

Network Coding-Based Relay for IEEE 802.16j Multi-hop Relay Network

Adisak Sukul*, J. Morris Chang**, Pattarasinee Bhattarakosol*

*Department of Mathematics, Faculty of Science, Chulalongkorn University, Thailand.

**Department of Electrical and Computer Engineering, Iowa State University, Ames, IA, USA.

adisak.suk@student.chula.ac.th, morris@iastate.edu, bpattara@sc.chula.ac.th

Abstract— IEEE 802.16j is to enable the operation of multi-hop Relay Stations (RS). It aims to enhance the coverage, per user throughput and system capacity of IEEE 802.16e. However, the Mobile Stations (MSs) which connect to the RS are suffering from exponentially throughput degradation and end-to-end delay increase in congested network. As the number of RS hops increases, so does the degradation and the delay growth, especially on over 3 hops scenarios.

This paper proposes a Network Coding-based Relay scheme for multi-hop relay networks, called NC-based Relay. It allows RSs to combine multiple wireless backhaul transmissions into single transmission using network coding technique. We also propose an improved OFDMA frame structure design for multi-hop relay network, which provides higher utilization for the relay zone by reorganizing the RSs transmission sequence. The analysis and simulation results confirm that the proposed scheme can enhance the throughput gain up to 140%, and reduce the end-to-end delay by up to 83%.

Keywords— WiMAX; IEEE 802.16j; Multi-hop Relay Network; Network Coding.

I. INTRODUCTION

IEEE 802.16j [1] is to enable the operation of multi-hop

Relay Stations (RS). It aims to enhance the coverage, per user throughput and system capacity of IEEE 802.16e [2]. However, the Mobile Stations (MSs) which connect to the RS are suffering from throughput degradation and end-to-end delay increase [3][4]. As the number of RS hops increase, so does the degradation and the delay growth.

The IEEE 802.16j frame structure standard [1] supports two approaches. The first approach allows one or more RS or MR-BS frames to be grouped into a multi-frame with a repeating pattern of allocated relay zones. This approach causes limitation to the relay zone utilization, especially on over 3 hops scenarios. The second approach enables a single-frame frame structure consisting of more than one relay zones. This approach is appropriated to accommodate the network coding. However, the more RS hops increase, the more relay zones of RSs and MR-BS need to stay in idle mode. This will lead to lower the frame structure utilization and cause throughput degradation.

In this paper, we propose a Network Coding-based Relay scheme, called NC-based relay, and the corresponding frame structure. This allows RS to combine multiple sets of data in the wireless backhaul, and transmit it in a single

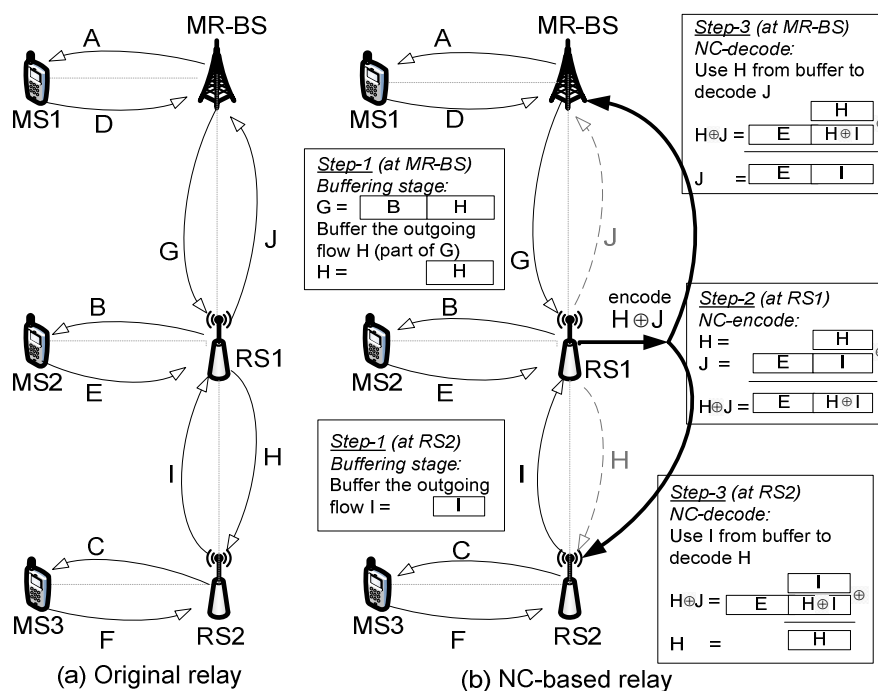


Figure 1. The NC-based relay overview.

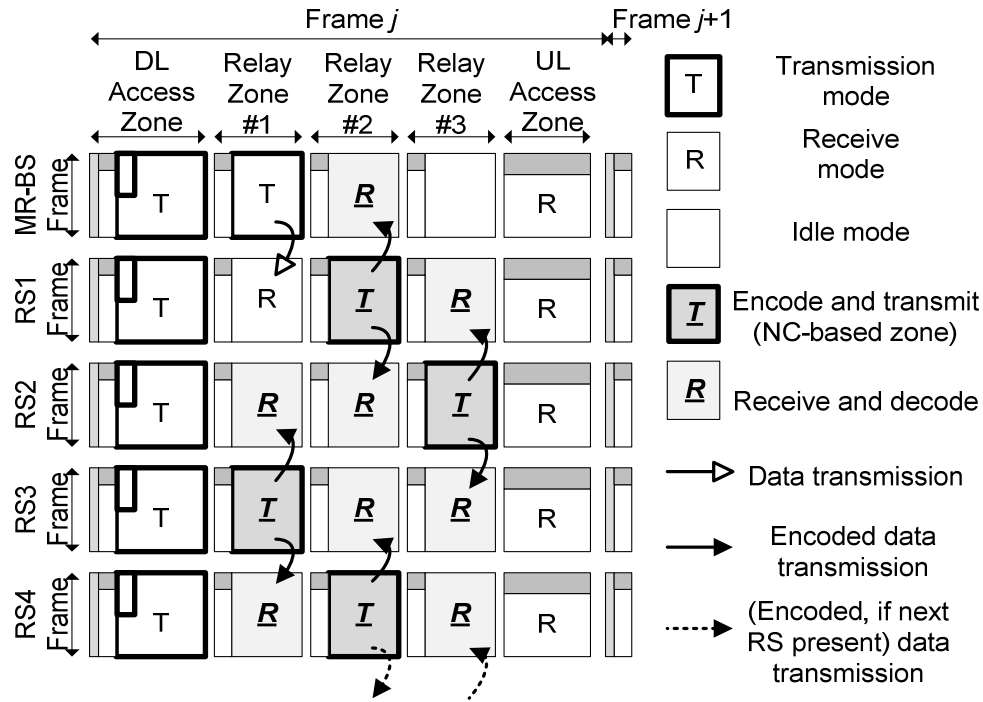


Figure 2. NC-based relay OFDMA frame structure.

transmission instead of two. As a result, it improves both the throughput and the delay. The basic of network coding in IEEE 802.11x wireless network been discussed in [5]. This is the first time that the network coding has been well studied on IEEE 802.16j Multi-hop Relay Network, and the result shows substantial advantage on multi-hop network over 3 hops scenarios. Table 1 lists all notations used in analysis of the following sections.

II. NC-BASED RELAY AND FRAME STRUCTURE DESIGN

A. NC-based relay Overview

Fig. 1 (a) shows the original RS traffic flows. The operations of RS1 are to receive the traffic flows G and I , and transmit the traffic flows J and H . Fig. 1 (b) shows the traffic flows of the proposed NC-based relay. The operations of RS1 were modified to receive the traffic flows G and I , then transmit only one encoded traffic flow which is $H \oplus J$. The encoded flow $H \oplus J$ is encoded from flows H and I which does not have to be in the same length. When RS1 transmit $H \oplus J$, both the MR-BS and RS2 can overhear the encoded traffic over the wireless backhaul. The RS1 needs only three operations instead of four to complete its task. The NC-based relay process spans over three MAC frames (i.e. frame t , $t+1$ and $t+2$). Fig. 1 (b) shows the example of NC-based relay process, which comprises three operations as follows:

1) Step-1 Buffering stage: In the frame t , MR-BS transmits the flow G to RS1, and RS2 transmits the flow I to RS1. MR-BS and RS2 will need to buffer the outgoing data of the flow H (part of G) and flow I , respectively. This allows both MR-BS and RS2 to decode the traffic from RS1 in the step-3.

2) Step-2 NC-encode: In the frame $t+1$, RS1 encodes flows H and J together by the XOR operation. In this

operation, right alignment is used for the shorter flow. Moreover, data bits of the longer flow that have no opponent in this XOR operation will leave unencoded. Then, the RS1 will transmit the encoded flow $H \oplus J$ over the wireless channel, which will be overheard by both MR-BS and RS2.

3) Step-3 NC-decode: In the frame $t+2$, MR-BS decodes the flow $H \oplus J$ by XOR with the buffered data of the flow H . The decoded result is the data of the flow J . Similarly, the RS2 decodes the flow $H \oplus J$ by XOR with the buffered data from the flow I . The decoded result is the data of the flow H .

B. Frame Structure Design

Fig. 2 shows the proposed frame structure that corresponds to the NC-based relay scheme. Each MAC frame of MR-BS or RS comprises DL access zone, UL access zone and three relay zones. These access zones are used for communicating with their covered MSs. Moreover, the three relay zones are used for MR-BS to communicate with the RS, and used for RS to communicate with their super-ordinate and sub-ordinate RSs.

Fig. 2 also presents the transmission sequence within relay zone. Each zone in the transmission sequence can be in either transmission, receive or idle mode. The NC-based relay can be applied to the transmission mode zone, called the NC-based zone. The transmission sequence of MR-BS is assigned to transmission mode in relay zone #1, the receive mode in the relay zone #2, and idle mode in relay zone #3. The transmission sequence of RS1 is assigned to receiving data from the MR-BS on the relay zone #1. The NC-based zone can be applied to the relay zone #2, which encodes and transmits data to both directions (MR-BS and RS2) in a single transmission. The relay zone #3 is to receive and decode an encoded data from RS2. The NC-based zone in each RS transmission sequence is denoted by $RS_{i-NC-zone}$, and can be expressed by

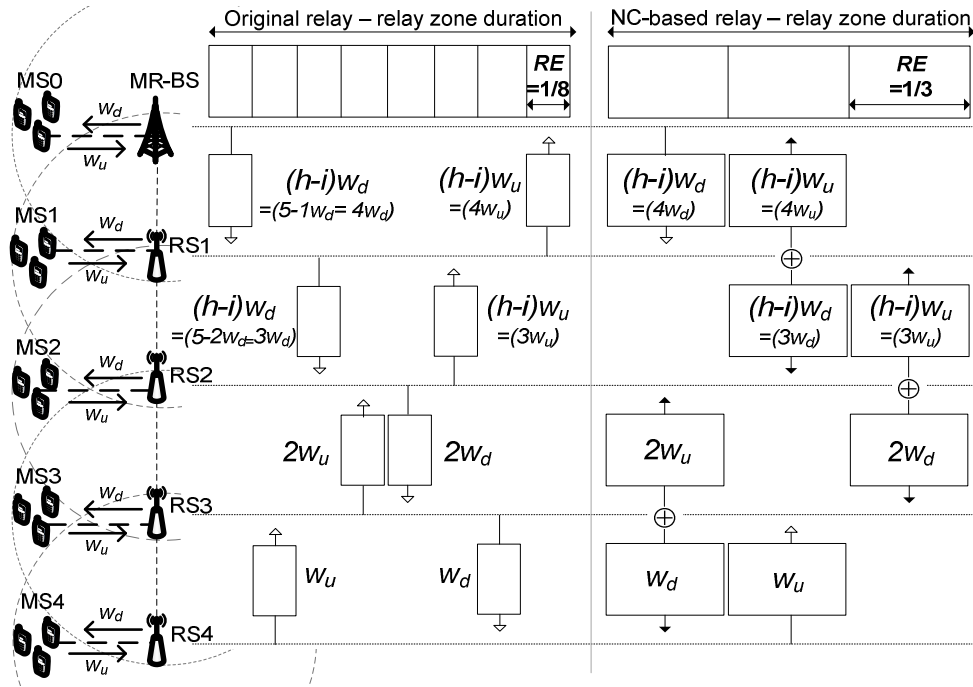


Figure 3. Traffic handled by the relay zone efficiency (RE).

$$RS_{i-NC-zone} = \begin{cases} \text{none} & , i = 0 \\ (i \bmod 3) + 1 & , 0 < i < h \\ \text{none} & , i = h. \end{cases} \quad (1)$$

It is worth noticing that the number of relay zones in the NC-based relay frame is independent to the number of RS hops. However, in the original relay scheme, the idle mode has to be assigned to more zones in the transmission sequence to avoid the transmission interference when the number of RS hops is increased. The idle mode is considered as waste.

III. PERFORMANCE ANALYSIS

We have developed a model to study the throughput degradation and delay increase in IEEE 802.16j Multi-hop Relay Network. For simplicity, we assumed that all MR-BS and RSs operate in the same transmission power and range. Highest modulation is used on all wireless backhaul links. The coverage and interference ranges of each RS can cover super-ordinate RS/MR-BS, sub-ordinate RS and MSs of the RS.

Table 1. Notations Used

Term	Definition
h	Number of total hop
i	Hop count of from MR-BS to considered RS
w, w_d, w_u	Traffic between MR-BS and each MS, Downlink traffic, Uplink traffic
TP_{MSi}	Average throughput on MS_i
F_d	Frame duration
R_d	Relay zone duration
B_w	Channel bandwidth
RE	Relay zone efficiency
ALD_i	Access link maximum throughput archived
DM_{Si}	Average end-to-end delay on MS_i
DM_i	Base station/Relay station operation delay
DP_i	Propagation delay on access link i
DPR_i	Propagation delay on relay link i

A. Relay zone efficiency

Due to the NC-base relay having higher utilization in the relay zone, it results in higher RE than the original relay. Fig. 3 shows RE of 5-hop scenarios of the original relay and the NC-based relay scheme that are 1/8 and 1/3, respectively. The RE of the original relay scheme can be expressed by

$$RE = \frac{1}{2(h-1)} \quad (2)$$

The RE of 3-hop and 4-hop scenarios of the original relay scheme are 1/4 and 1/6, respectively. On one hand, when more RS hops are added to the scenario, RE will decrease in the case of original relay scheme. On the other hand, RE for NC-based relay is always 1/3 and independent from number of RS hops.

B. Throughput Analysis

The fair comparison between the NC-based relay and the original relay scheme was created by making the size equal for following parameters: F_d , R_d and w . We assumed that the ratio of $\frac{w_d}{w}$ and $\frac{R_d}{F_d}$ are both 1/2. The TP_{MSi} of the downlink traffic can be expressed by

$$TP_{MSi} = \begin{cases} \left(\frac{F_d - R_d}{F_d}\right) \left(\frac{w_d}{w}\right) \cdot B_w & , i = 0 \\ RE \cdot \left(\frac{R_d}{F_d}\right) \left(\frac{w_d}{(h-1)w_d}\right) \left(\frac{B_w \cdot F_d}{i}\right) & , i > 0. \end{cases} \quad (3)$$

Note that in (3), the maximum traffic handled by the relay link is given by $\left(\frac{w_d}{(h-1)w_d}\right)$. The end-to-end data rate through the multi-hop link is given by $\left(\frac{B_w \cdot F_d}{i}\right)$. The end-to-end throughputs of 3-5 hops scenarios are shown in Fig. 4 (a).

C. End-to-end Delay Analysis

The proposed NC-based relay and the frame structure can reduce the end-to-end delay. By reordering the transmission sequence of RSs, they allow traffic flow to travel up to 3 RS hops in single MAC frame. The result

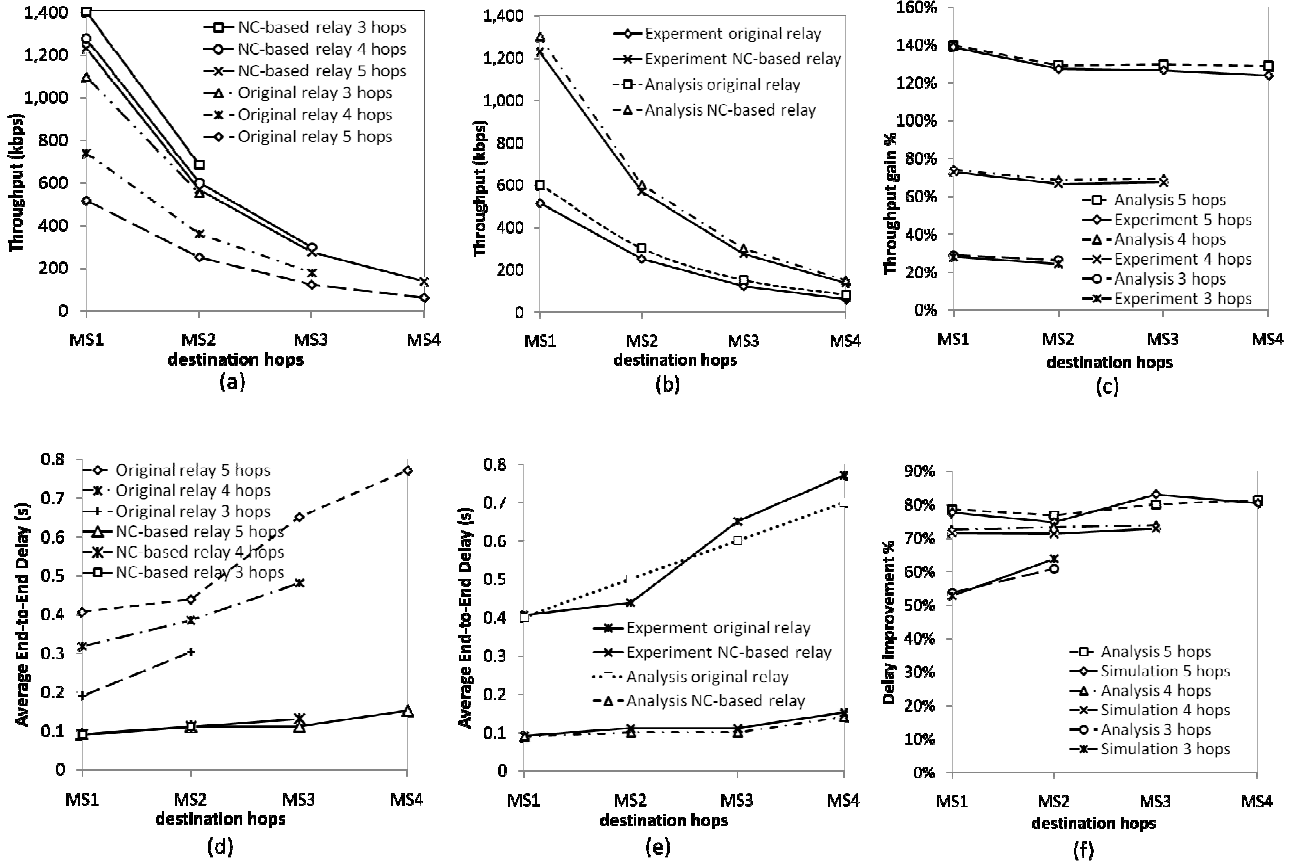


Figure 4 (a). Throughput of NC-based relay compare to original relay, 3-5 hops scenario. (b) Throughput of original and NC-based relay compare to analysis result, 5 hops scenario. (c) Percentage of throughput gain by NC-based relay, 3-5 hops scenario. (d) Average end-to-end delay of original relay compare to NC-based relay, 3-5 hops scenario. (e) Average end-to-end delay of original and NC-based relay compare to analysis result, 5 hops scenario. (f) Percentage of delay improvement by NC-based relay, 3-5 hops scenario.

shows that they reduce the delay in case of multi-hop flow by up to 3 MAC frames duration. Hence, the value of i' is equal to i in original relay scheme. However, in NC-based relay, value of i' is equal to $(i \div 3)$. Average end-to-end delay on each hop can be expressed by

$$D_{MSi} = \begin{cases} DM_0 + DP_0 & , i = 0 \\ (i_r F_d) + \sum_{j=0}^i DM_j + \sum_{k=0}^{i-1} DPR_k + DP_i + \left(\left[\frac{wd}{(h-1)wd} \right] F_d \cdot RE \right) & , i > 0 \end{cases} \quad (4)$$

Note that in (6), the delay from the multi-hop frame structure is given by $(i_r F_d)$. The traffic delay, which is the time that RSs need to clear their buffers, is given by $\left(\left[\frac{wd}{(h-1)wd} \right] F_d \cdot RE \right)$. The operation delay and propagation

delay are given by $\sum_{j=0}^i DM_j$ and $\sum_{k=0}^{i-1} DPR_k + DP_i$, respectively.

IV. EXPERIMENTAL RESULT

In this section, we present the simulation results to demonstrate the performance of the proposed scheme. QualNet 4.5 was extended to support the multi-hop relay function.

A. Simulation Model

To represent a realistic IEEE 802.16j Multi-hop Network, our simulation model has six scenarios which are 3-hop, 4-hop, and 5-hop scenarios with and without the NC-based

relay scheme. Each MR-BS/RS covers 20 MSs. Each MS communicates to the MR-BS with similar traffic. Fig. 3 shows an example of 5-hop scenario configuration. We use the following parameters in the simulation: 300s of traffic flows generated, 64QAM modulation, 20ms for frame duration, 10us for TTG/RTG, 4us for SSTG, Pareto distribution 32-2048 bytes for data size and Poisson distribution arrival with 0.1ms mean interval.

B. Simulation Results

According to the experimental results in Fig. 4, the throughput was measured in (a), (b) and (c). Fig. 4 (a) shows comparisons between throughputs of 3-5 hops scenarios of the original relay against the NC-based relay. The results show a significantly higher throughput of the NC-based relay comparing with the original relay scheme. Fig. 4(b) shows the comparison between the theoretical values from the Equation (3) against the simulation results of 5 hops scenario, based on the original relay and the NC-based relay. The results show that the analysis results and the simulation results are closed to each other; thus, the accuracy of the theoretical model (3) is confirmed.

Additionally, Fig. 4(c) shows the percentage of the throughput gained from the NC-based relay, comparing with the original relay approach from the results shown in Fig. 4 (a). Referring to Fig. 4(c), the throughput gain is 24-28% on 3 hops scenarios, 67-73% on 4 hops scenarios, and 124-140% on 5 hops scenarios.

Delay was measured and shown in Fig. 4(d) to Fig. 4(f). According to Fig. 4(d), the comparison between the average end-to-end delays of total six scenarios, 3-5 hops scenarios of the original relay comparing against the NC-based relay. The results show that in the case of the number of hops is equal, the NC-based relay scenarios provides significantly lower the end-to-end delay than the original relay scheme.

Fig. 4(e) shows the comparison between the theoretical values calculated from the theoretical model (4) against the simulation results of 5 hops scenario, with the original relay and the NC-based relay. The result shows that, on the NC-based relay, there is a small difference between the analysis and the simulation results; this confirms the accuracy of the proposed theoretical model (4). Based on Fig. 4(e), the difference between the simulation and theoretical values of the original relays is occur because there is an unpredictable delay variation from the queue length and packet dropped at each hop during the simulation period.

In order to obtain a clear picture of the performance improvement after applying the NC-based relay, improvement metrics, the percentage of delay improvement are used as the indicators as shown in Fig. 4(f). According to Fig. 4(f), the delay improvement is 53-64% on 3 hops scenarios, 71-73% on 4 hops scenarios and 75-83% on 5 hops scenarios.

V. CONCLUSION

In this paper, we propose a Network Coding-based Relay scheme and the corresponding frame structure that uses XOR network coding. This allows each RS in the multi-hop network to combine multiple set of data in wireless backhaul, and transmit it in a single transmission instead of two. As a result, it improves both the throughput and the delay. Simulation and analysis results confirm that our proposed scheme can enhance up to 140% of throughput gain and can reduce the end-to-end delay by up to 83%. Due to the operations in the proposed scheme are simple to RSs, the proposed scheme can be a practical implement to the IEEE 802.16j multi-hop network.

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