Adaptive Frame Structure for Mobile Multihop Relay (MMR) Networks

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TR2007-119 September 2008

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ICICS 2007

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***Abstract*— Frame structure is essential to the proper operation of a Mobile Multiphop Relay networks such as the IEEE 802.16e OFDMA network, as it governs the fundamental channel access in both time and frequency domain. The frame structure design is more challenging 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 multi-zone 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].**

***Keywords*—Frame structure, Adaptive Frame Structure, Multi-hop Relay, IEEE802.16j, WiMax**

I. INTRODUCTION

IEEE 802.16 [3] [4] recently has gained industry wide attention as a potential primary technology for broadband wireless access (BWA). 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 coverage area for a specific high data rate is often of limited geographical size. One known solution to this problem is the use of a relay-based approach, wherein low cost relay stations (RSs) are introduced into the network to help extend the range, improve service, boost network capacity, reduce terminal power consumption and eliminate dead spots, all in a cost effective fashion [5]. In March 2006, a new task group 'j' was officially established within the IEEE 802.16, which attempts to amend current IEEE 802.16e standard [4] in order to support mobile multihop relay (MMR) operation in wireless broadband network. 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 complicated in the new MMR network architecture, as numerous dimensions of design constraints and challenges have been introduced therein. Given its nascent nature, however, this subject matter has been scarcely treated. Only until recently, were two frame structures that support multihop communication in the OFDM mode of IEEE 802.16 system presented in [6]. 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 of IEEE 802.16e. The rest of the paper is organized as follows. Section II first briefly describes the frame structure specified in the current IEEE 802.16e OFDMA standard [4] and explains the requirements and challenges posed by 802.16j MMR operation. The proposed generic frame structure design is then elaborated in Section III. The performance evaluation results are presented in Section IV, followed by the conclusion and future work in Section V.

II. BACKGROUND

A. Legacy Frame Format 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. The detail of the frame structure for the access is given in References 3 and 4. 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. Corresponding time gap (e.g., TTG, RTG, R-TTG and R-RTG) is inserted between two consecutive zones, in order to give wireless device sufficient time to switch from the transmission mode to reception mode, or vice versa.

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[1] Some concepts and results contained herein have been previously presented at IEEE 802.12 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

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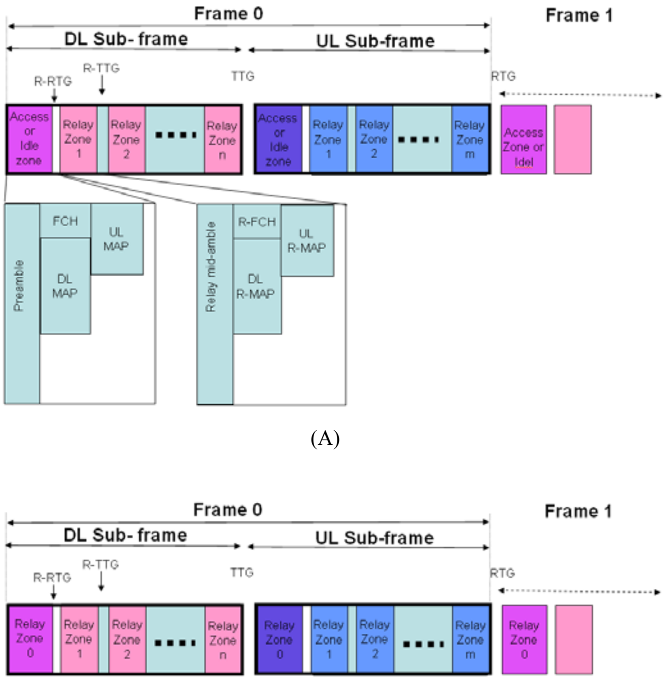


(A)

(B)

Figure 1. Frame Structure for MMR. (A) is for in-band and out-of-band frame structure. Out-of-band frame structure in (a) requires the Access zone to become an idle zone because its carrier frequency is too close to the access carrier frequency of the MS. (B) is for is out-of-band frame structure when the carrier frequency is largely separated from access carrier frequency of the MS. Note: assume R-RTG=RTG, R-TTG=TTG

B. 802.16j Network

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. IEEE 802.16j intends to support multihop relaying function, wherein a BS and multiple RSs can form a multi-level tree topology. A station is called access station, if it is at the point of direct access into the network. Note that an access station can be a BS or RS.

III. FRAME STRUCTURE FOR MMR NETWORKS

Similar to the legacy design, the new frame structure for MMR network is also composed of a DL and an UL portion. However, in order to enable multhop communication, the DL and UL subframe is further divided into multiple zones in the time domain. As depicted in Fig. 1A, the first zone in both the DL and UL subframe is dedicated for communication that directly engages MSs, and thus is naturally called the access zone. More specifically, MSs receive from or transmit to the BS or RS they are associated with in the access zone of the DL and UL subframe, respectively. The access zone in both DL and UL 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 scope of this paper, the case where each DL and UL subframe comprises of more than one relay zones as shown in Fig. 1 will be examined.

As depicted in the Fig. 1A (with first zone as the access zone), the frame structure is meant for in-band relay operation. The number of relay zone in the Dl sub-frame "n", may or may not be equal to the number of relay zone in the UL sub-frame. Both "n" and "m" can be equal to 1 which implies that there is only one relay zone in the sub-frames. When "n" and "m" equals to zero, it implies that the frame structure becomes the frame structure of the 802.16e standards. The duration of both the access and relay are flexible as long as they are confined within the duration of the sub-frame.

The frame structure of Fig. 1 is flexible to support for two or more hops, whether the hops are in a chain or a tree like structure as shown in Fig. 2. It is also flexible to address services where short latency is critical and those which are not.

The number of DL relay zones per sub-frame will be determined by the scheduler and the latency and bandwidth requirements. Similarly the allocations of the sub-channels will also be determined by the scheduler to maximize frequency reuse and minimize RF interference.

Fig. 1A (with first zone as idle rather than Access) and Fig. 1B depicted a frame structure for an out-of-band relaying network. If the carrier frequency of the relaying is closed to that of the in-band carrier, isolation between the two radios would become a challenge. Under these circumstances, Fig. 1A (with idle zone) of the out-of-band option has to be in synchronization with the in-band access zone of the frame structure. If the carrier frequency of the relaying is largely separated in frequency from that of the in-band carrier, then simple filtering is sufficient to isolate the two radios. Under these circumstances, the former access zone can be used also as the relay zone as depicted in Fig. 1B. In this case, the first relay zone (zone 0) mid-amble becomes the preamble. There is also the possibility that post amble be used for the relay zones.

To improve the overall network performance, multiple wireless transmissions can occur simultaneously, if there is no destructive interference of a transmission by others. Fig. 2 shown by the dotted arrows, provides an illustration of possible parallel communications between two pair of nodes during the relay zone, due to possible frequency reuse. Certainly, additional interference measurement and report mechanism are needed to enable frequency reuse. Scheduling also plays a key role in fully leveraging the available channel resources. However, both of these subjects are beyond the scope of this paper and will not be discussed hereafter.

IV. PERFORMANCE EVALUATION

Performance of the MMR network is investigated in terms of throughput capacity and transport capacity solely from a frame structure perspective. Perfect scheduling and adaptive modulation and coding are assumed. Furthermore, to eliminate the performance degradation due to starving of user traffic, saturated traffic arrivals are assumed on all the MSs. Thus, each MS always has packets for transmission

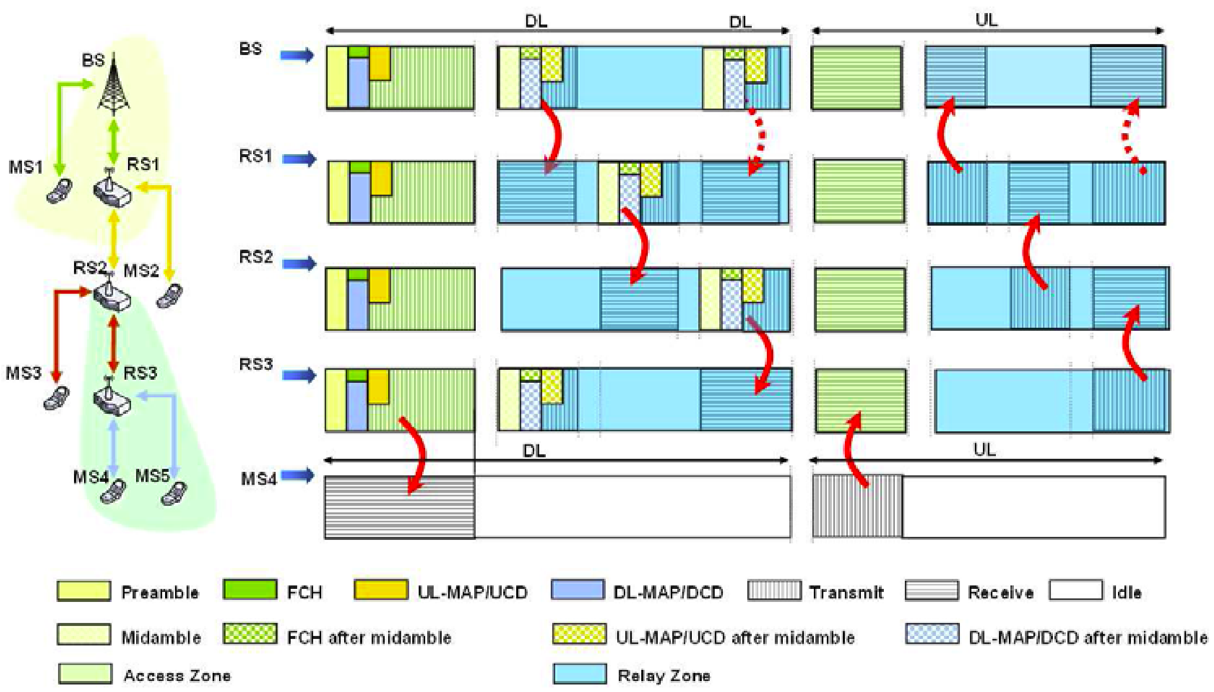


Figure 2. Frame structure for MMR without (solid arrows) and with (dotted arrows) frequency reuse

whenever transmission opportunity is granted. The performance evaluation is solely based upon the frame structures depicted in Fig. 2, wherein more than one relay zones exists in both DL and UL. 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. Some other key PHY and MAC parameters used in the simulation are summarized in Table 1. In the simulation, a single cell with radius of 16 kilometers is considered. A number of MSs are assumed to be geographical-uniformly placed in the cell. Two types of networks, time-division duplex (TDD) single hop IEEE 802.16e (single hop) and TDD MMR IEEE 802.16j (two or more hops) systems are simulated in the cell separately. In the single hop IEEE 802.16e system, no RS is used and three modulation schemes, namely, 64 QAM, 16 QAM and QPSK, are used for transmissions between 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.

TABLE I. KEY PHY AND MAC SIMULATOR

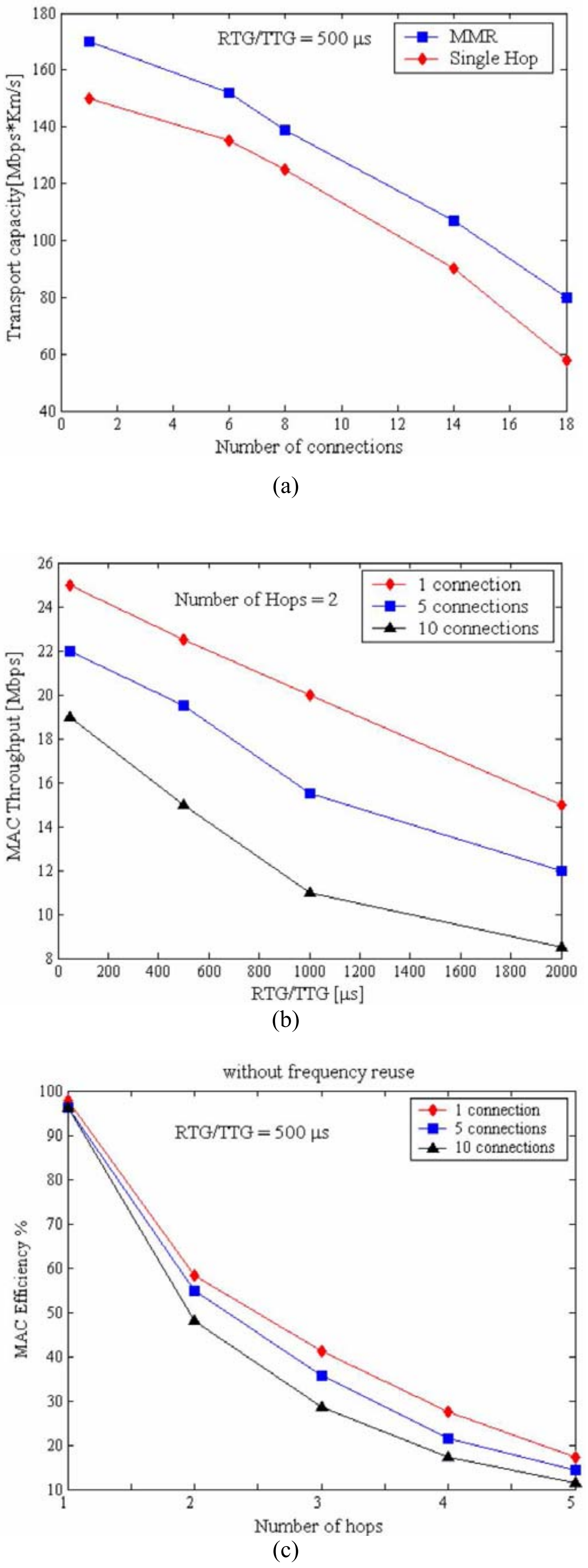
Parameter	**PHY and MAC values**		
DL	PUSC (2 ymbols/slots)	No. of subchannels	30
UL	PUSC (3 ymbols/slots)	No. of data subcarriers/subchannel (DL PUSC)	24
FFT size	1024	No. of subchannels (UL PUSC)	24
Channel bandwidth	20 MHz	No. of data subcarriers/subchannel (UL PUSC)	35
(MCS) for data	64 QAM with ¾ coding rate	No. of UL BW/RNG subchannels	6
MCS for preamble and MAP	QPSK with ½ coding rate	RTG/TTG (us)	50us/50us to 2ms/2ms
Cyclic prefix (G)	1/32	MSDU size (bytes)	1500
Sampling factor (n)	57/50	Cell coverage (km)	16
Frame Length	20ms	No. of CIDs	variable
Preamble	1 symbol	No. of hops for MMR	variable
MCS configuration for MSs of different distance away from BS in single hop simulation			
Within 1 km	64 QAM with ¾ coding rate	1.5 km – 6 km	16 QAM with ¾ coding rate
6 km – 16 km	QPSK with ½ coding rate		

In the seminal paper by P. Gupta et al. [7], throughput capacity was defined as the number of bits that the network can deliver from the original source to the final destination in a time unit in a multihop 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 [7] 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.

The transport capacity of an MMR network is compared with that of a legacy 802.16e system (single hop) in Fig. 3(a) and clearly reveals that relay network can achieve a higher capacity.

Another important message Fig. 3 conveys is that the number of connections plays a critical role in determining the MAC capacity. Indeed, it has already been demonstrated and discussed in [8]–[10] 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 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.

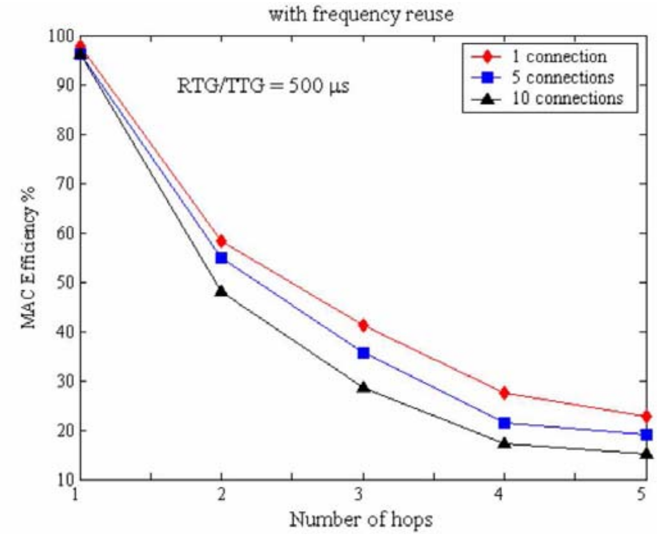
The impact of another key system parameter, namely the number of hops in an MMR network, is examined in Fig. 3. Besides focusing on the capacity improvement effect of relaying, Fig. 3 also concentrates on the range extension aspect and the effect of frequency reuse. Herein, the traffic between an MS 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. The simulation results evidently suggest that the MAC efficiency derivation is based upon throughput capacity continuously declines, 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 established [11]. The simulation results in Fig. 3 also illustrate the degradation of MAC throughput as a function of R-RTG/R-TTG. 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 use 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. It is also worthwhile to note that if potential frequency reuse exemplified in Fig. 2 (dotted arrows) is taken into consideration, the MAC efficiency would experience a boost, as shown in Fig. 3.



(a)

(b)

(c)



(d)

Figure 3. Throughput and MAC efficiency as functions of connectivity and hops

V. CONCLUSIONS AND FUTURE WORK

This paper introduces a generic frame structure to support the 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 that the need to introduce relay 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. A more profound understanding of the influence that scheduling and OFDMA symbol mapping algorithms may exert should be established.

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