Selection in IEEE 802.16 Mobile Multi-hop Relay Networks," in *Proc. Euro-Par 2007*, (Rennes, France), Aug. 2007.

[7] R. Ahlswede, N. Cai, SYR. Li, and RW. Yeung, "Network Information Flow," *IEEE Trans. Inform. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[8] S. Katti, H. Rahul, W Hu, D. Katabi, M. Medard, and J. Crowcroft, "XORs in the air: practical wireless network coding," in *Proc. ACM SIGCOMM*, (Pisa, Italy), Sep. 2006.

[9] P. Larsson, N. Johansson, and K.-E. Sunell, "Coded bi-directional relaying," in *the 5th Scandinavian Workshop on Wireless ad-hoc networks*, (Stockholm, Sweden) May 2005.

[10] M. Effros, T. Ho, and S. Kim, "A tiling approach to network code design for wireless networks," in *Proc. IEEE ITW*, pp. 62–66, Mar. 2006.

[11] F. Xue, and S. Sandhu, "Phy-layer network coding for broadcast channel with side information," in *Proc. IEEE ITW*, pp. 108–113, Sep. 2007.

[12] CH Liu, F Xue, "Network Coding for Two-Way Relaying: Rate Region, Sum Rate and Opportunistic Scheduling," in *Proc. IEEE ICC*, pp. 1044–1049, May 2008.

[13] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical layer network coding," in *Proc. ACM MobiCom*, (LA, USA), pp. 358–365, 2006.

[14] S. Katti, I. Maric, A. Goldsmith, D. Katabi, and M. Medard, "Joint Relaying and Network Coding in Wireless Networks," in *Proc. ISIT*, (Nice, France), pp. 1101–1105, Jun. 2007.

[15] S. Katti, S. Gollakota, and D. Katabi, "Embracing Wireless Interference: Analog Network Coding," in *Proc. ACM SIGCOMM*, (Kyoto, Japan), pp. 397–408, Aug. 2007.

[16] IEEE Std 802.16e, "IEEE Standard for Local and metropolitan area networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control

Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1," Feb. 2006.

[17] L. Nuaymi, "WiMAX Technology for broadband wireless access", John Wiley & Sons, Ltd, 2007.

[18] GS. Chu, D. Wang, S. Mei, "A QoS architecture for the MAC protocol of IEEE 802.16 BWA system," *Communications, Circuits and Systems and West Sino Expositions, IEEE 2002 International Conference on*, vol. 1, pp. 435–439, Jul. 2002.

[19] R. Pabst, B. H. Walke, D. C. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. D. Falconer and G. P. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband radio," *in IEEE Commun. Mag.*, vol. 42, no. 5, pp. 80–89, Sep. 2004.

[20] G. Senarath, W. Tong, P. Zhu, H. Zhang, D. Steer, and D. Yu *et al*., "Multihop Relay System Evaluation Methodology (Channel Model and Performance Metric)," Feb. 2007.

[21] J. W. Mark, and W. Zhuang, "Wireless Communications and Networking", Pearson Education, Inc., 2003.

[22] TTAR-0016#, "Evaluation Criteria of Radio Access Technology for 2.3GHz Portable Internet," Aug. 2004.

[23] "Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation," Aug. 2006.

[24] "WiMAX Forum Mobile System Profile Release 1.0 Approved Specification (Revision 1.4.0: 2007-05-02)," Apr. 2007.

[25] W. H. Park, and S. Bahk, "Resource Management Policies for Fixed Relays in Cellular Networks," in *Proc. GLOBECOM*, (San Francisco, USA), p.1-5, Nov. 2006.

[26] M. G. Larrode, A. M. J. Koonen, J. J. V. Olmos, G. J. Rijckenberg, "Transparent transport of wireless communication signals in Radio-over-Fibre systems," *presented at the NOC*, (London, UK), Jul. 2005.

Kyungjun Lee was born in Daejeon, Korea, on March 23, 1982. He received the B.S. degree in Electronic Engineering from Sogang University, Seoul, Korea in 2006. He is currently pursuing his M.S. degree in Electronic Engineering at Sogang University. His major interests include packet based IP protocol, in wireless communications and next generation networks. He is a member of the Korean Institute of Communication Sciences (KICS).

Wonjin Sung received his B.S. degree from Seoul National University, Korea in 1990, and the M.S. and Ph.D. degrees in Electrical Engineering from University of Michigan, Ann Arbor, MI, in 1992 and 1995, respectively. From January 1996 through August 2000, Dr. Sung worked at Hughes Network Systems, Germantown, MD,USA, where he participated in development projects for cellular and satellite systems including base station modems for the IS-136 North American TDMA, multi-mode terminals for medium orbit satellites, and the Inmarsat air interface design. Since September 2000, he has been with the Department of Electronic Engineering at Sogang University, Seoul, Korea, where he is currently an Associate Professor. His research interests are in the areas of mobile wireless transmission, statistical communication theory, distributed antenna systems, and satellite modems.

Ju Wook Jang received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, the M.S. degree in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), and the Ph.D. degree in electrical engineering from the University of Southern California (USC), Los Angeles. From 1985 to 1988 and 1993 to 1994, he was with Samsung Electronics, Suwon, Korea, where he was involved in the development of a 1.5-Mb/s video codec and a parallel computer. Since 1995, he has been with Sogang University, Seoul, Korea, where he is currently a Professor. His current research interests include WiMAX protocols, mobile networks and next generation networks. He received LG Yonam overseas research grant in 2001. He has also built systems for videoconferencing, streaming, home networks and ad hoc networks using protocols like RTP, SIP, multicast, and IPv6.