MITSUBISHI ELECTRIC RESEARCH LABORATORIES
http://www.merl.com

Frame Structure Design for IEEE 802.16j Mobile Multihop Relay MMR Networks

Zhifeng Tao, Anfei Li, Koon Hoo Teo, Jinyun Zhang

TR2007-120 September 2008

Abstract

Frame structure is critical to an IEEE 802.16e OFDMA network, as it governs the fundamental channel access in both time and frequency domain. The framework structure design is tremendously complicated in the new mobile multi-hop relay-based (MMR) network architecture, as numerous dimensions of design constraints and challenges have been introduced therein. In this paper, we propose a simple yet flexible framework based upon the current 802.16e OFDMA frame structure design, which enables multihop operation while still maintaining the backward compatibility with the legacy mobile stations. Further performance evaluation not only demonstrates the capacity improvement an MMR network can achieve based upon the proposed frame structure, but also establishes a more profound understanding on the range extension aspect of a relay network.

GLOBECOM 2007

Frame Structure Design for IEEE 802.16j Mobile Multihop Relay (MMR) Networks

Zhifeng Tao[◇], Anfei Li[†], Koon Hoo Teo[◇], Jinyun Zhang[◇]
◇ Mitsubishi Electric Research Laboratories, Cambridge, MA 02139
† Department of Electrical and Computer Engineering, University of Illinois at Chicago, Chicago, IL 60607
Email: {tao,teo,jzhang}@merl.com, ali2@uic.edu

Abstract— **Frame structure is critical to an IEEE 802.16e OFDMA network, as it governs the fundamental channel access in both time and frequency domain. The frame structure design is even more complicated in the new mobile multi-hop relay-based (MMR) network architecture, as numerous dimensions of design constraints and challenges have been introduced therein. In this paper, we propose a simple yet flexible framework based upon the current 802.16e OFDMA frame structure design, which enables multihop operation while still maintaining the backward compatibility with the legacy mobile stations[1]. Further performance evaluation not only demonstrates the capacity improvement an MMR network can achieve based upon the proposed frame structure, but also establishes a more profound understanding on the range extension aspect of a relay network[2].**

I. Introduction

IEEE 802.16 [3] [4] 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 [5] deployment pledged by service providers within United States has already totaled 4 billion USD [6] [7].

However, due to significant loss of signal strength along the propagation path and the transmit power constraint of IEEE 802.16/16e mobile stations (MSs), the sustainable coverage area for a specific high data rate is often of limited geographical size. In addition, blocking and random fading frequently result in areas of poor reception or even dead spot within the coverage region. Conventionally, this problem has been addressed by deploying BSs in a denser manner. However, the high cost of BSs and potential aggravation of interference, among others, render this approach less desirable. As an alternative, a relay-based approach can be pursued, wherein low cost relay stations (RSs) are introduced into the network to help extend the range, improve service, boost network capacity, and eliminate dead spots, all in a cost-effective fashion [8].

In March 2006, a new task group '*j*' was officially established within IEEE 802.16 [9], which attempts to amend current IEEE 802.16e standard [4] in order to support mobile multihop relay (*MMR*) operation in wireless broadband network.

[1]Some concepts and results contained herein have been previously presented at IEEE 802.16 standard meeting in November 2006 and January 2007 as a part of Mitsubishi's proposal for IEEE 802.16j [1] [2]

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

Frame structure is critical to an OFDMA-based 802.16 system, as it governs the fundamental channel access in both time and frequency domain. The design of frame structure for the new mobile multihop relay network architecture is even more complicated, as numerous dimensions of design constraints and challenges have been introduced therein.

Given its nascent nature, however, even the frame structure design for single hop 802.16 OFDMA network has been scarcely discussed or treated, let alone that for a multihop system. Only until recently, for instance, were two frame structures supporting multihop communication in the OFDM mode of IEEE 802.16 system presented in [10]. Unfortunately, since the OFDM and OFDMA mode of 802.16e assume different frame structure, the design proposed in [10] cannot find *direct* application in IEEE 802.16j network, wherein an OFDMA physical layer is a mandate [9].

Based upon the current 802.16e OFDMA frame structure, we propose in this paper a simple yet flexible framework, which enables multihop operation without compromising the backward compatibility with the legacy mobile stations.

The rest of the paper is organized as follows. To supply the necessary background, Section II first briefly describes the frame structure specified in the current IEEE 802.16e OFDMA standard [4] and explains the peculiarities of an MMR system. The proposed generic frame structure design is then elaborated in Section III, and the performance evaluation results are presented in Section IV, further followed by the conclusion and future work in Section V.

II. Background

A. Legacy Frame Structure for IEEE 802.16e

IEEE 802.16 [3] and 802.16e [4] have adopted orthogonal frequency-division multiple access (OFDMA) as the primary channel access mechanism for non-line-of-sight (NLOS) communications in the frequency bands below 11 GHz. The basic unit of resource for allocation in OFDMA is a *slot*, which comprises a number of symbols in time domain, and one subchannel in frequency domain. The base station divides the timeline into contiguous *frames*, each of which further consists of a downlink (*DL*) and an uplink (*UL*) *subframe*.

As illustrated in Figure 1, a DL subframe starts with a preamble, which helps mobile stations (MSs) perform synchronization and channel estimation. The first two subchannels in the first *data* OFDMA symbol in the downlink is called frame

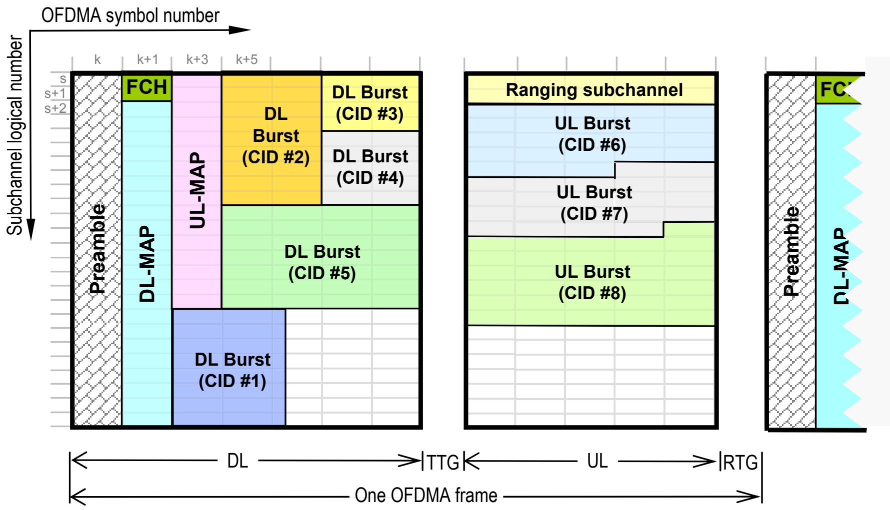


Fig. 1: Legacy 802.16e OFDMA frame structure

control header (FCH), which shall be transmitted using QPSK rate 1/2 with 4 repetitions. The FCH specifies the length of the immediately succeeding downlink MAP (DL-MAP) message and the repetition coding used for DL-MAP. BS uses a downlink MAP (DL-MAP) and an uplink MAP (UL-MAP) message to notify MSs of the corresponding resources allocated to them in the downlink and uplink direction, respectively, within the current frame. Based upon the schedule received from the BS, each MS can determine when (i.e., OFDMA symbols) and where (i.e., subchannels) should it receive from and transmit to BS.

Proper time gap, namely receive/transmit transition gap (RTG) and transmit/receive transition gap, has to be inserted between two consecutive subframes, in order to give wireless devices sufficient time to switch from the transmission mode to reception mode, or vice versa.

Zone is another key concept introduced in 802.16 standard [3], which refers to a number of contiguous OFDMA symbols in the downlink or uplink that use the same *permutation*. IEEE 802.16 standard has defined a handful of permutations, each of which specifies the detailed subcarrier allocation and the mapping of physical subcarriers to logical subchannels. The technique of *zoning* has been extensively used in 802.16e [4] to accommodate a wide variety of antenna and physical layer configurations. BS would inform MSs of the location, format and length of each zone by using certain *information element* (IE) in the DL-MAP and UL-MAP.

B. 802.16j Mobile Multihop Relay Networks

In order to improve capacity and extend coverage range without compromising the backward compatibility with the legacy MSs, IEEE 802.16j task group has been concentrating on designing a minimal set of function enhancement and extension to support mobile multihop relay capability.

An envisioned topology of future IEEE 802.16j MMR network is depicted in Figure 2, wherein RSs help BS communicate with those MSs that are either too far away from the BS (e.g., MS3 to MS7) or placed in an area where direct communication with BS experiences unsatisfactory level of services (e.g., MS1). As indicated in Figure 2, IEEE 802.16j intends to support multihop relaying function, wherein a BS and a multitude of RSs can form a multi-level tree topology and the footprint of such an 802.16 network thus can be significantly expanded in a highly economical manner.

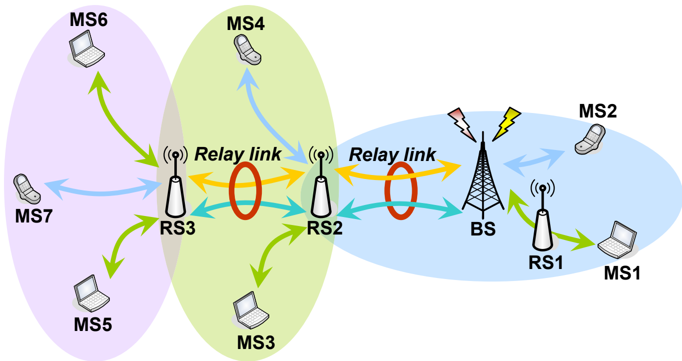


Fig. 2: Topology of a mobile multihop relay network

To facilitate the discussion that follows, several terminologies are defined here. A station is called *access station*, if it is at the point of direct access into the network for a given MS or RS [11]. Note that an access station can be a BS or a RS. A RS is a *subordinate RS* of another station, if that station serves as the access station for that RS. The wireless link that directly connects an access station with its subordinate RS is called a *relay link*, while the link between MS and its access RS is known as *access link*.

III. Frame Structure for MMR Networks

In this section, we set out to introduce the proposed generic MMR frame structure, elaborate the associated signaling, and illustrate the effect of frequency reuse.

Figure 3 and 4 are provided to facilitate the ensuing discussion for the case with and without frequency reuse,

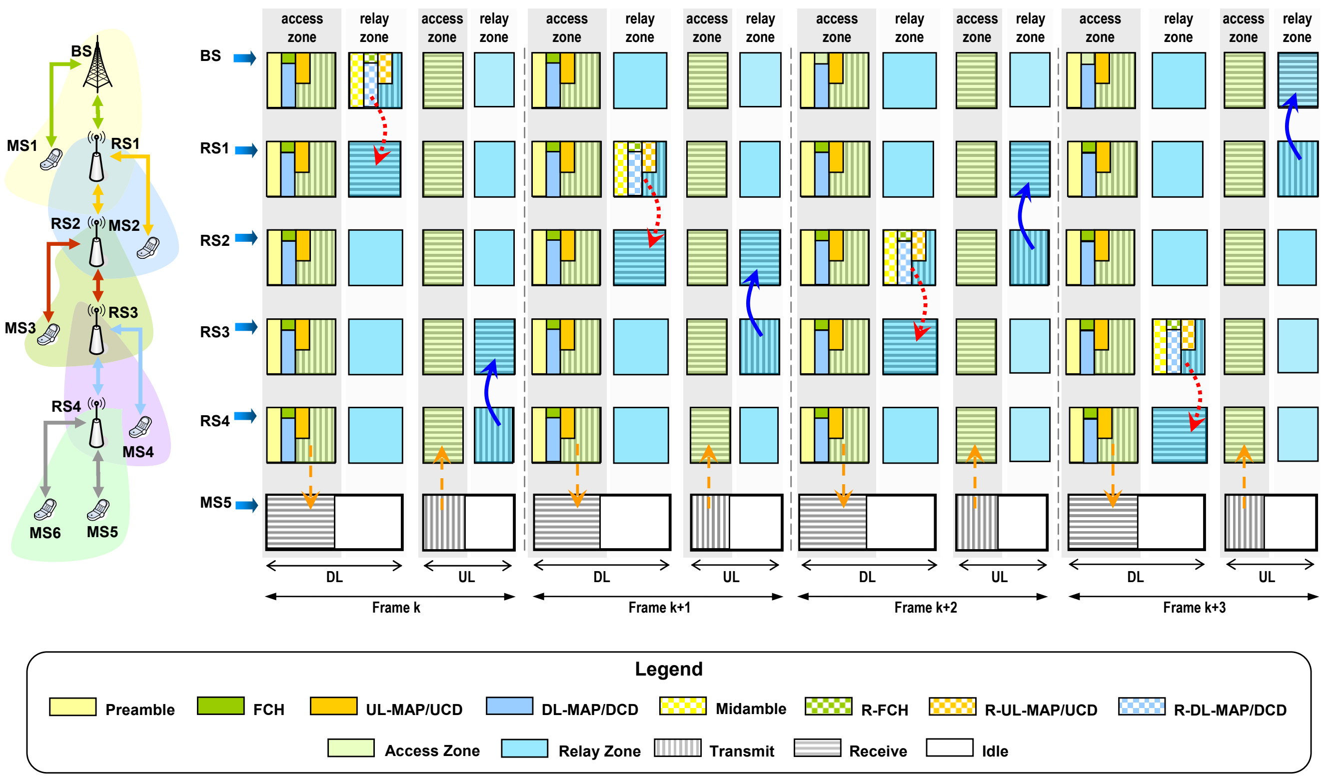


Fig. 3: An illustration of the proposed OFDMA frame structure for 802.16j MMR network - without frequency reuse

respectively. A typical MMR network topology and end-to-end communications occuring therein are illustrated on the left side of these two figures, while the corresponding frame structure perceived at the BS, MS and the intermediate RS along the path is depicted on the right side.

A. Framework

Similar to the legacy design, the new frame structure for MMR netowrk is also composed of a downlink and a uplink portion. However, in order to enable multhop communication, the downlink and uplink subframe is further divided into multiple *zones* in the time domain. As depicted in Figure 3, the first zone in both the downlink and uplink subframe is dedicated for communication that directly engages MSs, and thus is naturally called *access zone*. More specifically, MSs receive from or transmit to the BS or RS with which they are associated in the access zone of the downlink and uplink subframe, respectively.

The access zone in both downlink and uplink may be followed by one or multiple relay zones. In each relay zone, BS and RS can stay in the mode of transmission, reception or being idle. However, it is not expected to have BS or RS switch from one mode to the other within the same zone. For the sake of simplicity, the case where each downlink and uplink subframe further comprises more than one relay zones is not demonstrated in Figure 3 and 4. Nevertheless, the generic frame structure presented herein can accommodate the multi-relay-zone configuration.

B. Signaling

Certainly, proper signaling function has to be installed to support the frequent switch of the zones, without confusing the legacy MSs. The discussion hereafter will concentrate on the functional design, while the detailed format of the signaling messages carried in relay zone will be omitted due to the space limit.

At the beginning of each downlink access zone, the BS and all the RSs should transmit the same preamble as that defined in the legacy 802.16e [3], which can facilitate an 802.16e MS to conduct network entry and synchronize with the BS or the access RS that it associates with.

Similar to the legacy frame structure, both BS and RS transmit in the first data OFDMA symbol in the downlink access zone an FCH, which is immediately followed by a DL-MAP and an UL-MAP. However, the DL-MAP and UL-MAP in MMR frame structure have to convey the new information pertaining to the succeeding relay zone(s) in the same frame. The notion of relay zone remains transparent to legacy MSs, as they will only become aware of the existence of some new zones following the access zone based upon the UL-MAP and DL-MAP, and thus simply stay idle during these relay zones.

Meanwhile, when a RS initially enters the MMR network, it would lock onto the preamble transmitted by BS or existent RSs in the access zone, and establish proper synchronization with the network. The RS can then extract complete information related to succeeding relay zones from the DL-MAP and UL-MAP, and thus become prepared to receive further

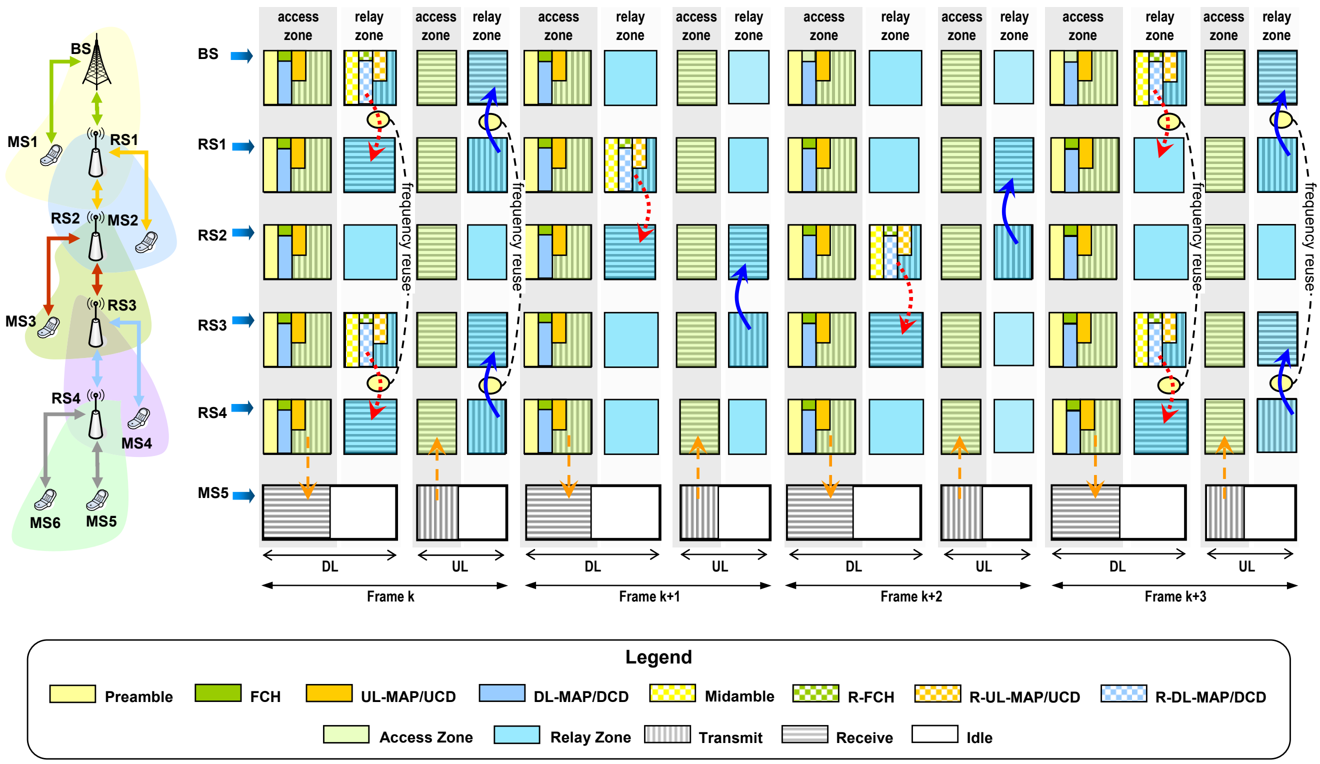


Fig. 4: An illustration of the proposed OFDMA frame structure for 802.16j MMR network - with frequency reuse

signaling instruction in the first downlink relay zone.

In the first downlink relay zone, BS and access RS will transmit its own *preamble*, *relay FCH* (R-FCH), *relay DL-MAP* (R-DL-MAP) and *relay UL-MAP* (R-UL-MAP) consecutively. Since this preamble is placed in an intermediate zone within a downlink subframe, it is also known as *midamble*. Midamble can help further synchronize subordinate RSs with the BS or access RS, while R-FCH specifies the length of the R-DL-MAP. Since the channel on a relay link is expected to enjoy better quality, R-DL-MAP may can be transmitted using a higher modulation scheme and less repetition coding, thereby reducing the signaling overhead. All the detailed burst allocations within each downlink and uplink relay zone of the current frame then will be provided by R-DL-MAP and R-UL-MAP, respectively. Moreover, R-DL-MAP and R-UL-MAP can also indicate the partition of the access zone and relay zone(s) within the frame that immediately follows, therey enabling a flexible and adaptive frame structure configration on a per-frame basis.

C. Frequency Reuse

To improve the overall network performance, multiple wireless transmissions at the same frequency band can occur simultaneously, if there is no destructive interference to a transmission made by others. Figure 4 provides an illustration of possible parallel communications between two pair of nodes in the relay zone (e.g., from BS to RS1, and from RS3 to RS4 in the downlink relay zone of frame k), thanks to frequency reuse.

Apparently, the framework and signaling method proposed in Section III-A and III-B provide sufficient support to exploit frequency reuse. Certainly, in order to fully leverage the channel resources made available by frequency reuse, additional interference measurement and report mechanism will be needed, and intelligent scheduling will be resorted to. However, both subject matters are beyond the scope of this paper and will not be discussed hereafter.

IV. Performance Evaluation

Simulation has been conducted to further evaluate the performance of the proposed MMR frame structure. To concentrate on the proposed schemes, a perfect scheduling and adaptive modulation are assumed. In addition, the performance evaluation is solely based upon the frame structure depicted in Figure 3 and 4, wherein only *one* relay zone exists in both downlink and uplink. Moreover, suppose each MS has only *one* transport connection, which has infinite traffic supply and thus always has packets with a length of 1500 bytes to transmit during the OFDMA symbols assigned to it. Other key PHY and MAC parameters used in evaluation are summarized in Table I.

The throughput capacity and transport capacity of an MMR network is compared with that of a legacy 802.16e system in Figure 5(a) and 5(b), respectively. In the seminal paper by P. Gupta et al. [12], *throughput* capacity was defined as the number of bits that the network can deliver from the original source to the final destination in a unit time in a multihop

TABLE I: Key PHY and MAC parameters

DL/UL Permutation	FFT size	Channel bandwidth	MCS (data)	MCS (MAP and preamble)	Cyclic prefix (G)
PUSC/PUSC	1024	20 MHz	64 QAM 3/4	QPSK 1/2	1/32
Sampling factor (n)	Period for UCD/DCD	Frame duration	Number of UL BW/RNG subchannels	RTG	TTG
28/25	every 10 frames	20 ms	6	10 μs	10 μs

ad hoc network. Meanwhile, *transport* capacity, which is the sum of product of bits and distances over which the bits are carried, is used in [12] to indicate the transport capability of a network. These two metrics are adopted herein to measure the effectiveness of the frame structure in an MMR network.

In this study, a number of MSs are placed in a single cell, which assumes a circular shape with radius of 16 kilometers. Different modulation, namely 64 QAM, 16 QAM or QPSK, is used between the BS and MS, depending on the distance between them.

To model an MMR network, RSs are then deployed in that coverage circle such that all the MSs that previously could reach BS only by using QPSK or 16 QAM now can communicate with BS via a RS through two faster hops.

Both Figure 5(a) and 5(b) clearly reveal that relay network can achieve a significantly higher capacity, regardless of whether it is measured in the end-to-end throughput sense or link-by-link transport fashion. This again confirms that the introduction of relay station in 802.16e network is adequately justifiable, at least from the system performance perspective.

Another important message Figure 5 conveys is that the number of connections plays a critical role in determining the MAC capacity. Indeed, it has already been demonstrated in [13] [14] and discussed in [15] that as the number of connections increases in the legacy 802.16e system, the overhead entailed thereby can cost as much as over 50% MAC efficiency degradation. Given the multihop nature, a more severe performance deterioration can be observed in Figure 5 for an MMR network, when the number of connections grows. This further highlights the imperative need to streamline the MMR protocol and minimize its signaling overhead.

The impact of another key system parameter, namely the *number of hops* in an MMR network, is examined in Figure 6. Instead of focusing on the capacity improvement impact of relaying, Figure 6 intends to concentrate more on the range extension aspect and the effect of frequency reuse. Herein, the traffic between an MS and the BS may need to traverse multiple intermediate RSs to reach intended destination. In addition, all these RSs are carefully spaced so that the relay link between any two adjacent RSs on the same path can sustain 64 QAM modulation.

Figure 6(a) evidently suggests that the MAC efficiency derived based upon throughput capacity would continuously decline, as the number of hops on the communication path increases. Similar conclusion regarding the end-to-end throughput in a chain topology of an IEEE 802.11 ad hoc and mesh network has been known for long in both academia [16] and industry [17]. Instead of having adjacent nodes in an 802.11 ad hoc network compete for channel access in a random manner, an 802.16 MMR network uses the underlying frame structure to coordinate channel access and avoid contention. Nonetheless, the strict structure imposed by this approach and the fact that significant amount of signaling has to be duplicated on each hop to maintain this structure ultimately lead to a throughput degradation of similar degree.

Last but not least, it is also worthwhile to note that if potential frequency reuse exemplified in Figure 4 is taken into consideration, the MAC efficiency would experience an *appreciable* boost, as shown in Figure 6(b).

V. Conclusion and Future Work

This paper introduces a generic frame structure to support mobile multihop relay (MMR) operation of IEEE 802.16j, while maintaining the backward compatibility with the legacy 802.16e mobile stations. The performance evaluation results reported in the paper confirm the need to introduce relays when capacity enhancement in a single cell is desired. Moreover, range extension aspect of relay network has also been examined and impact of frequency reuse on end-to-end capacity has been demonstrated.

Regarding future work, it is worthwhile to evaluate the network performance, when the downlink and uplink relay zone in a single frame of the proposed structure are further partitioned to support alternating among transmission, reception and idle mode. Furthermore, a more comprehensive understanding of the influence that scheduling algorithm may exert shall also be further developed.

References

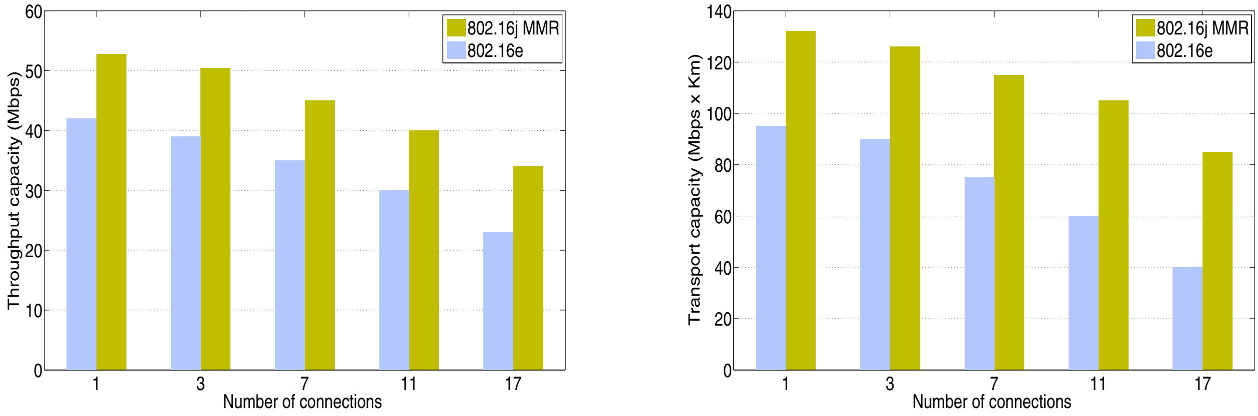
[1] Z. Tao, K. Teo, J. Zhang, and T. Kuze, “A Frame Structure Design for OFDMA-based Multihop Relay Networks,” IEEE C802.16j-06/226, November 2006, http://ieee802.org/16/relay/index.html.

[2] Z. Tao, K. Teo, J. Zhang, and T. Kuze, “An Adaptive Frame Structure for OFDMA-based Mobile Multi-hop Relay Networks,” IEEE C802.16j-07/117, January 2007, http://ieee802.org/16/relay/index.html.

[3] “IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems,” *IEEE Computer Society and the IEEE Microwave Theory and Techniques Society*, October 2004.

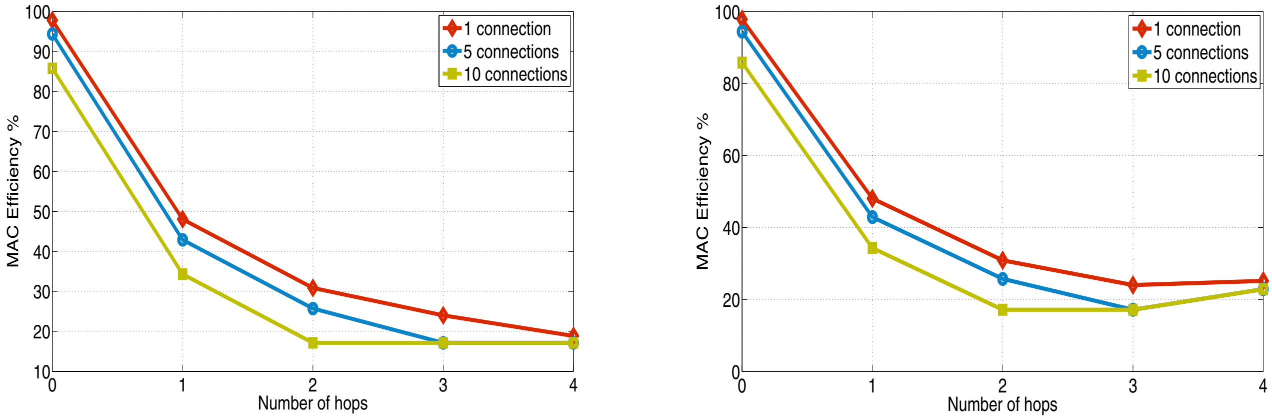
[4] “IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands,” *IEEE Computer Society and the IEEE Microwave Theory and Techniques Society*, February 2006.

[5] “Worldwide Interoperability for Microwave Access,” http://www.wimaxforum.org/home/.



(a) Throughput capacity (b) Transport capacity

Fig. 5: Comparison of MAC capacity between legacy 802.16e and MMR system



(a) Without frequency reuse (b) With frequency reuse

Fig. 6: MAC efficiency versus number of hops

[6] "Sprint Nextel Announces 4G Wireless Broadband Initiative with Intel, Motorola and Samsung," `http://www2.sprint.com/mr/news_dtl.do?id=12960`.

[7] "Clearwire Secures $900M In Financing Round Led by Intel Capital and Announces the Sale of NextNet Wireless to Motorola," `http://www.clearwire.com/company/news/07_05_06.php`.

[8] 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," *IEEE Communications Magazine*, vol. 42, pp. 80 – 89, September 2004.

[9] "IEEE 802.16j Mobile Multihop Relay Project Authorization Request (PAR)," *Official IEEE 802.16j Website: http://standards.ieee.org/board/nes/projects/802-16j.pdf*, March 2006.

[10] C. Hoymann and K. Klagges, "MAC Frame Concepts to Support Multihop Communication in IEEE 802.16 Networks," in *Proceedings of the 16th Wireless World Research Forum*, (Shanghai, China), April 2006.

[11] "Harmonized definitions and terminology for 802.16j Mobile Multihop Relay," *IEEE 802.16j-06/014r1 http://www.ieee802.org/16/relay/index.html*, October 2006.

[12] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, 2000.

[13] S. Redana, M. Lott, and A. Capone, "Performance evaluation of point-to-multi-point (PMP) and mesh air-interface in IEEE standard 802.16a," in *Proceedings of IEEE 60th Vehicular Technology Conference (VTC 2004-Fall)*, (Los Angeles, CA), September 2005.

[14] A. E. Xhafa, S. Kangude, and X. Lu, "MAC performance of IEEE 802.16e," in *Proceedings of IEEE 62nd Vehicular Technology Conference (VTC 2005-Fall)*, (Dallas, Texas), September 2005.

[15] Z. Tao, K. H. Teo, and J. Zhang, "Aggregation and Concatenation in IEEE 802.16j Mobile Multihop Relay (MMR) Networks," in *Proceedings of IEEE Mobile WiMax Symposium*, (Orlando, FL), March 2007.

[16] J. Li, C. Blake, D. S. J. De Couto, H. I. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *Proceedings of the 7th ACM International Conference on Mobile Computing and Networking*, (Rome, Italy), pp. 61–69, July 2001.

[17] "White Paper Capacity of Wireless Mesh Networks," *Whitepaper by Belairnetworks*, 2006, `www.belairnetworks.com/resources/pdfs/Mesh_Capacity_BDMC00040-C02.pdf`.