ADAPTIVE FRAME STRUCTURE AND OFDMA RESOURCE ALLOCATION IN MOBILE MULTI-HOP RELAY NETWORKS

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ADAPTIVE FRAME STRUCTURE AND OFDMA RESOURCE ALLOCATION IN MOBILE MULTI-HOP RELAY NETWORKS

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To my wife and daughter

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LIST OF SYMBOLS AND ABBREVIATIONS

WMAN	Wireless Metropolitan Area Networks
BS	Base Station
RS	Relay Station
SS	Subscriber Station
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave access
MMR	Mobile Multi-hop Relay
PMP	Point to Multi-Point
TDD	Time Division Duplex
FDD	Frequency Division Duplex
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
nt-RS	non-transparent Relay Station
t-RS	transparent Relay Station
UL	uplink
DL	downlink
TTG	Transmit/receive Transition Gap
RTG	Receive/transmission Transition Gap
SSRTG	Subscriber Stations Receive/transmission Transition Gap
SSTTG	Subscriber Stations Transmit/receive Transition Gap

ASR	Adaptive Split Ratio
BE	Best Effort
PPF	Partial Proportional Fairness
THPF	Two-Hop Proportional Fairness
R-TTG	Relay Transmit/receive Transition gap
R-RTG	Relay Receive/transmission Transition gap
BW	bandwidth
AWGN	Additive White Gaussian Noise
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation

SUMMARY

The objective of this thesis research is to optimize network throughput and fairness, and enhance bandwidth utilization in wireless mobile multi-hop relay (MMR) networks. To enhance bandwidth utilization, we propose an adaptive OFDMA frame structure which is used by the base station and the non-transparent relay stations. To optimize throughput and fairness, we develop an adaptive OFDMA allocation algorithm by using the proposed adaptive OFDMA frame. The effectiveness of the proposed schemes has been verified by numeric simulations.

Providing ubiquitous coverage with wireless metropolitan area networks (WMANs) can be costly, especially in sparsely populated areas. In this scenario, cheaper relay stations (RSs) can be used to provide coverage instead of expensive base stations (BSs). The RS extends the coverage area of traditional BSs. This sort of network is known as a wireless MMR network. This thesis focuses on MMR networks that use orthogonal frequency division multiple access (OFDMA) and time division duplex (TDD) as a multiple access scheme and a duplex communication technique (e.g., WiMAX). The use of OFDMA resources (e.g., OFDMA symbols and subcarriers) and how they are shared in current schemes can reduce system capacity and network throughput in certain scenarios. To increase the capacity of the MMR network, we propose a new protocol that uses an adaptive OFDMA frame structure for BSs and RSs. We also propose adaptive OFDMA resource allocation for subscriber stations (SSs) within a BS or RS. We derive the maximum OFDMA resources that RSs can be assigned and synchronize access zones and relay zones between a superior station and its

subordinate RSs. This is bounded by three properties defined in this thesis: a data relay property, a maximum balance property, and a relay zone limitation property. Finally, we propose max-min and proportional fairness schemes that use the proposed adaptive frame structure. The proposed scheme is the first approach that incorporates the adaptive technique for wireless MMR networks. We evaluate our scheme using simulations and numerical analysis. Results show that our technique improves resource allocation in wireless MMR networks. Further, in asymmetric distributions of SSs between access zones and relay zones, the proposed OFDMA allocation scheme performs two times better than the non-adaptive allocation scheme in terms of average max-min fairness and 70% better in terms of average throughput.

However, the extension of the cell coverage of the BS by placing nt-RSs has two drawbacks: less bandwidth utilization of the nt-RSs and a decrease in the MMR network capacity. The reason for the lower bandwidth utilization is that nt-RSs can use only some amount of the bandwidth assigned by their superior station. The reason for the decreased network capacity is that the first hop nt-RSs are located near the cell boundary, where the signal strength between them and the BS is not sufficient and does not generate an efficient modulation scheme or coding rate. To overcome the first drawback, we introduce a local traffic concept, and to overcome the second, place transparent RSs (t-RSs). The reason for these is that the local traffic of nt-RSs is independent of their superior stations and the t-RSs can enhance the signal strength between the BS and the first-hop nt-RSs.

CHAPTER 1

INTRODUCTION

Due to its ease of deployment and management, the point-to-multipoint (PMP) topology is the most frequently used topology in wireless networks. However, mesh and relay topologies have attracted considerable attention because they increase wireless coverage. In the PMP topology, unlike the mesh and relay topologies, one base station can serve hundreds of subscriber stations, and traffic occurs only between the base station and subscriber stations. In the mesh topology, a subscriber station can create direct communication links to other neighbor subscriber stations. Finally, in the relay topology, subscriber stations can communicate with either a base station or a relay station that is connected to the base station or another relay station. That is, multi-hop communication as well as one-hop communication occur in mesh and relay topologies, increasing wireless coverage. The main difference between the two is that the relay topology uses a dedicated carrier-owned infrastructure (i.e., relay stations) whereas the mesh topology uses subscriber stations (i.e., customer equipment). These topologies are illustrated in Figure 1 [4].

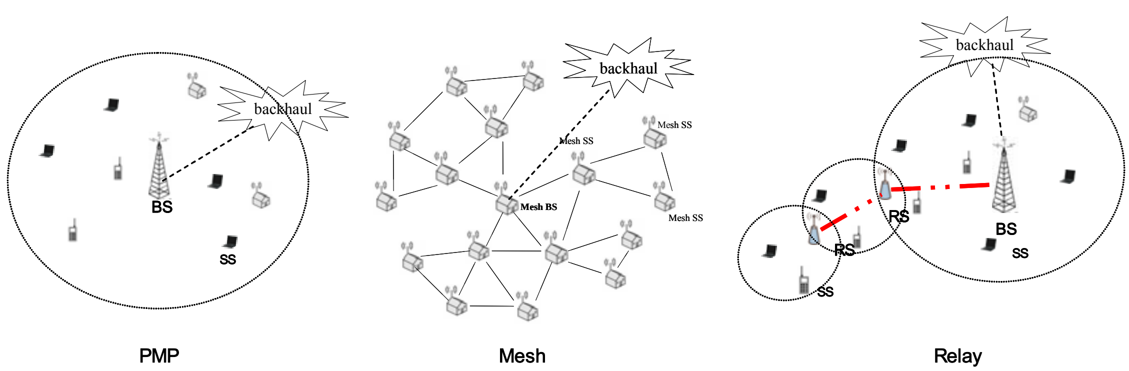

Figure 1. Different types of network topologies.

1.1 Wireless Multi-hop Relay Networks

Recently, wireless mobile multi-hop relay (MMR) networks have been the focus of considerable interest because they enhance network coverage, throughput, and system capacity at a reduced cost by deploying relay stations (RSs) rather than expensive base stations. The newly formed IEEE 802.16j working group, which has introduced MMR networks, is actively standardizing relay schemes for worldwide interoperability for microwave access (WiMAX) [1], [2], [3], [5]-[10]. Over the classical point-to-multipoint (PMP) topology, an MMR network topology can also provide other benefits: flexible cell site placement, decreased subscriber station power, and load sharing [11]. At the same time, however, it has several drawbacks such as increased latency, overhead caused by multi-hop communication, and a complex infrastructure.

MMR networks consist of a base station, relay stations, and subscriber stations, shown in Figure 2. RSs play an important role because they not only supply network access to far-off subscriber stations or hidden subscriber stations but also relay links to a base station or other relay stations. MMR networks consist of two types of communication links: a relay link, which is a link between a base station (BS) and an RS or between a pair of RSs, and an access link, which is a link between a BS and an SS or between a RS and an SS. The access link always originates from or terminates at an SS [12] ~ [18].

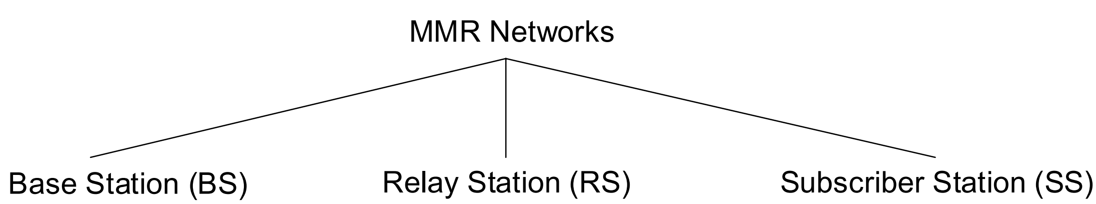

Figure 2. Components of wireless MMR networks.

The IEEE 802.16j MMR network [3], [19] ~ [23] is one example of wireless MMR networks. IEEE 802.16j further classifies MMR networks according to their multi-hop relay functionality, channel information announcement, and mobility. A BS that has mobile multi-hop relay capabilities is called an MMR-BS, and a relay station that broadcasts channel information is called a non-transparent relay station (nt-RS). An nt-RS can operate in either a centralized or distributed scheduling mode while a transparent RS (t-RS) can operate only in centralized scheduling mode determined by the MMR-BS. This detailed classification is shown in Figure 3, and the difference between the nt-RS and the t-RS is shown in Figure 4.

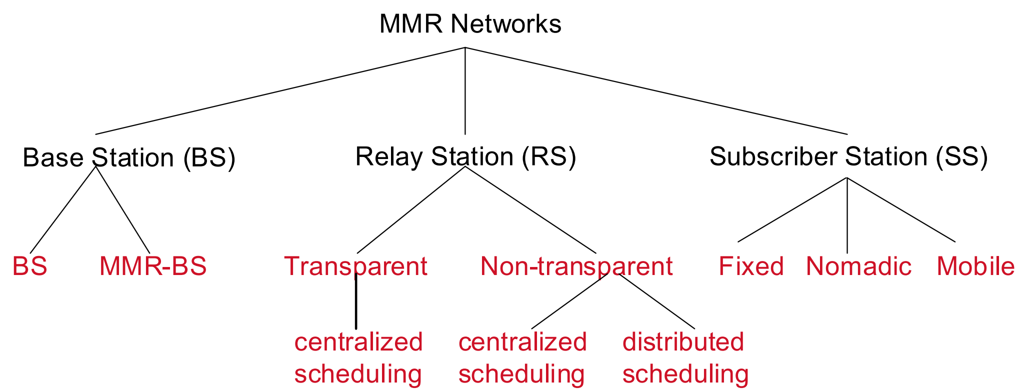

Figure 3. Classification of the MMR networks based on the IEEE 802.16j WG.

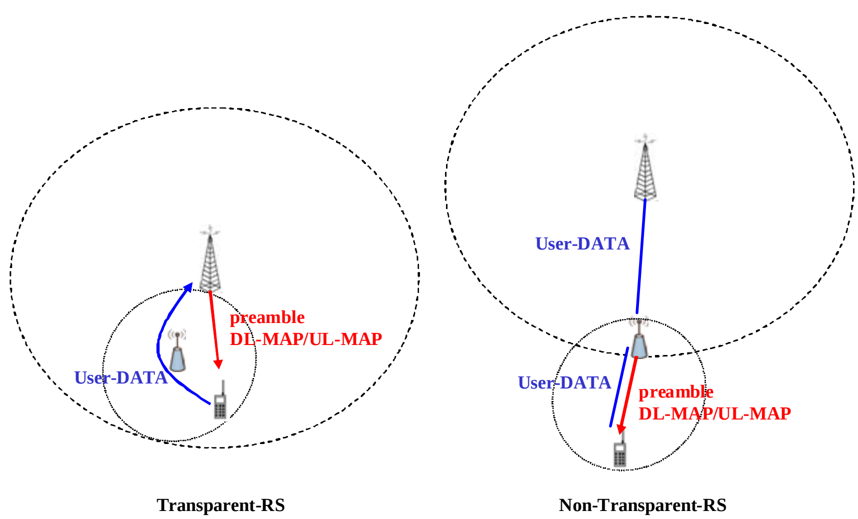

Figure 4. A transparent RS and a non-transparent RS.

1.2 OFDMA and TDD

To understand orthogonal frequency division multiple access (OFDMA), it is useful to start with frequency division multiplexing (FDM) and orthogonal frequency division multiplexing (OFDM). FDM is a technology that transmits multiple signals simultaneously (at the same time slot) over multiple frequencies. Like FDM, OFDM also uses multiple sub-carriers, but they are closely spaced and orthogonal. Because of this orthogonality, OFDM can have more carriers to modulate, so it ends up with more data throughput. OFDMA is referred to as multiuser-OFDM that allows multiple access on the same channel consisting of a group of sub-carriers. In other words, while only one user can use a channel at any given time in the OFDM technique, multiple users can use the same channel simultaneously because they use different sub-carriers (sub-channel). Figure 5 shows the difference between the OFDM and the OFDMA.

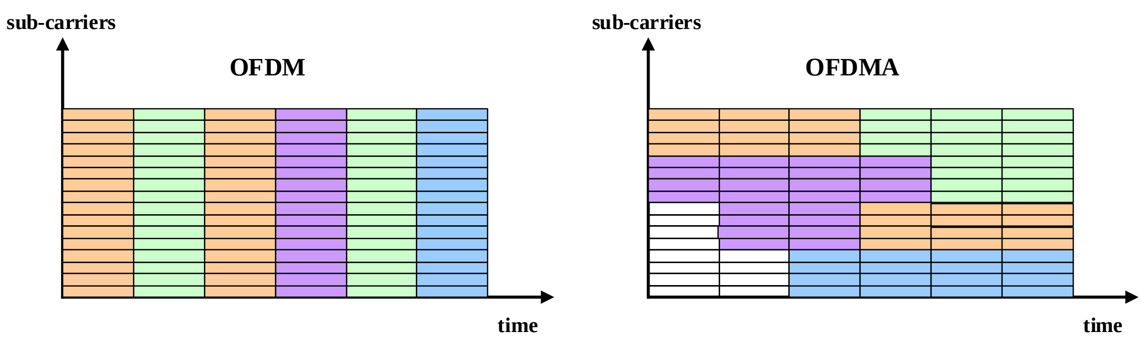

Figure 5. OFDM and OFDMA.

Time division duplex (TDD) and frequency division duplex (FDD) are the two most prevalent duplexing schemes in wireless networks. In TDD, uplink and downlink transmissions occur at different times but share the same frequency. A frame in the TDD mode consists of a downlink sub-frame and an uplink sub-frame, shown in Figure 1 (a downlink sub-frame is followed by an uplink sub-frame). In FDD, uplink and downlink transmissions occur simultaneously because they use different frequencies. In this mode, a downlink sub-frame and an uplink sub-frame are used for downlink transmissions and uplink transmissions, respectively [1], [2].

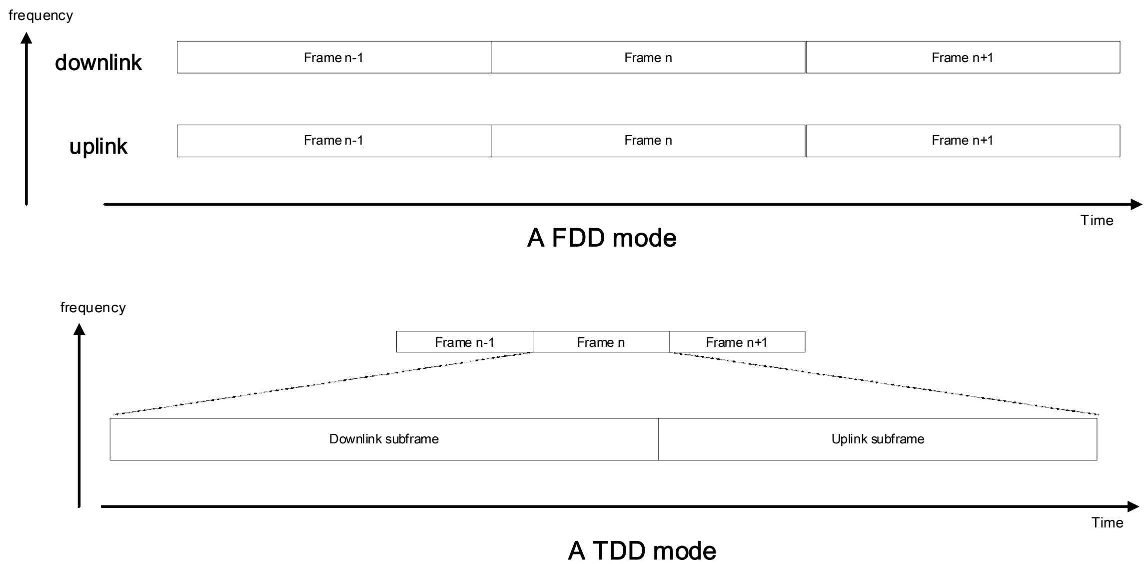

Figure 6. Frequency division duplex and time division duplex.

In this thesis, we have chosen OFDMA and TDD as a multiple access scheme and duplex communication technique, respectively.

CHAPTER 2

BACKGROUND

2.1 OFDMA Resource Allocation

As we explained in Chapter 1, only a single user can transmit on all of the subcarriers at any given time in the OFDM system, and time division or frequency division multiple access is needed to support multiple users. The major drawback to this static multiple access scheme makes different users see the wireless channel differently [24]. OFDMA, on the other hand, allows multiple users to transmit simultaneously on the different subcarriers per OFDM symbol [25], [26], [27]. As a result, subcarriers are assigned to the users who see good channel gains on them. That is, subcarriers and OFDMA symbols need to be managed efficiently to obtain large data throughput. The difference between OFDMA symbols and subcarriers is that symbols are allocated in the time domain whereas subcarriers are allocated in the frequency domain.

Much research has been devoted to finding the most efficient way of assigning a subset of the available radio resources (here, the OFDMA symbol and sub-carriers) to each user in the OFDMA system according to a certain optimality criterion on the basis of the experienced link quality. Generally speaking, OFDMA resource allocation has almost always been addressed with other resource allocation, e.g., power allocation [28], [29], modulation, and the coding rate. For power allocation, the concern is how to maximize the channel capacity given the constrained transmission power, and how to minimize transmission power while providing fixed bit rate. For modulation and the coding rate, SSs close to a BS usually have high channel gains, so they can be assigned higher-order modulation and higher coding rates, but SSs far from the BS be assigned lower-order modulation and lower coding rates because of low channel gains caused by long distance.

Another research issue related to OFDMA resource allocation is the diversity scheme. In such a scheme, three kinds of diversity are defined: multi-user diversity, channel diversity, and cooperative diversity. Multi-user diversity indicates that different users have different fading statistics in a given sub-channel. The main goal of using this diversity is to pick a user with a better signal gain. Channel diversity is sub-channel gain that can vary from one user to another, so users can be assigned to their best sub-channels. In cooperative diversity, a receiver combines relayed signals and a direct signal to improve the SNR. That is, it can be used in wireless multi-hop networks. The basic concept of user diversity is shown in Figure 7 [30], [31].

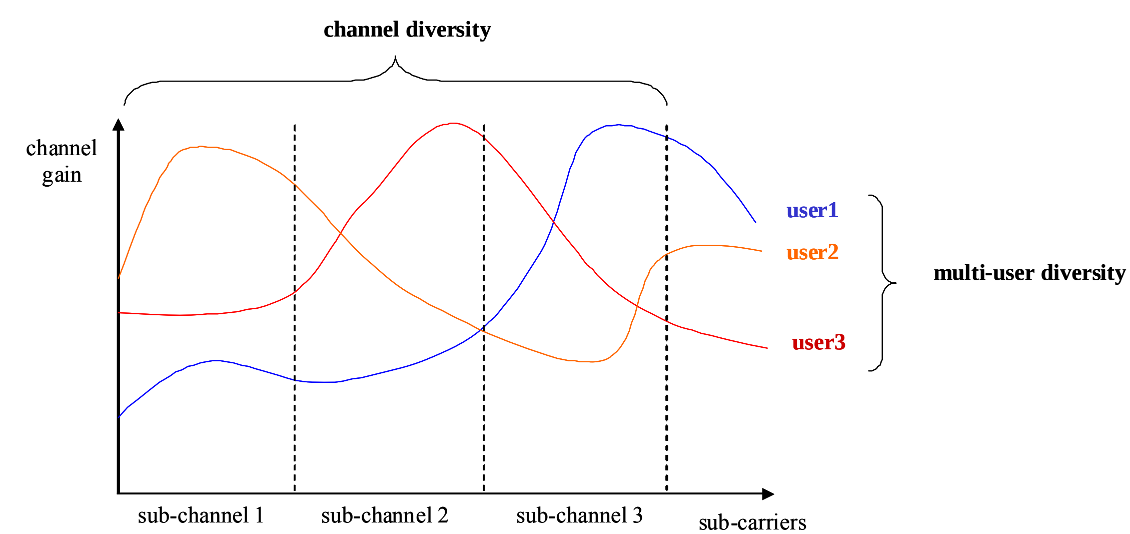

Figure 7. Multi-user and channel diversity.

2.2 *OFDMA Frame Structure in TDD systems*

2.2.1 Frame structure in the PMP topology

The OFDMA frame in PMP networks is built at a BS and transmitted to all SSs associated with the BS. The frame in the downlink transmission (from a BS to SSs) begins with a preamble followed by a downlink (DL) transmission period and an uplink (UL) transmission period. In each frame, the transmit/receive transition gap (TTG) and receive/transmission transition gap (RTG) are inserted between the DL and UL and at the end of each frame, respectively, to allow the BS to turn around. In TDD systems, an SS allowance must be made by an SS Rx/Tx gap (SSRTG) and by an SS Tx/Rx gap (SSTTG). The BS should not transmit DL information to SSs later than SSRTG + RTD before its scheduled UL allocation, and it should not transmit DL information to them earlier than SSTTG – RTD, which stands for "round-trip delay," after the end of the scheduled UL allocation.

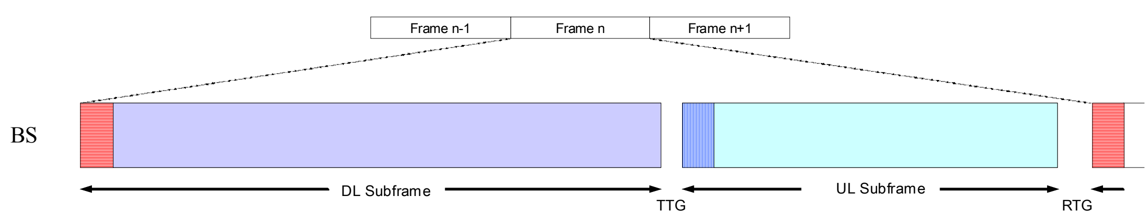

Figure 8. Frame structure with TDD in the PMP networks.

The fixed size of the DL/UL sub-frame has a disadvantage with bandwidth utilization because the load of the downlink and uplink traffic is very hard to match to the pre-determined DL/UL sub-frame size. Due to this problem, the concept of the adaptive

OFDMA frame structure in the PMP networks is shown in Figure 9. In this adaptive frame structure, the duration of the downlink and uplink sub-frame is flexible. The main advantage of the adaptive frame structure is that the downlink and uplink allocation ratio is not fixed. Further, it provides maximum flexibility and system throughput according to the variance in the traffic.

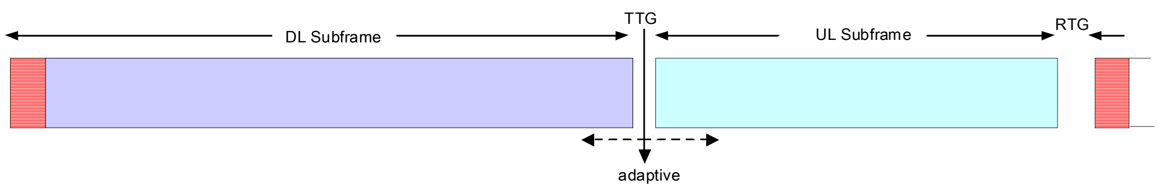

Figure 9. The concept of the adaptive frame structure in the PMP mode.

2.2.2 Frame structure in the MMR topology

Unlike the frame structure in PMP topology, some OFDMA resources should be assigned to RSs to relay data from/to their superior stations and subscriber stations. These are referred to as "relay zones" in the OFDMA frame structure. We introduce how the frame structure is constructed for two types of relay stations: the transparent RS and the non-transparent RS. No two types of relay stations can coexist.

Frame structure for transparent RS (t-RS)

The frame structure for t-RS consists of a DL sub-frame and an UL sub-frame. Each sub-frame might be divided into two parts: an access zone and a relay zone. The DL sub-frame of a BS includes at least one access zone and may include optional a transparent zone for t-RS to support subordinate station transmission. The UL sub-frame of the BS includes an access zone and a relay zone. The DL sub-frame of an RS also includes one access zone for the BS to transmit data to the RS and include optional transparent zone for the RS to serve subordinate stations. Different from the DL sub-frame of the BS, R-RTG should be inserted for the t-RS to switch from a receiving mode to a sending mode [3].

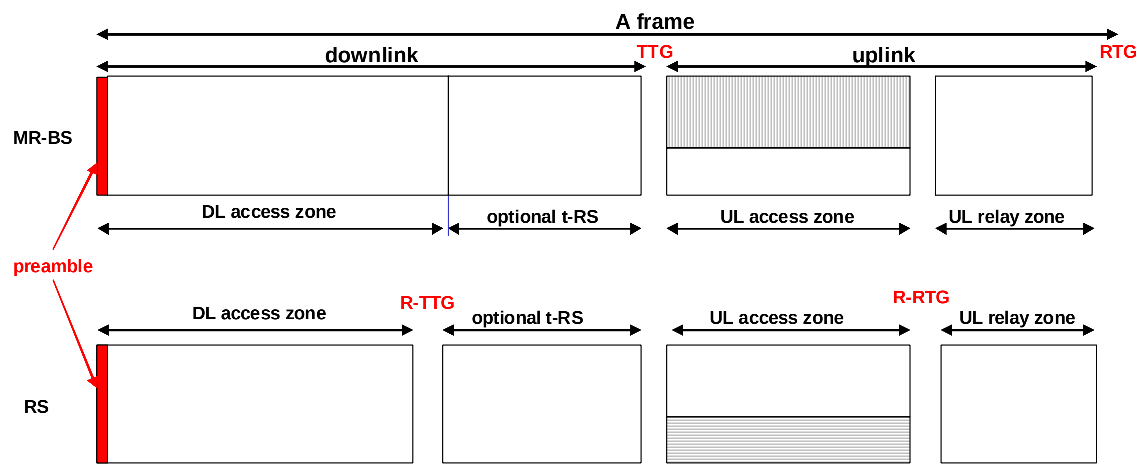

Figure 10. Frame structure for t-RSs.

Frame structure for non-transparent RSs (nt-RSs)

While the relay zone in a DL sub-frame is optional for a t-RS, a DL sub-frame of the nt-RS should have at least one access zone and one or more relay zones to enable the nt-RS to operate in either the transmit or receive mode. The main reason the frame structure is designed differently for each RS is that the t-RS is located within the BS coverage, and the nt-RS is deployed around the edge of the BS coverage. Using the relay zone of the DL sub-frame, the nt-RS can relay data to its SS from a BS. In general, two types of frame structures that support more than two hop relays, a multi-frame structure and a single frame structure, are introduced for the nt-RS. In the multi-frame structure, a BS and RSs are assigned to transmit, receive, or be idle during each of the relay zones within the multi-frame. For example, odd hop RSs transmit in the DL relay zone of an odd number of frames, and the BS and even hop RSs transmit in the DL relay zone of an even number of frames in the multi-frame consisting of two frames. In the single frame structure, the DL sub-frame consists of more than one relay zone. The BS and RSs are assigned to transmit, receive, or be idle in each relay zone within the frame [3].

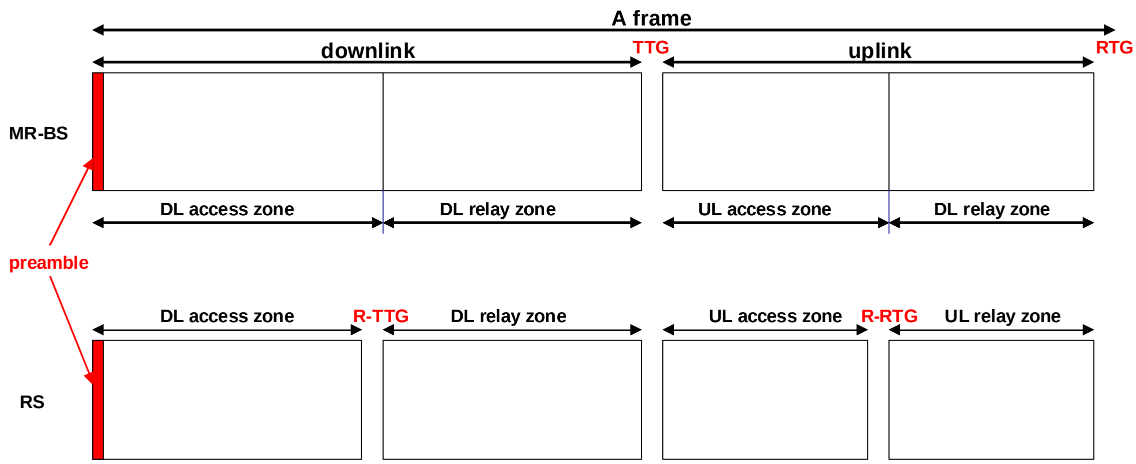

Figure 11. Frame structure for nt-RSs.

2.3 *Fairness and QoS*

Fairness is one of the most important properties in computer networks in which all stations have to share network resources. Without proper fairness, no type of computer network can be successful. This fairness issue has also been a concern in wireless networks because it affects the serviceability of the wireless networks. Much research on the fairness issue has been conducted on wireless networks with PMP configuration. In these networks, a BS is responsible to allocate radio resources fairly to its associated SSs. In this section, we introduce three types of fairness: general fairness, min-max fairness, and proportional fairness.

General fairness is simple but not practical fairness because it gives same amount of resource to all associated nodes. All other fairness is based on this general fairness. The main drawback of general fairness is that it does not consider the difference among the nodes, which ends up with less utilization of radio resources. Min-max fairness shares resources equally based on different resource demands [32] ~ [35]. Resource capacity (C) is first divided by the number of stations (n), and C/n is given to the station with the smallest demand. If the demand is smaller than C/n, the remaining resource from the station is added to another resource and divided by n-1 stations. This process ends when each station has no more than its demand or when no resource to be assigned remains. That is, stations with small demands will be assigned resources that they request, and the remaining resources are distributed to stations with large demand. The main drawback of max-min fairness is that users with the best channel conditions obtain a lower number of resources than users with worst channel conditions. Proportional fairness tries to maximize total wireless network throughput while at the same time allowing all users at least a minimal level of service. The basic procedure of proportional fairness in wireless networks is that it assigns different weight to different stations based on the channel condition and then gives resources to each station with respect to an assigned weight.

2.4 Related Work

2.4.1 OFDMA resource allocation

The authors of [37] proposed the adaptive subcarrier allocation scheme to minimize the total transmission power in the networks while satisfying the data rate requirement of each link. The authors of [38] proposed a low complexity sub-optimal power and subcarrier allocation for the OFDMA system. They designed a heuristic non-iterative method as an extension of the ordered subcarrier selection algorithm for a single user case. The authors of [31] proposed adaptive subcarrier allocation schemes for a wireless OFDMA system in the WiMAX network. They defined the size of a slot consisting of a set of OFDMA symbols and subcarriers and then allocated slots to users based on multi-user diversity. They also considered both fair and proportional allocation, the latter of which will increase bandwidth efficiency. However, the proposed adaptive subcarrier allocation is only for the PMP network topology. The authors of [18] theoretically analyzed bandwidth allocation in an n-hop MMR network consisting of n access links and n-1 backhaul links (relay link). The spectrum efficiency-based adaptive resource allocation (SEBARA) method was also proposed to fully utilize a given overall bandwidth spectrum in an MMR network.

2.4.2 Frame structure with TDD

In terms of the adaptive frame structure with TDD, the authors of [38] proposed an adaptive split ratio (ASR) algorithm for TDD-based WiMAX PMP networks. In the algorithm, a BS determines the downlink and uplink split ratios in a frame according to TCP-based traffic from SSs. The main motivation of this algorithm is that improper downlink and uplink allocation can cause TCP ACK packets that accumulate in an uplink queue to be sent, which eventually degrades the system performance. However, they consider only the best effort (BE) service class to determine the split ratio. The authors of [39] compared different TDD split ratios with different traffic loads and proposed an adaptive TDD split algorithm based on the current traffic load within one cell coverage. As it considers all downlink and uplink traffic, this approach differs from that of [38].

The algorithm first starts with a 50:50 ratio and then measures each downlink and uplink load during the last n frame duration. Based on the measurement, it decides whether to increase the downlink or uplink sub-frame. Even though both [38] and [39] used an adaptive frame, their design is only for the PMP network topology.

With regard to the frame structure in wireless MMR networks, the authors of [40] proposed two types of MAC frame concepts to support multi-hop communication in IEEE 802.16j MMR networks. In the first concept, called the “centralized approach,” a BS has full control over one mobile multi-hop relay (MMR) cell, whereas in the second concept, an RS can control its associated SSs, referred to as the “semi-distributed approach.” The proposed method places a multi-hop sub-frame within either an uplink sub-frame or both downlink and uplink sub-frames, based on which concept has been chosen. Through this approach, any legacy SSs can interpret new MAC frames with a multi-hop sub-frame. The authors of [20] designed a new OFDMA frame structure, in which downlink and uplink sub-frames are divided into multiple zones in a time domain. The first zone in both the downlink and uplink sub-frames is dedicated for access links and followed by one or multiple relay links. In addition, when multiple relay links exist, frequency reuse is also considered in the design. To the best of our knowledge, however, no paper has mentioned the adaptive frame structure in wireless MMR networks.

2.4.3 Fairness and QoS

The authors of [41] introduced temporal and throughput fairness in WiMAX networks with the PMP topology, and proposed a generalized weighted fairness (GWF). In temporal fairness, resources are allocated with an equal number of slots for all active users while they are allocated fairly in terms of the number of transmitted bytes in throughput fairness. The proposed GWF allows wireless carriers to implement temporal fairness, throughput fairness, or a combination of the two. The weight value in the GWF determines what kind of fairness is supported. In addition, they analyzed the proposed GWF with three scheduling algorithms: general processor sharing (GPS), deficit round robin (DRR), and DRR with fragmentation (DRRF).

The authors in [42] analyzed an upper bound blocking probability for four types of QoS classes by using the Gaussian model and the Chernoff bound method. Based on the results of their analysis, they proposed admission control and a bandwidth allocation scheme in IEEE 802.16 networks. The authors of [43] provided a performance analysis of admission control for three types of QoS classes (UGS, rtPS, and nrtPS) after assigning different levels of priority and blocking probability to each class based on a continuous-time Markow chain model. Haidar Safa et al [43] proposed a preemptive deficit fair priority queue (PDFPQ) model that enhanced the DFPQ scheduling algorithm in order to have more chance to serve the rtPS service class. Based on the expected delay of each rtPS connection calculated by the reference time, generation time, and deadline, the proposed scheduler determines whether each connection is critical or not. The authors of [10] implemented a QoS module for IEEE 802.16 networks in the NS-2 simulator, and the authors of [44] proposed a design approach for QoS architecture in 802.16 networks. However, most of these studies pertain to only IEEE 802.16d [1] and IEEE 802.16e standards [2]. That is, few papers have been published in the area of IEEE 802.16j standard drafts. One was conducted by Debalina Ghosh et al [45], who proposed an efficient heuristic algorithm for scheduling data flows within a centrally scheduled multi-hop WiMAX networks. The basic concept of the algorithm is as follows. First, the scheduler tries to allocate bandwidth to satisfy a maximum sustained traffic parameter by tagging extra bandwidth beyond a minimum sustained traffic parameter. Second, if the bandwidth assigned to the service flows is less than the value of minimum sustained traffic, the scheduler looks for the tagged bandwidth and gives it to the service flows that needs more bandwidth.

All the studies mentioned above except for [45] have been conducted using wireless networks with a PMP configuration. In these networks, proportional fairness usually achieves the best tradeoff between system throughput and user fairness, explained Section 2.3. However, this proportional fairness cannot be applied directly in wireless MMR networks since the direct link and relay link are present simultaneously. The authors of [12] proposed a partial proportional fairness (PPF) algorithm based on two-dimensional proportional fairness, which takes advantage of channel variations in the time domain as well as in the frequency domain. However, the authors of [13] pointed out that the PPF algorithm gives an absolute priority to RSs when assigning the two-dimensional resources consisting of time sub-slots and frequency sub-channels. Therefore, they proposed two-hop proportional fairness (THPF) to compensate for the unfairness between RSs and SSs. In the proposed THPF, sub-channels in the first time sub-slot are fairly allocated to RSs and direct link users, and sub-channels in the second time sub-slot are allocated only to relay link users.

2.4.4 Other issues in wireless MMR network

A number of studies have used other approaches in wireless MMR networks. The authors of [48] proposed a way to determine optimal node locations for BSs and RSs in IEEE 802.16j MMR networks. Among a set of candidate BS and RS locations within a given area, the proposed function finds the best located set of BSs and RSs to accommodate user traffic demand. In terms of the MAC protocol, the authors of [49] proposed new MAC protocol data unit (MPDU) concatenation and MAC service data unit (MSDU) aggregation schemes by modifying the packet construction mechanism used in the current IEEE 802.16/16e standard. A new resource scheduling method with directional antennas, especially for Manhattan style environments, where many hidden subscriber stations between buildings resides, was proposed in [50].

CHAPTER 3

ADAPTIVE FRAME STRUCTURE FOR nt-RSs

We consider wireless mobile multi-hop relay (MMR) networks that use OFDMA and TDD as a multiple access scheme and a duplex communication technique, respectively. In this chapter, we have selected non-transparent RSs (nt-RSs) as relay nodes by which the coverage of a BS can be extended. In this system configuration, we propose an adaptive OFDMA frame structure and OFDMA resource allocation for the BS and the nt-RSs. To derive the maximum OFDMA resources that nt-RSs can be assigned given system parameters, we create three properties: a data relay property, a maximum balance property, and a relay zone limitation property. At the same time, we also consider how to adaptively change the size of the downlink and uplink sub-frames on both an access zone and a relay zone.

3.1 Adaptive Frame Structure With One Relay Direction

Based on the basic concept of the adaptive OFDMA frame structure used in PMP networks and the TDD system [1, 8, 9], we first propose an adaptive OFDMA frame structure that can be used in wireless MMR networks. Figure 12 shows that the coverage of a BS is extended into one relay direction. Figure 13 illustrates the proposed adaptive frame structure used in Figure 12. In the first stage (1), the BS splits a frame into a DL and a UL sub-frame, the ratio of which is changeable according to the DL and UL traffic variance. Then, using each sub-frame, the BS assigned OFDMA resources (shadow regions in DL/UL relay zones of the BS) to an nt-RS ($nt\text{-}RS_1^1$). Using the data rate given by the BS (shadow regions in the DL/UL access zones of the nt-RS), the nt-RS serves its associated SSs. The data rate is determined by a combination of OFDMA resources, a modulation scheme, and a coding rate. The ratio of the relay zone to the access zone between the BS and the nt-RS is also changeable, and only the nt-RS requires extra time to switch from a receiving mode/a transmit mode to a transmit mode/a receiving mode. The relay transmit/receive transition gap (R-TTG) and the relay receive/transmit transition gap (R-RTG) show these time durations. In the second stage (2), the second hop nt-RS (nt-RS_1^2) is placed to extend the coverage more. After the nt-RS_1^1 is assigned more OFDMA resources from the BS, the ratio of the DL/UL access to the DL/UL relay zone between the BS and the nt-RS_1^1 changes. Finally, the nt-RS_1^1 can support its nt-RS_1^2 by using the data rate of its relay zone, and the nt-RS_1^2 can serve its SSs by using the assigned access zone.

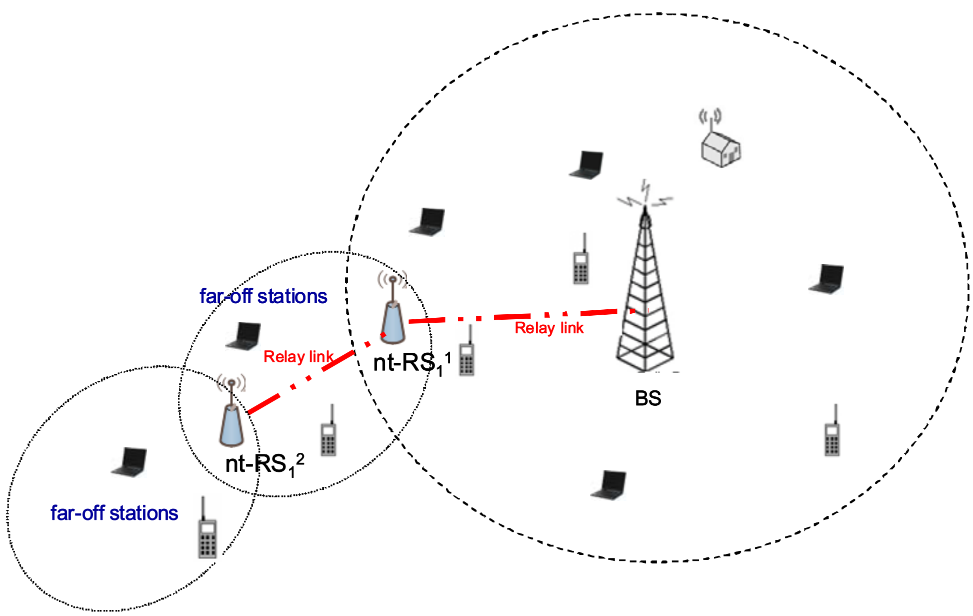

Figure 12. An MMR network with one relay direction

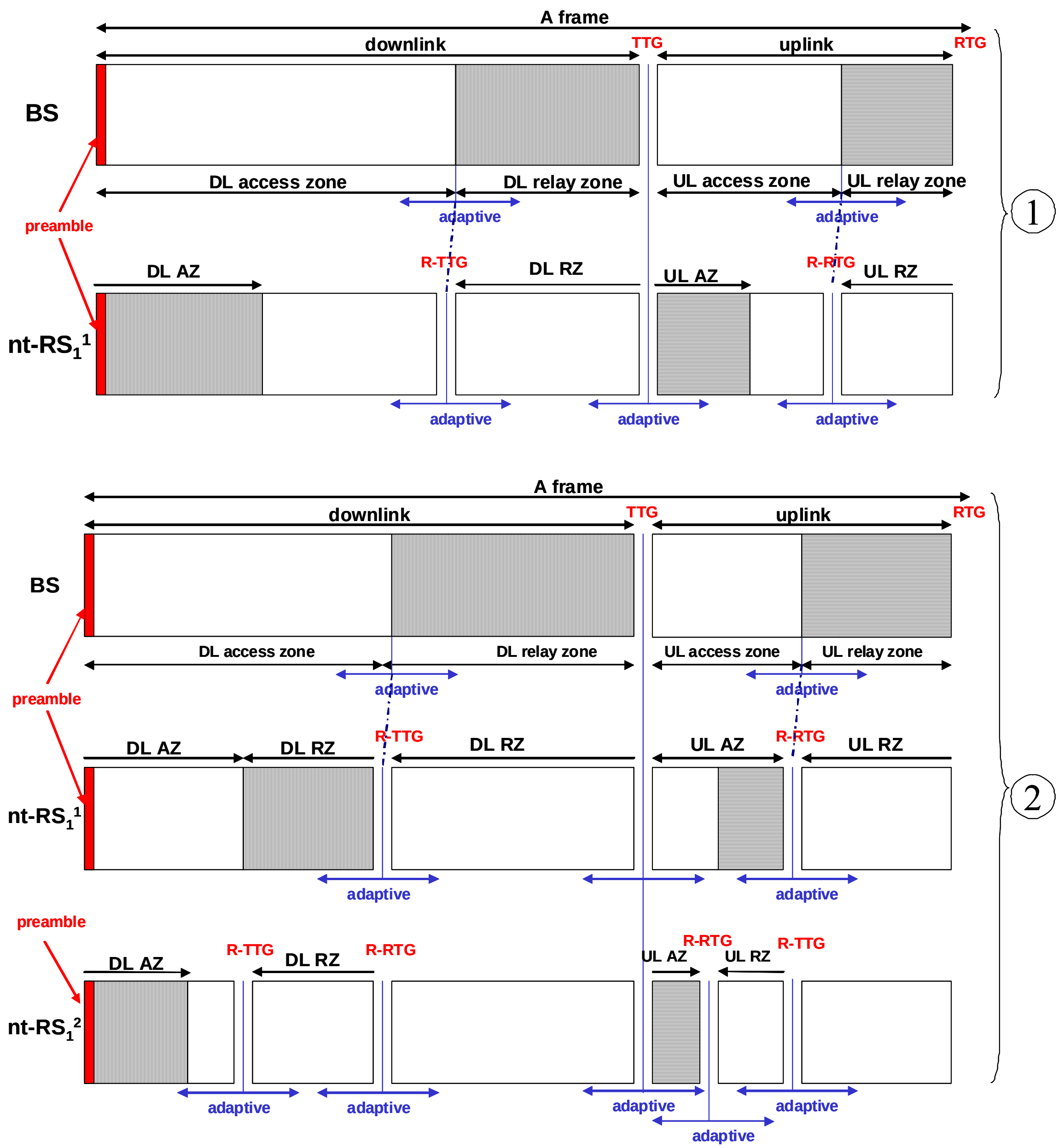

Figure 13. Adaptive frame structure with one relay direction

3.2 Adaptive Frame Structure With Multiple Relay Directions

While Figure 12 shows one relay direction, Figure 14 shows the MMR cell extending in multiple directions. In the first stage (1) of Figure 15, the first hop three nt-RSs share the OFDMA resources of the relay zone in the BS. That is, the sum of the data rate that each nt-RS uses as its access zone should be equal to the data rate of the relay zone in the BS. Through the assigned access zone, each nt-RS supports its own SSs. In the second stage (2), a new nt-RS (nt-RS_1^2) associated with the nt-RS_3^1 is added to extend to one of multiple directions. Only the nt-RS_3^1 splits its access zone into an access zone and a relay zone to support its nt-RS (nt-RS_1^2). Finally, the RS_1^2 can serve its SSs by using the assigned data rate of its access zone.

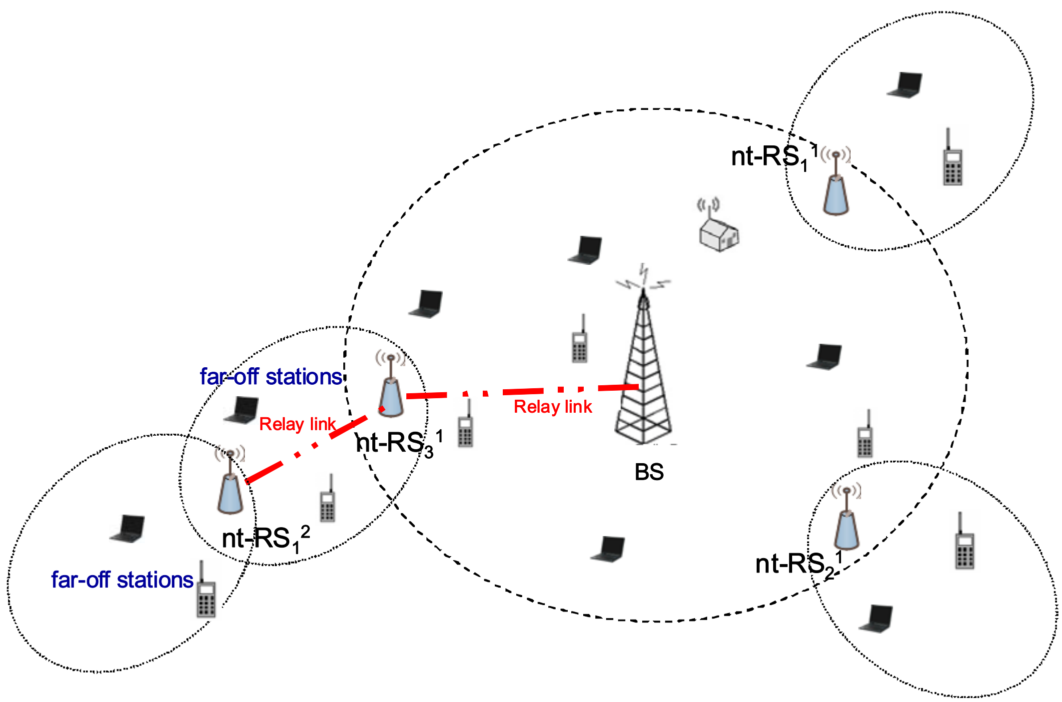

Figure 14. An MMR networks with multiple relay directions

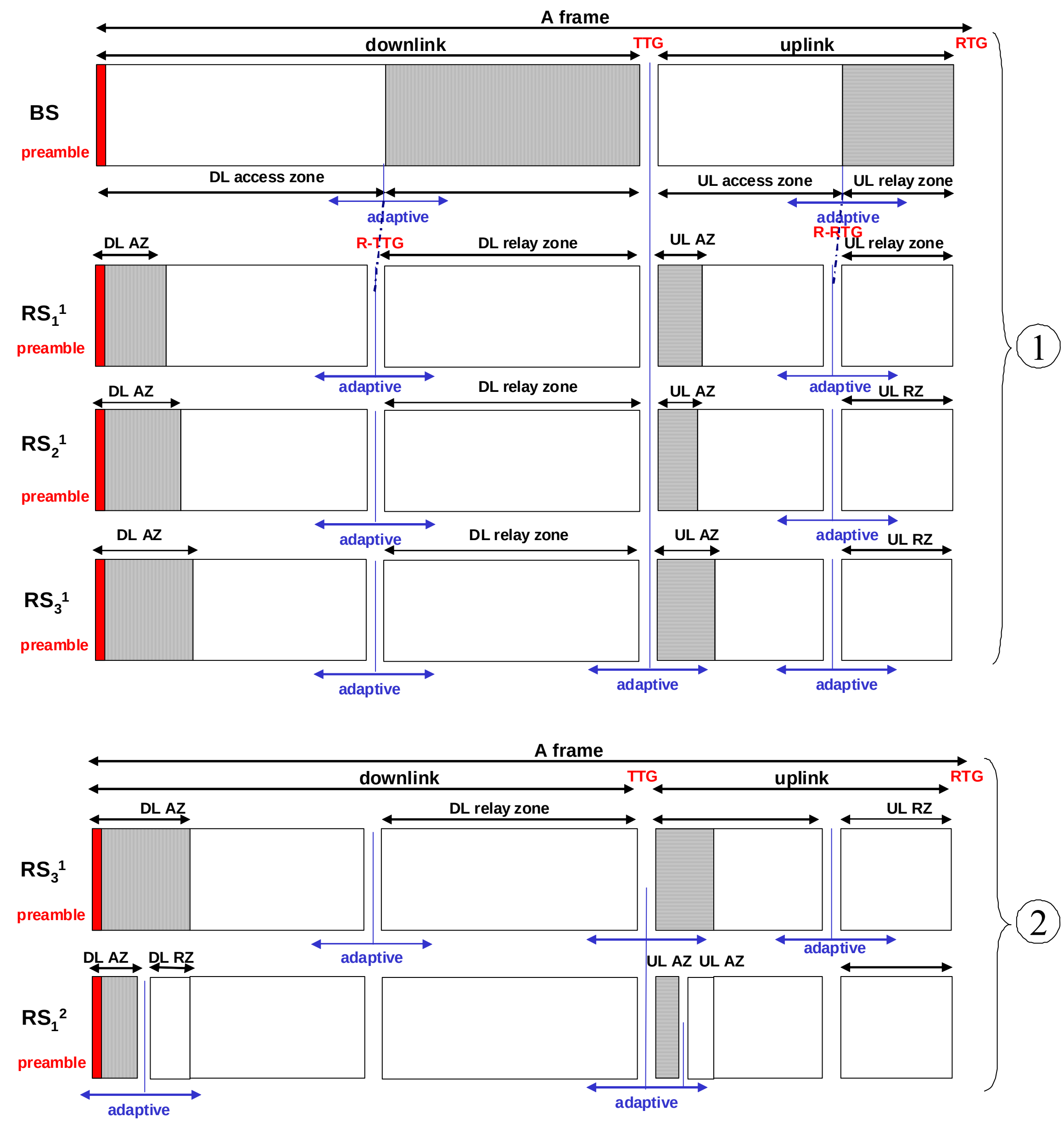

Figure 15. Adaptive frame structure with multiple directions

3.3 Numerical Analysis

We numerically present how a BS and nt-RSs allocate OFDMA symbols and subcarriers when they adopt an adaptive frame structure. Table 1 shows notations used for this numerical analysis.

Table 1. Notations for numerical analysis

Notations	Explanation
DL_{BS} , UL_{BS}	Downlink and uplink of a BS
DL_AZ_{BS} , DL_RZ_{BS}	Downlink access zone and relay zone of a BS
UL_AZ_{BS} , UL_RZ_{BS}	Uplink access zone and relay zone of a BS
$DL\_AZ_{nt-RS_k^{i-hop}}$	Downlink access zone of the *i*-th hop nt-RS *k*
$DL\_RZ_{nt-RS_k^{i-hop}}$	Downlink relay zone of the *i*-th hop nt-RS *k*
$R(DL\_RZ_{BS})$	Data rate assigned to the relay zone of the BS
$R(DL\_AZ_{nt-RS_k^{i-hop}})$	Data rate assigned to the access zone of the *i*-th hop nt-RS *k*
$N_{BS}(nt-RS^1)$	The number of the *i*-th hop RSs associated with a BS
$N_{nt-RS_k^{i-1}}(nt-RS^i)$	The number of the *i*-th hop RSs associated with the (*i*-1)-th nt-RS in which 2 < *i* < max hop
$G_{BS}\{R(DL\_AZ_{nt-RS^1})\}$	Group of data rates that each first hop nt-RS is assigned
$\max\{G_{BS}\{R(DL\_AZ_{nt-RS^1})\}\}$	The maximum value of the data rate group above
$N_{BS}^{DL\_RZ}(t\_slot)$	The number of slots of the relay zone of a BS in the time domain
$N_{nt-RS_k^1}^{DL\_AZ}(t\_slot)$	The number of slots of the access zone of the first hop nt-RS in the time domain

First, we need to calculate the time duration of an OFDMA symbol in an OFDMA frame, given system parameters, including the number of subcarriers that determines the FFT size used:

$$T_s^{frame} = (1+G)\frac{N_{FFT}}{\lfloor(\eta \times BW \div 8000)\rfloor \times 8000}$$

where BW is the channel bandwidth used by a BS, G is the ratio of Tg (cyclic prefix time) to Tb (useful symbol time), and η is the sampling factor determined by the channel bandwidth. Using the N_s^{frame} obtained by dividing the frame time duration by T_s^{frame}, the capacity of a subcarrier in an OFDMA frame is calculated by the following equation:

$$C_{sc}^{frame} = \frac{BW}{N_{sc}^{frame}} \log_2(1+\frac{E_s}{N_0}), \qquad (1)$$

where N_{sc}^{frame} is the number of subcarriers in an OFDMA frame, E_s is the mean symbol energy, and N_0 is the power spectral density of the additive white Gaussian noise (AWGN). Equation 1 explains the maximum capacity of a subcarrier. To calculate the maximum capacity of an OFDMA resource unit that comprises an OFDMA subcarrier and an OFDMA symbol, Equation 1 needs to be divided by the N_s^{frame}, the number of the OFDMA symbol.

$$C_{sc,symbol}^{frame} = \frac{C_{sc}^{frame}}{N_s^{frame}} = \frac{BW}{N_{sc}^{frame} \times N_s^{frame}} \log_2(1+\frac{E_s}{N_0}), \qquad (2)$$

From Equation 2, we can define a slot, the smallest allocation unit that a BS or an nt-RS can assign to its subordinate nt-RS. We assume that a slot is formed by a group of adjacent subcarriers and symbols. Then, the capacity of the slot is obtained by Equation 3:

$$C_{sc,symbol}^{slot} = \frac{BW}{N_{sc}^{frame} \times N_s^{frame}} \times N_{sc}^{slot} \times N_s^{slot} \times \log_2(1+\frac{E_s}{N_0}), \qquad (3)$$

where N_{sc}^{slot} is the number of subcarriers in a slot, and N_s^{slot} is the number of OFDMA symbols in a slot.

Now that we have the minimum resource allocation unit called an OFDMA slot, an OFDMA frame can be indexed with this slot:

- i (1, 2, …, x): the slot index along the frequency domain in a frame, where x = $N_{sc}^{frame} / N_{sc}^{slot}$

- j (1, 2, …, y): the slot index along the time domain in a frame, where y = N_s^{frame} / N_s^{slot}

As a practical allocation scheme, we can calculate the capacity of a slot that was assigned to the subscriber station *k* associated with a BS or an nt-RS, based on Equation (3) and the modulation scheme and the coding rate.

- $$C_{SS_k}^{BS}(slot(i,j)) = \frac{BW}{N_{sc} \times N_s} \times N_{sc}^{slot} \times N_s^{slot} \times M_{BS-SS_k} \times CR_{BS-SS_k} \qquad (4)$$

where M_{BS-SS_k} and CR_{BS-SS_k} are the modulation scheme and the coding rate between a *BS* and the SS_k, respectively. They are determined by the SNR value of the SS_k. We assume that M_{BS-SS_k} and CR_{BS-SS_k} are the same in all slots to which the SS_k is assigned. Therefore, the total capacity of the SS_k can be expressed as

$$C_{SS_k}^{BS} = \sum_{i=a}^{a+N_{f\_slot}^{SS_k}} \sum_{j=b}^{b+N_{t\_slot}^{SS_k}} C_{SS_k}^{BS}(slot(i,j)), \qquad (5)$$

where $N_{f\_slot}^{SS_k}$ is the number of the OFDMA slots in the frequency domain to which the SS_k is assigned, and $N_{t\_slot}^{SS_k}$ is the number of the OFDMA slot in the time domain.

To derive the maximum OFDMA resource that nt-RSs can be assigned, and synchronize access zones and relay zones between a superior station and its subordinate nt-RSs, we create three properties for the BS and the nt-RSs: a data relay property, a maximum balance property, and a relay zone limitation property. The introduced properties will be used also in the proposed fairness allocation explained in the next section.

● Data Relay Property

To relay data from a superior station (a BS or a superior nt-RS), the total data rate used for the access zones of the downlink in the subordinate nt-RSs should not exceed the total data rate used for a relay zone of the downlink in a superior station.

$$\sum_{k=1}^{n} R(DL\_AZ_{nt-RS_k^1}) \le R(DL\_RZ_{BS}) \text{ ,} \tag{C1-1}$$

$$\sum_{k=1}^{n} R(DL\_AZ_{nt-RS_k^i}) \le R(DL\_RZ_{nt-RS^{i-1}}) \text{ , where i > 1} \tag{C1-2}$$

To relay data from the subscriber stations of the nt-RSs, the total data rate used for the access zones of the uplink in the subordinate nt-RSs should not exceed the total data rate used for a relay zone of the uplink in a superior station.

$$\sum_{k=1}^{n} R(UL\_AZ_{nt-RS_k^1}) \le R_{BS}(UL\_RZ) \text{ ,} \tag{C1-3}$$

$$\sum_{k=1}^{n} R(UL\_AZ_{nt-RS_k^i}) \le R(UL\_RZ_{nt-RS^{i-1}}) \text{ , where i > 1} \tag{C1-4}$$

● Relay Zone Limitation Property

The maximum number of slots of the relay zone in the time domain that a BS or a superior nt-RS can assign depends on the maximum number of slots of the access zone in the time domain among all the subordinate stations.

$$\max\{N_{BS}^{DL\_RZ}(t\_slot)\} = N_{BS}^{DL}(t\_slot) - \max\{G\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}\} \tag{C2-1}$$

$$\max\{N_{BS}^{UL\_RZ}(t\_slot)\} = N_{BS}^{UL}(t\_slot) - \max\{G\{N_{nt-RS^1}^{UL\_AZ}(t\_slot)\}\} \tag{C2-2}$$

$$\max\{N_{nt-RS_k^{i-1}}^{DL\_RZ}(t\_slot)\} = N_{nt-RS_k^{i-1}}^{DL}(t\_slot) - \max\{G\{N_{nt-RS^i}^{DL\_AZ}(t\_slot)\}\} \tag{C2-3}$$

$$\max\{N^{UL\_RZ}_{nt-RS^{i-1}_k}(t\_slot)\} = N^{UL}_{nt-RS^{i-1}_k}(t\_slot) - \max\{G\{N^{UL\_AZ}_{nt-RS^{i}}(t\_slot)\}\} \qquad \text{(C2-4)}$$

● Maximum Balance Property

Based on the data relay property, the relay zone limitation property, and the adaptive modulation and coding rate between the superior station and its subordinate nt-RSs, the maximum data rate of the DL/UL relay zone in a superior station should be acceptable enough for the nt-RSs can use the same data rate for their DL/UL access zone.

$$\max C_{DL\_RZ_{BS}} \approx \max \sum_{k=1}^{N_{BS}(nt-RS^1_k)} C_{DL\_AZ_{nt-RS^1_k}} \ , \qquad \text{(C3-1)}$$

$$\max \sum_{k=1}^{A} C_{DL\_RZ_{nt-RS^{i-1}_k}} \approx \max \sum_{k=1}^{A} C_{DL\_AZ_{nt-RS^{i}_k}} \ , \quad where, 2 < i < \max hop, A = N_{nt-RS^{i-1}}(nt-RS^{i}) \qquad \text{(C3-2)}$$

$$\max C_{UL\_RZ_{BS}} \approx \max \sum_{r=1}^{N_{BS}(nt-RS^1_k)} C_{UL\_AZ_{nt-RS^1_r}} \ , \qquad \text{(C3-3)}$$

$$\max \sum_{r=1}^{A} C_{UL\_RZ_{nt-RS^{i-1}_k}} \approx \max \sum_{k=1}^{A} C_{UL\_AZ_{nt-RS^{i}_k}} \ , \quad where, 2 < i < \max hop, A = N_{nt-RS^{i-1}}(nt-RS^{i}) \qquad \text{(C3-4)}$$

Using Equations 4 and 5, we can obtain the maxim capacity of the relay zone within a DL sub-frame of a BS (Equation 6) that should be acceptable for all of the first hop nt-RSs to serve their SSs using the capacity of their access zones (Equation 7). Equations 8 and 9 show the same calculation between all of the i-th hop nt-RSs and their subordinate nt-RSs with regard to the DL sub-frame.

$$\max C_{DL\_RZ_{BS}} = \sum_{k}^{N_{BS}(nt-RS^1)} \sum_{i=1}^{N_{sc}^{frame}/N_{slot}^{frame}} \sum_{j=b}^{(b+N_{t\_slot}^{nt-RS_k^1})} C_{nt-RS_k^1}^{BS}(slot(i,j)) \quad (6)$$

$$\max C_{DL\_AZ_{nt-RS_r^1}} = \sum_{k}^{N_{nt-RS_r^1}(SS)} \sum_{i=a}^{(a+N_{f\_slot}^{SS_k})} \sum_{j=b}^{(b+N_{t\_slot}^{SS_k})} C_{SS_k}^{nt-RS_r^1}(slot(i,j)) \quad (7)$$

$$\max C_{DL\_RZ_{nt-RS_r^{i-1}}} = \sum_{k}^{N_{nt-RS^i}(nt-RS_r^{i-1})} \sum_{i=1}^{N_{sc}^{frame}/N_{slot}^{frame}} \sum_{j=b}^{(b+N_{t\_slot}^{nt-RS_k^i})} C_{nt-RS_r^i}^{nt-RS^{i-1}}(slot(i,j)) \quad (8)$$

$$\max C_{DL\_AZ_{nt-RS_r^i}} = \sum_{k}^{N_{nt-RS^i}(nt-RS_r^{i-1})} \sum_{i=1}^{N_{sc}^{frame}/N_{slot}^{frame}} \sum_{j=b}^{(b+N_{t\_slot}^{nt-RS_k^i})} C_{SS_k}^{nt-RS^i}(slot(i,j)) \quad (9)$$

3.4 OFDMA Resource Allocation

Based on the previous numerical analysis and the introduced three properties, we propose OFDMA resource allocation schemes for a BS and its subordinate nt-RSs in wireless MMR networks. Through the proposed algorithms, we show how a superior station yields the maximum number of OFDMA slots to its subordinate stations. The notations used in the proposed schemes are described in Table 2.

Table 2. Notations used in OFDMA resource allocation algorithms

Notations	Explanation
$DL_{percent}^{BS}$	The percentage of downlink within a frame used by a BS
$\max(N_{t\_slot}^{DL})$	The maximum number of the slot index in the DL sub-frame = $\lfloor (N_s^{frame}/N_s^{slot}) \times DL_{percent}^{BS} \rfloor$
$\max(N_{t\_slot}^{UL})$	The maximum number of the slot index in the UL sub-frame = $(N_s^{frame}/N_s^{slot}) - \max(N_{t\_slot}^{DL})$
$\max(N_{f\_slot}^{DL})$	The maximum number of the slot index in the DL sub-frame = $(N_{ss}^{frame}/N_{sc}^{slot})$
$\max(N_{f\_slot}^{UL})$	The maximum number of the slot index in the UL sub-frame = $(N_{ss}^{frame}/N_{sc}^{slot})$

Table 2. Notations used in OFDMA resource allocation algorithms (Continued)

Notations	Explanation
$(R(DL_{BS})_{req}^{SS_k}, R(UL_{BS})_{req}^{SS_k})$	The pair of the DL and UL data rate requested from SS_k associated with a BS
$(R(DL_{BS})_{a\,\text{sgn}}^{SS_k}, R(UL_{BS})_{a\,\text{sgn}}^{SS_k})$	The pair of the DL and UL data rate assigned to SS_k by a BS
$R(DL\_RZ_{BS})_{req}^{nt-RS_k^1}$	The data rate of the relay zone requested from the first hop k-th nt-RS associated with a BS
$R(DL\_RZ_{BS})_{a\,\text{sgn}}^{nt-RS^1}$	The data rate of the relay zone assigned to the first hop k-th nt-RS by a BS
$G_{BS}\{index(N(_{t\_slot}^{DL})\}$	A group of indices in the time domain for the downlink sub-frame
$G_{BS}\{index(N(_{t\_slot}^{DL\_AZ})\}$	A group of indices in the time domain for the access zone of the downlink
$G_{BS}\{index(N(_{t\_slot}^{DL\_RZ})\}$	A group of indices in the time domain for the relay zone of the downlink
$G_{BS}^{avail}\{index(N(_{t\_slot}^{DL\_RZ})\}$	A group of available indices in the time domain for the relay zone of the downlink
$G_{BS}^{avail}\{index(N(_{f\_slot}^{DL\_RZ})\}$	A group of available indices in the frequency domain for the relay zone of the downlink
$\max(G_{BS}^{avail}\{index(N(_{t\_slot}^{DL\_RZ})\})$	The maximum index number from the group of available indices
$\min(G_{BS}^{avail}\{index(N(_{t\_slot}^{DL\_RZ})\})$	The minimum index number from the group of available indices
$G_{BS}\{nt-RS_k^1)$	The group of the first hop nt-RSs that a BS has $=\{nt-RS_1^1, nt-RS_2^1, ..., nt-RS_k^1\}$
$G_{BS}\{SS_k)$	The group of SSs that a BS has $=\{SS_1, SS_2, ..., SS_k\}$

The allocation scheme (BS-A-1) represents how a BS initializes OFDMA slots to be assigned to its access zone, and relay zones. First, the BS has to determine how many slots can be used in the DL sub-frame, which is $DL_{percent}^{BS}$. Then, we can calculate the maximum number slot index in the time domain for the DL/UL sub-frame. The maximum number of slot indices in the frequency domain is already calculated by $N_{ss}^{frame} / N_{sc}^{slot}$. Using the maximum number of slot indices in the time domain, we adaptively assign OFDMA slots to the access zone and relay zones by varying the slot index in the time domain. As a final step in this initialization phase, all possible OFDMA slots will be assigned into available slots that will be allocated in the future.

[BS-A-1] Initialization phase in a BS

assign $DL^{BS}_{percent}$ and $UL^{BS}_{percent}$

obtain the maximum number of the slot index in the time domain for the DL/UL sub-frame

$\max(N^{DL}_{t\_slot})$, $\max(N^{UL}_{t\_slot})$, $\max(N^{DL}_{f\_slot})$, $\max(N^{UL}_{f\_slot})$

// initialize available slot index in the time domain

$G_{avail}\{index(N(^{DL}_{t\_slot})\} = 0, 1, \ldots, \max(N^{DL}_{t\_slot})$

$G_{avail}\{index(N(^{UL}_{t\_slot})\} = 0, 1, \ldots, \max(N^{UL}_{t\_slot})$

// initialize the maximum number of slots in the access zone of its nt-RSs

$\max\{G\{N^{DL\_AZ}_{nt-RS^1}(t\_slot)\}\} = 0$, $\max\{G\{N^{UL\_AZ}_{nt-RS^1}(t\_slot)\}\}$

[BS-A-2] slot allocation for nt-RSs

```
// first assign resources for nt-RSs
while  $G_{BS}\{nt-RS_k^1) \neq 0$
    If $N_{slot}(G_{avail}\{index(N(^{DL}_{t\_slot})\})$ == $\max\{G\{N^{UL\_AZ}_{nt-RS^1}(t\_slot)\}\}$
        breaks
    find the nt-RS such that $R(DL_{BS})^{nt-RS_x^1}_{req} < R(DL_{BS})^{nt-RS_y^1}_{req}$ ( y ≠ x and y =1,2,..k)
    // the starting point to assign OFDMA slots for the relay zone of a BS
    j_init = $\max(G^{avail}_{BS}\{index(N(^{DL}_{t\_slot})\})$
    // assign slots to meet $R(DL\_RZ_{BS})^{nt-RS_x^1}_{req}$
    $R(DL_{BS})^{nt-RS_x^1}_{\mathrm{asgn}} = 0$
    for j = j_init; j < 1; j-- :
        // checking limitation of relay zone
        If $N_{slot}(G_{avail}\{index(N(^{DL}_{t\_slot})\})$ = $\max\{G\{N^{UL\_AZ}_{nt-RS^1}(t\_slot)\}\}$
            break
        for i = i_init; i < $\max(N^{DL}_{f\_slot})$ ; i++
            $R(DL_{BS})^{nt-RS_x^1}_{\mathrm{asgn}} = slot(i,j) \times M_{BS-nt-RS_k^1} \times CR_{BS-nt-RS_k^1} + R(DL_{BS})^{nt-RS_x^1}_{\mathrm{asgn}}$
            // checking whether OFDMA resources are assigned
            if $R(DL_{BS})^{nt-RS_x^1}_{\mathrm{asgn}} \geq R(DL_{BS})^{nt-RS_x^1}_{req}$
                update $\max\{G\{N^{UL\_AZ}_{nt-RS^1}(t\_slot)\}\}$
                break
    if $G^{avail}_{BS}\{index(N(^{DL}_{f\_slot})\} = 0$:
        i_init = 0
        $G_{avail}\{index(N(^{DL}_{t\_slot})\} = G_{avail}\{index(N(^{DL}_{t\_slot}) - index(j)\}$
    else :  i_init = i
```

After the initialization phase, the BS-A-2 algorithm shows how the BS assigns OFDMA slots to the relay zone of its DL sub-frame. Slot allocation for its nt-RS ends when every first hop nt-RS is allocated slots or when the remaining OFDMA slots in the time domain are equal to the maximum number of slots of the access zone in the time domain among its first hop nt-RSs, $\max\{G\{N^{UL\_AZ}_{nt-RS^1}(t\_slot)\}\}$. The BS first finds an nt-

RS with the lowest data rate and the maximum slot index number in the available slot index group in the time domain, $\max(G_{BS}^{avail}\{index(N(_{t\_slot}^{DL})\})$. With this index, it starts to allocate OFDMA slots along with the slot index number of the relay zone in the frequency domain. The slot index in the time domain continuously decreases by one slot index until the requested data rate of the nt-RS is allocated. While the requested data rate is being allocated, the available slot index of the time domain and the frequency domain ($G_{avail}\{index(N(_{t\_slot}^{DL})\}, G_{BS}^{avail}\{index(N(_{f\_slot}^{DL})\}$) is updated by removing the slot index that is already used for allocation from the available slot index. When the nt-RS is allocated OFDMA slots, the BS updates the $\max\{G\{N_{nt-RS^1}^{UL\_AZ}(t\_slot)\}\}$ value by communicating with the nt-RS.

[BS-A-3] slot allocation for SSs

```
while  G{SS_k} ≠ 0
   find the SS_k  such that R(DL_BS)_req^{SS_k} < R(DL_BS)_req^{SS_k}  ( y ≠ x and y =1,2,..k)
   // assign available slot range in the time domain for the access zone of a BS
   j_init = min(G_BS^avail {index(N(_{t_slot}^{DL_RZ})}), j_max = max(G_BS^avail {index(N(_{t_slot}^{DL})})
   //assign slots to meet R(DL_AZ_BS)_req^{SS_k}
   R(DL_BS)_asgn^{SS_k} = 0
   for j = j_init; j < j_max ; j++ :
       if R(DL_BS)_asgn^{SS_k} ≥ R(DL_BS)_req^{SS_k} :
           break
       for i = i_init; i < max(N_{f_slot}^{DL}) ; i++
              R(DL_BS)_asgn^{SS_k} = slot(i, j) × M_{BS-SS_k} × CR_{BS-SS_k} + R(DL_BS)_asgn^{SS_k}
              if R(DL_BS)_asgn^{SS_k} ≥ R(DL_BS)_req^{SS_k} :
                  break
   if G_BS^avail {index(N(_{f_slot}^{DL})} = 0:  i_init = 0
          G_avail {index(N(_{t_slot}^{DL})} = G_avail {index(N(_{t_slot}^{DL}) − index(j)}
   else :  i_init = i
```

After OFDMA allocation for the first hop nt-RSs, the BS-A-3 algorithm shows how the BS assigns OFDMA slots to the access zone of the DL sub-frame. This scheme is similar to the BS-A-2 algorithm except that slot allocation starts from the minimum index number of the available slot in the time domain. First, the BS obtains the minimum and maximum slot indices of the current available slots in the time domain. Then, it finds an SS with the lowest data rate and starts to allocate OFDMA slots. While it is allocating OFDMA slots to the SS, it updates the available slot index in the time and frequency domains. This allocation stops when every SS is assigned OFDMA slots or when no more slots remain.

The following allocation schemes show how an nt-RS allocates OFDMA slots for its associated SSs and subordinate nt-RSs.

[RS-A-1] Initialization phase in an nt-RS$_k^{i\text{-}th}$

obtain the maximum number of the slot indices of its access zone

$$\max(N_{t\_slot}^{DL\_AZ}),\ \max(N_{t\_slot}^{UL\_AZ}),\ \max(N_{f\_slot}^{DL\_AZ}),\ \max(N_{f\_slot}^{UL\_AZ})$$

Initialize available slot index in the time domain

$$G_{avail}\{index(N(_{t\_slot}^{DL\_AZ})\} = 0,\ 1,\ \ldots,\ \max(N_{t\_slot}^{DL\_AZ})$$

$$G_{avail}\{index(N(_{t\_slot}^{UL\_AZ})\} = 0,\ 1,\ \ldots,\ \max(N_{t\_slot}^{UL\_AZ})$$

$$\max\{G\{N_{nt-RS^{i+1}}^{DL\_AZ}(t\_slot)\}\} = 0,\ \max\{G\{N_{nt-RS^{i+1}}^{UL\_AZ}(t\_slot)\}\} = 0$$

The RS-A-1 algorithm illustrates the initialization phase of the nt-RS. The nt-RS can use only OFDMA slots assigned by its superior station. First, it calculates the maximum slot number of its access zone in the time and the frequency domains. From the maximum number, it creates the available slot index group of its access zone in the time domain.

[RS-A-2] slot allocation for nt-RS_k^{i+1}

while $G_{nt-RS_k^i}\{nt-RS_k^{i+1}) \neq 0$

If $N_{slot}(G_{avail}\{index(N(_{t\_slot}^{DL\_AZ})\}) == \max\{G\{N_{nt-RS^{i+1}}^{UL\_AZ}(t\_slot)\}\}$

break

find the subordinate nt-RS

such that $R(DL_{nt-RS_k^i})_{req}^{nt-RS_x^{i+1}} < R(DL_{nt-RS_k^i})_{req}^{nt-RS_y^{i+1}}$ (y ≠ x and y =1,2,..k)

// start point is the maximum number of slot index in the access zone of the nt-RS_k^i

j_init = $\max(G_{nt-RS_k^i}^{avail}\{index(N(_{t\_slot}^{DL\_AZ})\})$

// assign slots to meet $R(DL\_RZ_{nt-RS_k^i})_{req}^{nt-RS_x^{i+1}}$

$R(DL_{nt-RS_k^i})_{\text{asgn}}^{nt-RS_x^{i+1}} = 0$

for j = j_init; j < 1; j-- :

// checking limitation of relay zone

If $N_{slot}(G_{avail}\{index(N(_{t\_slot}^{DL\_AZ})\}) \leq N_{slot}(\max\{C_{DL\_AZ_{nt-RS_k^{i+1}}}\})$

break

for i = i_init; i < $\max(N_{f\_slot}^{DL})$; i++

$$R(DL_{nt-RS_k^i})_{\text{asgn}}^{nt-RS_x^1} = slot(i,j) \times M_{nt-RS_k^i-nt-RS_k^{i+1}} \times CR_{nt-RS_k^i-nt-RS_k^{i+1}} + R(DL_{BS})_{\text{asgn}}^{nt-RS_x^{i+1}}$$

if $R(DL_{nt-RS_k^i})_{\text{asgn}}^{nt-RS_x^{i+1}} \geq R(DL_{nt-RS_k^i})_{req}^{nt-RS_x^{i+1}}$

update $\max\{G\{N_{nt-RS^{i+1}}^{UL\_AZ}(t\_slot)\}\}$

break

if $G_{nt-RS_k^i}^{avail}\{index(N(_{f\_slot}^{DL\_AZ})\} = 0$:

i_init = 0

$G_{avail}\{index(N(_{t\_slot}^{DL\_AZ})\} = G_{avail}\{index(N(_{t\_slot}^{DL\_AZ}) - index(j)\}$

else : i_init = i

After the initialization phase, the RS-A-2 shows how the nt-RS assigns OFDMA slots to its subordinate nt-RSs by using its relay zone. Like the BS-A-2 algorithm, the slot allocation for its subordinate nt-RS ends when every subordinate nt-RS is allocated slots or when the remaining OFDMA slots in the time domain are equal to the maximum number of slots of the access zone in the time domain among its subordinate nt-RSs. The only difference from the BS-A-2 algorithm is that it can allocate OFDMA slots by using its access zone, which is allocated by the BS.

[RS-A-3] slot allocation for SSs

while $G\{SS_k) \neq 0$

find the SS_k such that $R(DL_{nt-RS_k^i})_{req}^{SS_k} < R(DL_{nt-RS_k^i})_{req}^{SS_k}$ (y ≠ x and y =1,2,..k)

// assign available slot range in the time domain for the access zone of a BS

j_init = $\min(G_{nt-RS_k^i}^{avail}\{index(N(_{t\_slot}^{DL\_AZ})\})$, j_max = $\max(G_{nt-RS_k^i}^{avail}\{index(N(_{t\_slot}^{DL\_AZ})\})$

//assign slots to meet $R(DL\_AZ_{nt-RS_k^i})_{req}^{SS_k}$

$R(DL_{nt-RS_k^i})_{\text{asgn}}^{SS_k} = 0$

for j = j_init; j < j_max ; j++ :

if $R(DL_{nt-RS_k^i})_{\text{asgn}}^{SS_k} \geq R(DL_{nt-RS_k^i})_{req}^{SS_k}$:

break

for i = i_init; i < $\max(N_{f\_slot}^{DL})$; i++

$R(DL_{nt-RS_k^i})_{\text{asgn}}^{SS_k} = slot(i, j) \times M_{nt-RS_k^i-SS_k} \times CR_{nt-RS_k^i-SS_k} + R(DL_{nt-RS_k^i})_{\text{asgn}}^{SS_k}$

if $R(DL_{nt-RS_k^i})_{\text{asgn}}^{SS_k} \geq R(DL_{nt-RS_k^i})_{req}^{SS_k}$:

break

if $G_{nt-RS_k^i}^{avail}\{index(N(_{f\_slot}^{DL\_AZ})\} = 0$:

i_init = 0

$G_{avail}\{index(N(_{t\_slot}^{DL})\} = G_{avail}\{index(N(_{t\_slot}^{DL\_AZ}) - index(j)\}$

else :

i_init = i

The RS-A-3 algorithm shows how the nt-RS allocates OFDMA slots to its associated SSs. The basic procedure is the same as that for the BS-A-3 algorithm, except that it can allocate OFDMA slots by using the remaining slots in its access zone.

3.5 Numerical Results and Simulations

Based on the proposed equations and properties (Section 3.3), we have conducted numerical simulations to see the maximum capacity of the access zone of each nt-RS and the maximum hop count a BS can have, given system parameters in an MMR network. We use the python script language and Matlab for the simulations. To determine how accurate the simulation result is, we use a 95% confidence level with 50 simulation runs for each scenario of the simulations. From the 95% confidence level, we construct 95% confidence interval for the average value as follows.

$$\pm \frac{Z_c \sigma}{\sqrt{n}} \tag{10}$$

where Z_c is the z-score associated with the 95% confidence level (Z_c =1.91), σ is the average standard deviation obtained from simulations, and n is the number of simulation (n = 50). In other words, the 95% confidence interval for the obtained mean is expressed as follows:

$$\mu - \frac{Z_c \sigma}{\sqrt{n}} \leq \mu \leq + \frac{Z_c \sigma}{\sqrt{n}} \tag{11}$$

The system model of this simulation is shown in Figure 16. In the simulations, the free space path loss model is used. It is also assumed that the signal does not suffer from any shadowing or fading effect and varies only by additive white Gaussian noise (AWGN) over time. The relationship between transmission range and SNR values are described in Table 2.

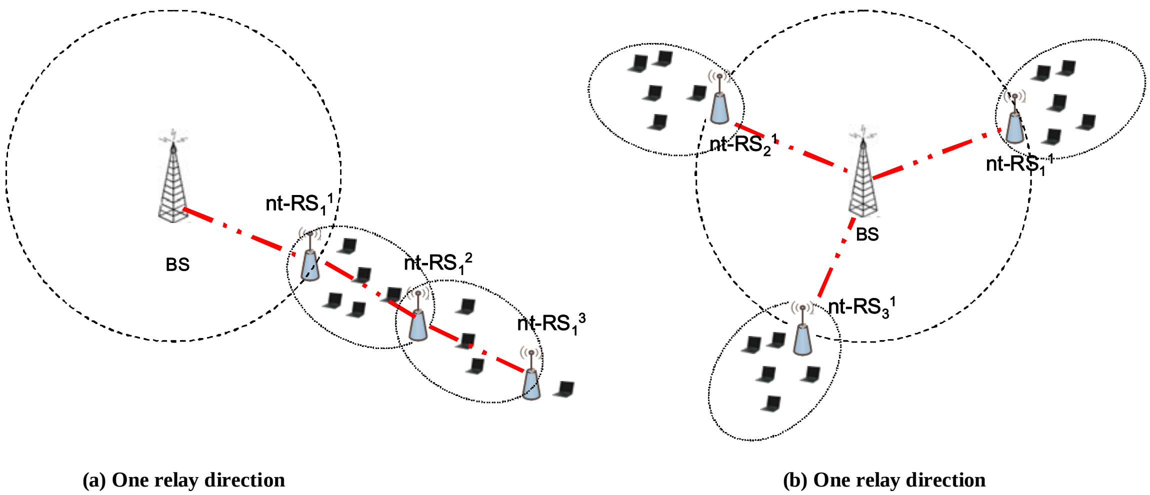

Figure 16. System model of numerical simulations.

Table 3. Relationship between the transmission range and SNR

Modulation	SNR	Range(km), {BS, SS}
QPSK 1/2	6	{11.4, 5.7}
QPSK3/4	9	{8.0, 4.0}
16 QAM 1/2	11.5	{6.0, 3.0}
16 QAM 3/4	15	{4.0, 2.0}
64 QAM 1/2	17	{3.2, 1.6}
64 QAM 2/3	19	{2.6, 1.3}
64 QAM 3/4	21	{2.0, 1.0}

The MMR network parameters used in our simulation are described in Table 3. In the simulation, when a subscriber stations is created, we randomly assign its data rate, the range of which is from 100,000 to 4,000,000 bps. For simulations, we run 50 simulations. First, we create subscriber stations and add them only to the first hop nt-RS until it reaches the relay zone limitation property. For the creation of each subscriber station, we assume that an OFDMA slot in this simulation (6 bytes) is used for a control message. After the first hop nt-RS reaches the threshold of the proposed relay zone limitation property, we create the second hop nt-RS and SSs and have SSs be associated with the nt-RS. Figure 17 shows the maximum data rate of each nt-RS only with one relay direction. In the simulation, the ratio of a DL sub-frame to a UL sub-frame is 8:2. In addition, QPSK, QAM16, and QAM64 modulation schemes have been used with 1/2, 2/3, and 3/4 coding rate depending on the signal strength between SSs and their superior station. This simulation indicates that the first hop nt-RS can serve around 7 Mbps, and the MMR network can have a third hop nt-RS theoretically. In a new simulation scenario, we limit the maximum data rate that the first hop nt-RS can provide with its SSs and add more first hop nt-RSs until each nt-RS reaches the relay zone limitation property. Figure 18 shows that the MMR network can have three first hop nt-RSs, and each first hop nt-RS can have around 2.7 Mbps data rate. This is because three nt-RSs are deployed exclusively and they can serve their associated SSs simultaneously based on the OFDMA allocation scheme in Figure 15.

Table 4. System parameters used in computer simulations

Radio parameters	value
Base frequency	5 GHz
Bandwidth	20 MHz
Duplex method	TDD
Frame duration	20msec
Number of subcarrier s	1790
Number of data subcarriers	1440
A slot unit	{ 2 symbols, 24 data subcarriers }
TTG (transmit/receive transition gap)	100 µsec
RTG (receive/transmit transition gap)	60 µsec
R-TTG (RS transmit/receive transition gap)	50 µsec
R-RTG (RS receive/transmit transition gap)	50 µsec

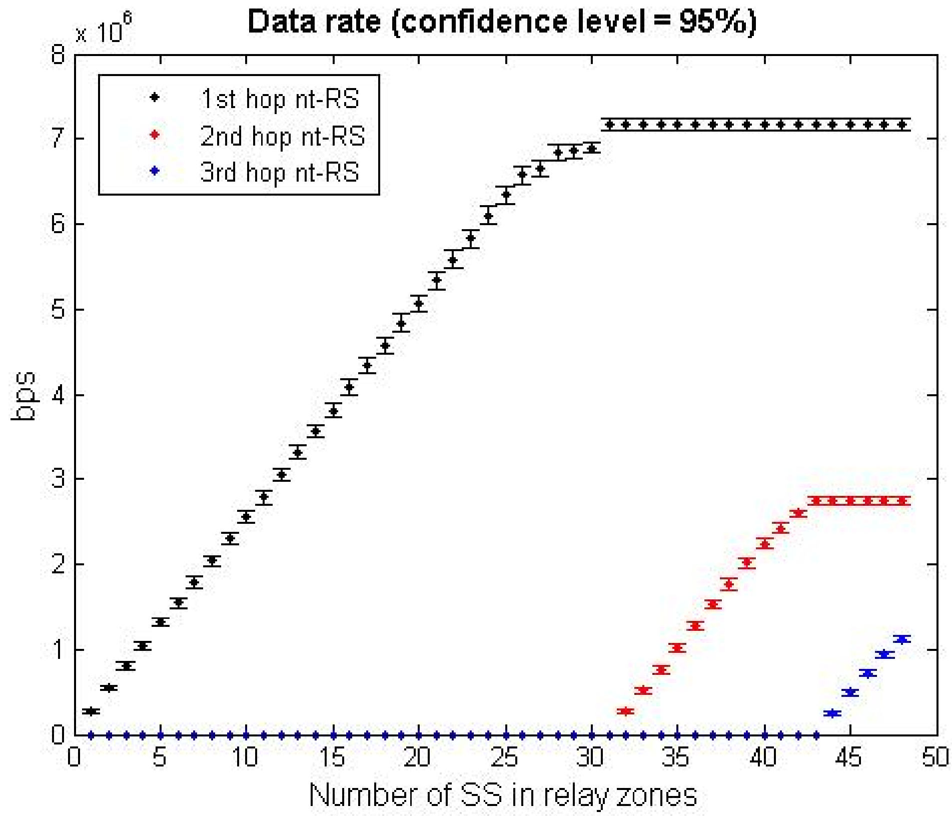

Figure 17. Maximum data rate of each nt-RS with one relay direction.

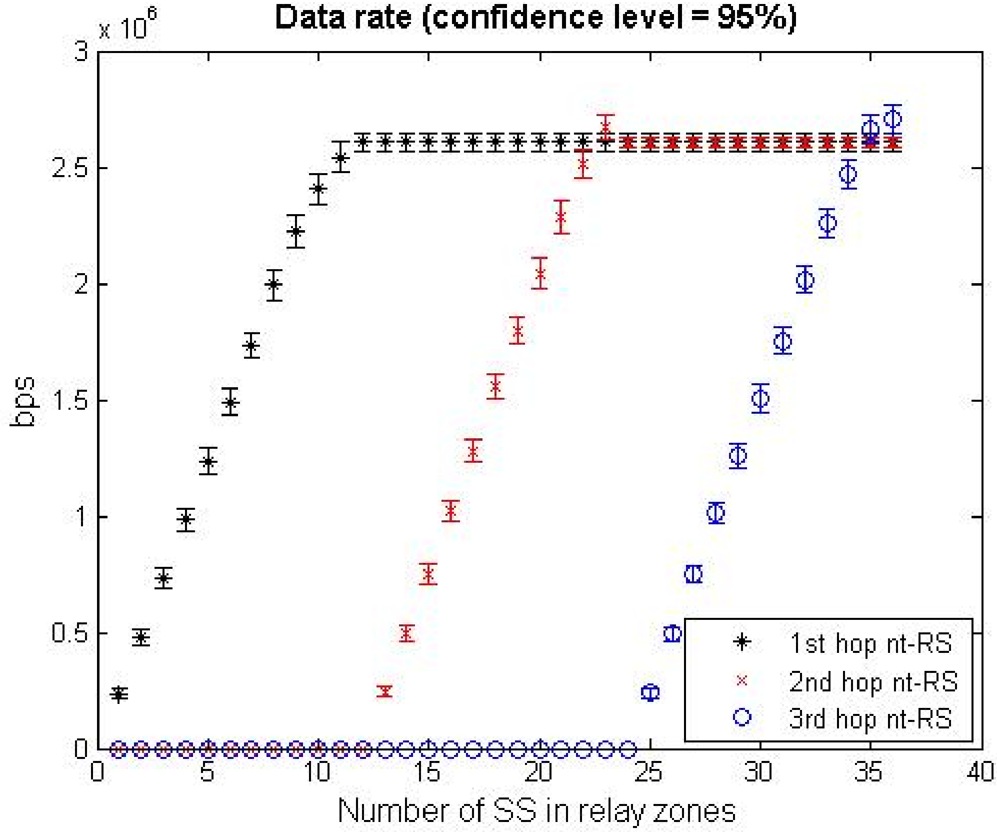

Figure 18. Maximum data rate with multiple relay directions.

In a new simulation, we compare the network throughput and the number of OFDMA slots allocated between the proposed adaptive allocation algorithm and a non-adaptive allocation scheme as the number of SSs associated with a BS increases. In this simulation, we can simulate how many subscriber stations and OFDMA slots each scheme can serve and allocate. Fairness is not considered in this simulation (it will be considered in the next chapter). When a subscriber stations is created within the BS's boundary, we randomly assign its data rate, the range of which is from 100,000 to 400,000 bps. In addition, we assign a different channel condition on each time slot of each SS. Depending on the channel condition, the BS and SSs use a different modulation scheme and a coding rate. Figure 20 shows the throughput of the proposed adaptive allocation scheme and the non-adaptive allocation scheme as the number of SSs associated with the BS increases. For the non-adaptive allocation scheme, we set the ratio of a relay zone to an access zone to 5:5 and 6:4. As we expected, the BS with the non-adaptive allocation scheme cannot allocate OFDMA slots after it allocates all the OFDMA resources of its access zone. However, our proposed allocation algorithm can give OFDMA slots because it can use the remaining OFDMA slots in a downlink/uplink sub-frame.

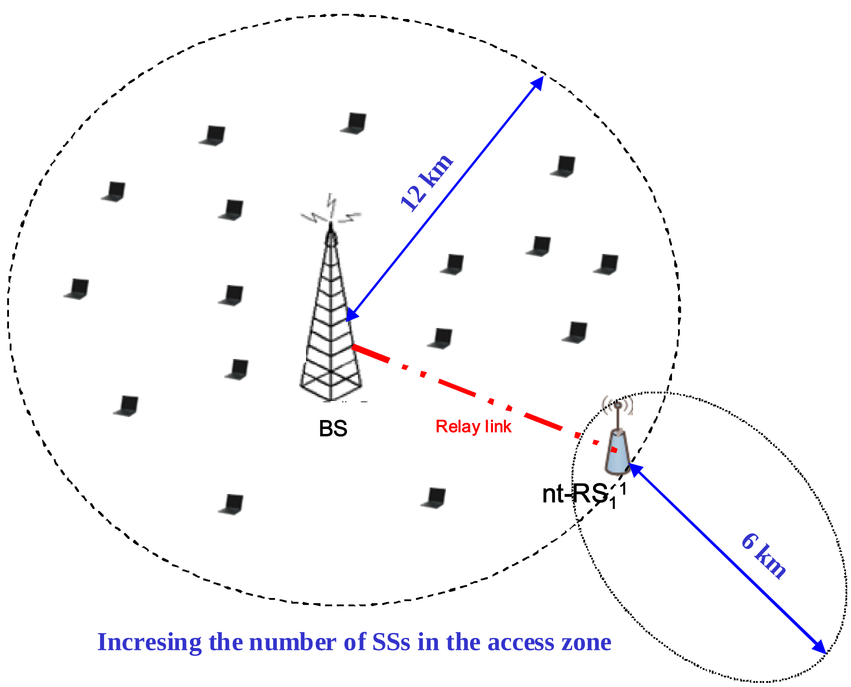

Figure 19. Another simulation scenario.

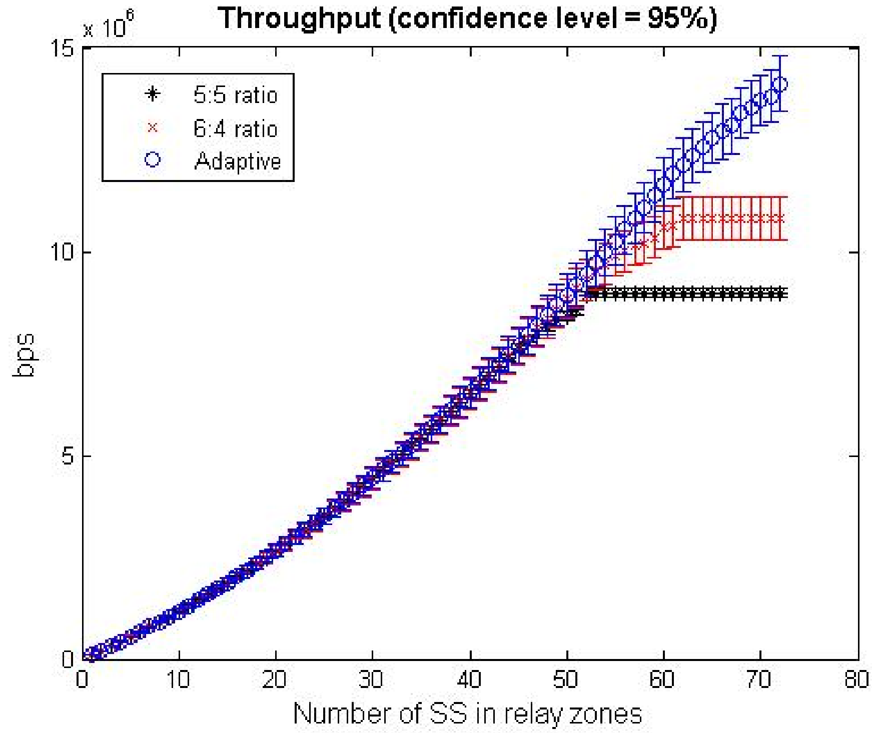

Figure 20. Throughput of the proposed algorithm and a non-adaptive allocation algorithm.

With the same scenario of Figure 20, Figure 21 shows the number of OFDMA slots allocated to SSs in the access link of the BS as the number of the SSs increases. The result indicates that if the BS has enough OFDMA slots to be allocated to the SSs, the non-adaptive allocation scheme uses less number of OFDMA slots than the proposed allocation algorithm. This is because the proposed one has to allocate data from the minimum number of slot index in the time domain whereas the non-adaptive allocation scheme can find the slot index with the best channel condition within its fixed size of the access zone. However, as the number of SSs in the access zone increase, the proposed algorithm can select a user that has the best channel condition for the minimum slot index of the available slot indices in the time domain. So, Figure 21 shows the difference of the number of OFDMA slots allocated between the proposed algorithm and the non-adaptive allocation algorithm.

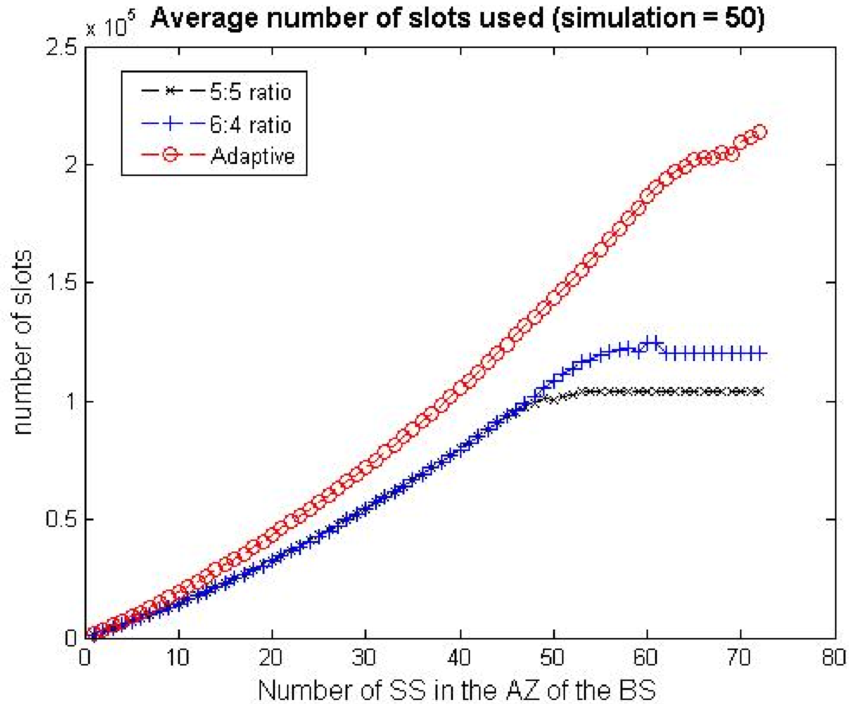

Figure 21. Number of slots allocated

CHAPTER 4

FAIRNESS

In Chapter 3, we give priority to the SSs that locate in the relay zone of the nt-RSs to see maximum OFDMA resources that the nt-RSs can be assigned. In this chapter, we proposed OFDMA resource allocation algorithms with two popular fairness schemes: a max-min fairness scheme and a proportional fairness scheme. These two fairness schemes are explained in Chapter 2. As we pointed out in Section 2.4.3, the existing max-min and the proportional fairness schemes cannot be directly applied to wireless MMR networks because all stations in the networks cannot share the same resources due to the access zone and the relay zone. That is, some stations are restricted to only some portion of the resources. Even in the MMR networks, we try to allocate the same amount of resources to all subscriber stations regardless of what superior station they are associated with. When it comes to any kinds of fairness schemes, we need to mention the number of slot indices in the time and frequency domains within an OFDMA frame again because one slot is the basic unit in the resource allocation by the BS and relay stations. In terms of general fairness, two types of fairness can be defined: slot fairness and throughput fairness. In slot fairness, OFDMA slots are equally allocated to all active subscriber stations regardless of where they are located. However, slots are allocated such that all active SSs obtain the same throughput in throughput fairness. Table 4 shows the notations used in this chapter.

Table 5. Notations for fairness schemes

Notations	Explanation
SS_x^{BS}	The x-th SS associated with a BS
$SS_x^{nt-RS_k^i}$	The x-th SS associated with the i-th hop k-th nt-RS
$N(t\_slot_{DL}(SS_x^{BS}))$	The number slot of the downlink in the time domain assigned to SS_x^{BS}
$N(f\_slot_{DL}(SS_x^{BS}))$	The number of slots of the downlink in the frequency domain assigned to SS_x^{BS}
$N(slot_{DL}(SS_x^{BS}))$	$\sum_{i=1}^{N(t\_slot_{DL}(SS_x^{BS}))} \sum_{j=1}^{N(f\_slot_{DL}(SS_x^{BS}))} slot(i,j)$
$N(SS)$	The total number of SSs in an MMR network
$N(SS_{DL\_AZ}^{BS})$	The number of SSs associated with the access zone of a BS
$N(SS_{DL\_RZ}^{BS})$	The number of SSs associated with the relay zone of a BS $= \sum_{k=1}^{k} N(SS_{DL\_RZ}^{nt-RS_k^i})$
$N(SS_{DL\_RZ}^{nt-RS_k^i})$	The number of SSs associated with the access zone of the i-th hop k-th nt-RS
$R(DL_{total}^{BS})$	Total downlink capacity of a BS
$R(DL_{avail}^{BS})$	Current available downlink capacity of a BS
$R(DL\_RZ_{\max}^{BS})$	The maximum relay zone capacity of a BS
$R(Unit_{DL})$	A common minimum allocation unit in a DL
$\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}$	The maximum slot number of the access zone in the time domain among the first hop nt-RS
$cur\{N_{BS}^{DL\_AZ}(t\_slot)\}$	The current slot number of the access zone of a BS in the time domain
$R(Unit_{DL\_RZ})$	A common minimum allocation unit only in the relay zone of the DL

Using notations, slot fairness is described as follows:

$N(slot_{DL}(SS_k^{BS})) = N(slot_{DL}(SS_k^{nt-RS_k^i}))$ where, i <= max hop count

$N(slot_{UL}(SS_k^{BS})) = N(slot_{UL}(SS_k^{nt-RS_k^i}))$ where, i <= max hop count

And, throughput fairness is also described as follows:

$R(DL(SS_k^{BS}) = R(DL(SS_k^{nt-RS_k^i})$ where, i <= max hop count

$R(UL(SS_k^{BS}) = R(UL(SS_k^{nt-RS_k^i})$ where, i <= max hop count

4.1 Max-Min Fairness

The main purpose of the proposed max-min fairness scheme is to allocate OFDMA slots to subscriber stations (SSs) to maximize the minimum number of all subscriber stations' assigned data rates regardless of what superior station they are associated with. In other words, some SSs are allocated OFDMA slots in the relay zone of the superior station, and some are allocated slots in the access zone of the superior station. Thus, the proposed max-min fairness scheme in the MMR network can be formulated as follows:

$$\arg\max_k \{\min R(SS_k^{DL})\} \text{ where } k \in N(SS_{DL\_AZ}) + N(SS_{DL\_RZ}) \quad (12)$$

$$\arg\max_k \{\min R(SS_k^{UL})\} \text{ where } k \in N(SS_{UL\_AZ}) + N(SS_{UL\_RZ}) \quad (13)$$

Based on Equations (10) and (11), the MM-BS-1 and MM-BS-2 algorithms show the proposed max-min fairness scheme in the wireless MMR network. In this section, we show the proposed scheme using a downlink sub-frame. The MM-BS-1 algorithm shows a BS's initialization phase. The BS first follows the BS-A-1 algorithm (Section 3.4) to initialize available slot indices in the time and frequency domain. Then, it obtains the number of its directly associated SSs ($N(SS_{DL\_AZ}^{BS})$) and the number of SSs that belongs to its first hop nt-RSs ($N(SS_{DL\_RZ}^{BS})$). Using the total number of SSs, the BS can calculate the minimum slot unit that can be equally assigned to its directly associated SSs and first hop nt-RSs. Finally, it calculates the minimum slot unit only for SSs associated with the first nt-RSs.

[MM-BS-1] Initialization phase in a BS

follow the BS-A-1 algorithm

obtain $N(SS^{BS}_{DL\_AZ})$, $N(SS^{BS}_{DL\_RZ}) = \sum_{k=1}^{k} N(SS^{nt-RS^{i}_{k}}_{DL\_RZ})$

calculate $N(SS) = N(SS^{BS}_{DL\_AZ}) + N(SS^{BS}_{DL\_RZ})$

$R(DL^{BS}_{avail}) = R(DL^{BS}_{total})$

$R(Unit_{DL}) = R(DL^{BS}_{avail}) \ / \ N(SS)$

$R(Unit_{DL\_RZ}) = R(Unit_{DL})$

$cur\{N^{DL-AZ}_{BS}(t\_slot)\} = 0$, $\max\{N^{DL-AZ}_{nt-RS^{1}}(t\_slot)\} = 0$

The MM-BS-2 algorithm shows how the BS allocates slots according to max-min fairness. The BS continuously assigns slots until all SSs in the MMR network are assigned their minimum data rate. The different point from general max-min fairness algorithms is that the proposed algorithm always checks the relay zone limitation property (Section 3.3). That is, the SSs that belong to relay zone in the BS are restricted to the maximum relay zone capacity even though OFDMA slots in the access zone are available. In this case, the BS maintains two minimum allocation slots: one is for SSs in the access zone and the other is for SSs in the relay zone.

The proposed max-min algorithm first finds an SS with the least data rate and allocates slots to the SS. If the requested date rate is smaller than the minimum data rate to be assigned, the BS re-calculated the minimum data rate based on the current data rate and the remaining number of SSs after it allocates slots to the SS. When the BS allocate a data rate to an SS in the access zone or the relay zone, it update $cur\{N^{DL-AZ}_{BS}(t\_slot)\}$ or

$\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}$, respectively. These two values are used to check the relay zone limitation property.

[MM-BS-2] max-min fairness allocation

while $N(SS) \neq 0$
  find the SS with the smallest rate
  if an ss $\in$ $SS_{DL\_AZ}^{BS}$ // this ss locates in the access zone
    res = assign_rate ($R(SS_k^{DL-AZ})_{req}, R(Unit_{DL})$, ss)
    $N(SS_{DL\_AZ}^{BS}) = N(SS_{DL\_AZ}^{BS})$ - 1
    $N(SS) = N(SS_{DL\_AZ}^{BS}) + N(SS_{DL\_RZ}^{BS})$
    update $cur\{N_{BS}^{DL-AZ}(t\_slot)\}$ // current number of slot used in the access zone
    if res > 0
      $R(DL_{avail}^{BS}) = R(DL_{avail}^{BS})$ - $R(SS_k^{DL-AZ})_{req}$
      $R(Unit_{DL}) = R(DL_{avail}^{BS})$ / $N(SS)$
      $R(Unit_{DL\_RZ}) = R(Unit_{DL})$
  else // this ss locates in the relay zone
    if $\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\} > cur\{N_{BS}^{DL-AZ}(t\_slot)\}$ // check relay limitation
      $R(Unit_{DL\_RZ}) = R(DL\_RZ_{\max}^{BS}) / N(SS_{DL\_RZ}^{BS})$
      $R(Unit_{DL}) = R(DL_{avail}^{BS})$ / $N(SS)$
    $R(Unit_{DL\_RZ})$ = min { $R(Unit_{DL\_RZ})$, $R(Unit_{DL})$ }
    res = assign_rate ($R(SS_k^{DL-RZ})_{req}, R(Unit_{DL\_RZ})$, ss)
    $N(SS_{DL\_RZ}^{BS}) = N(SS_{DL\_RZ}^{BS})$ -1
    $N(SS) = N(SS_{DL\_AZ}^{BS}) + N(SS_{DL\_RZ}^{BS})$
    Update $\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}$
    if res > 0
      $R(DL_{avail}^{BS}) = R(DL_{avail}^{BS})$ - $R(SS_k^{DL-AZ})_{req}$
      $R(Unit_{DL}) = R(DL_{avail}^{BS})$ / $N(SS)$
      $R(Unit_{DL\_RZ}) = R(Unit_{DL})$
function assign_rate ($req\_rate, unit\_rate$, ss) {
  if $req\_rate > unit\_rate$
    assign $unit\_rate$ to the ss and return 0
  else
    assign req_rate to the ss and return $unit\_rate$ - req_rate }

4.2 Proportional Fairness

The main drawback of the proposed max-min fairness scheme is that the SS associated with a subordinate nt-RS takes more OFDMA resources because the channel condition between a superior station and its subordinate nt-RSs has poor channel conditions due to the distance of their locations. Therefore, the network capacity is not fully exploited. To avoid this drawback, we propose a proportional fairness scheme. We also propose a two-layer proportional weight concept for the proposed scheme. In the first layer, a weight value is given to the access zone and the relay zone of the superior station. The sum of the assigned weight is one. However, how to assign the weight value in the first layer is outside the scope of this thesis. In the second layer, every SS is assigned a weight based on its channel condition with its associated station. Based on these two weight values, every SS is proportionally assigned OFDMA resources. So, the proposed proportional fairness scheme in the MMR network can be formulated as follows:

$$\arg\max_{i \in k} \{\min(w_z^1 w_i^2 R(SS_i^{DL}))\} \tag{14}$$

$$\arg\max_{i \in k} \{\min(w_z^1 w_i^2 R(SS_i^{UL}))\} \tag{15}$$

Where z is the access zone or the relay zone, k is the total number of SS in the MMR network, w^1 is the first weight value, and w^2 is the second weight value.

Based on Equation (12) and (13), the P-BS-1 and P-BS-2 algorithms show the proposed proportional fairness scheme in the wireless MMR network. First, the P-BS-1 algorithm shows the initialization phase of a BS. The BS assigns the first weight value to its access zone and relay zone and the second weight value to SSs associated with its access zone or relay zone. Using the first and second weight value, the BS initializes a weight array consisting of every weight value of SSs and another weight array only with SSs associated its subordinate nt-RSs. Finally, the BS obtains the total data rate that it can support and initializes current number of slot in its access zone and the maximum number of slot in its relay zone in the time domain.

[P-BS-1] Initialization phase in a BS

follow the BS-A-1 algorithm

assign w_{AZ}^1 and w_{RZ}^1 $(w_{AZ}^1 + w_{RZ}^1 = 1)$

obtain w_x^2 $(1 < x < N(SS_{DL\_AZ}^{BS}))$

obtain w_y^2 $(1 < \mathrm{y} < N(SS_{DL\_RZ}^{BS}))$

for all x in the access zone

$$w_x = w_{AZ}^1 * w_x^2 \quad (1 < x < N(SS_{DL\_AZ}^{BS}))$$

for all y in the relay zone

$$w_y = w_{RZ}^1 * w_y^2 \quad (1 < \mathrm{y} < N(SS_{DL\_RZ}^{BS}))$$

$Arary(w_k) = \{w_1, w_2, \ldots w_k\}$ $(\mathrm{k} = N(SS_{DL}^{BS}))$

$Rz\_Arrary(w_y) = \{w_1, w_2, \ldots w_y\}$ $(\mathrm{k} = N(SS_{DL\_RZ}^{BS}))$

$R(DL_{avail}^{BS}) = R(DL_{total}^{BS})$

$cur\{N_{BS}^{DL\_AZ}(t\_slot)\} = 0$, $\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\} = 0$

The P-BS-2 algorithm shows how the BS allocates slots according to proportional fairness. The BS continuously assigns slots until all SSs in the MMR network are assigned their minimum data rate based on their weights. Like the MM-BS-2 algorithm, the proposed algorithm checks relay zone limitation property when it assigns slots to the SS associated its relay zone. Another different point from general proportional fairness is that the proposed algorithm gives two weight values to all subscriber stations and allocates slots based on the mixed weight from the two.

Every time the proposed proportional algorithm allocates OFDMA slots to an SS, it first normalizes every SS's weight value. Then, the proposed algorithm finds the SS with the least data rate and allocates slots to the SS. Based on the normalized weight, the algorithm can calculate the minimum data rate of the SS ($R(Unit_{DL}^{SS_k})$). If the requested date rate of the SS is smaller than the minimum data rate to be assigned, the BS re-calculates the normalized weight value from the remaining SSs and their weight after it allocates slots to the SS. When the BS allocate a data rate to an SS in the access zone or the relay zone, it update $cur\{N_{BS}^{DL\_AZ}(t\_slot)\}$ or $\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}$, respectively. When a SS associated with the subordinate nt-RS is assigned slots, if the $\max\{N_{nt-RS^1}^{DL\_AZ}(t\_slot)\}$ is larger than $cur\{N_{BS}^{DL\_AZ}(t\_slot)\}$, which means the relay zone cannot be more extended within a sub-frame, the algorithm calculate the normalized weight from only the SSs associated the subordinate nt-RSs. Then, the minimum date rate is determined by selecting the minimum between the data rate calculated by all the SSs and the data rate calculated by only the SS associated with the subordinate nt-RS.

[P-BS-2] proportional fairness allocation

```
while  N(SS) ≠ 0
    nor_array(w_k^nor) = normalize_weight (Arrary(w_k))
    w_sum = w_1^nor + w_2^nor + …. + w_k^nor
    if max{N_{nt-RS^1}^{DL_AZ}(t_slot)} > cur{N_BS^{DL_AZ}(t_slot)}  // check relay limitation
        normalize_weight (Rz_Arrary(w_y))
    first find all the SSs in the access zone with the smallest rate, then SS in the relay zone
    if  SS_k ∈ SS_{DL_AZ}^{BS}    // this ss locates in the access zone
        R(Unit_DL^{SS_k}) = R(DL_avail^BS)×(w_k^nor / w_sum)
        res = assign_rate ( R(SS_k^{DL_AZ})_req , R(Unit_DL^{SS_k}) , ss)
        update cur{N_BS^{DL_AZ}(t_slot)}    // current number of slot used in the access zone
        if res > 0
            R(DL_avail^BS) = R(DL_avail^BS) - R(SS_k^{DL_AZ})_req
    else     //  this ss locates in the relay zone
        if max{N_{nt-RS^1}^{DL_AZ}(t_slot)} > cur{N_BS^{DL_AZ}(t_slot)}  // check relay limitation
            nor_rz_arrary(w_y^nor)= normalize_weight (Rz_Arrary(w_y))
            w_rz_sum = w_1^nor + w_2^nor + …. + w_y^nor
            R(Unit_{DL_RZ}^{SS_k}) = R(DL_RZ_max^BS)× w_y^nor / w_rz_sum
        R(Unit_{DL_RZ}) = min { R(Unit_{DL_RZ}) , R(Unit_DL) }
        res = assign_rate ( R(SS_k^{DL_RZ})_req , R(Unit_{DL_RZ}) , ss)
        update max{N_{nt-RS^1}^{DL_AZ}(t_slot)}
        if res > 0
            R(DL_avail^BS) = R(DL_avail^BS) - R(SS_k^{DL_AZ})_req
normalize_weight (Arary(w_k)) {
    nor_Array(w_k^nor) by normalizing Arary(w_k)
}
ssign_rate (req_rate, unit_rate, ss) {
    if req_rate > unit_rate
        assign unit_rate to the ss
        return 0
    else
        assign req_rate to the ss
        return unit_rate - req_rate }
```

4.3 Simulations

In this section, we focus on max-min and proportional fairness between the proposed adaptive allocation algorithm and a non-adaptive allocation scheme. For the max-min fairness scheme, we use the existing max-min fairness index [24] to measure fairness of the proposed algorithm and the non-adaptive allocation algorithm. For the proportional scheme, we assign different weight value to a relay zone and an access zone and compare the throughput between proportional and max-min fairness. The existing max-min fairness index used in our simulations is expressed as follows:

$$I(\text{max\_min}) = \frac{\min\{R(SS_x)_{\text{asgn}}\}}{\max\{R(SS_y)_{\text{asgn}}\}} \;\; (x \neq y) \tag{16}$$

The channel model used in this simulation is same as the model in Section 4.5. When we create subscriber stations, the same data rate in Section 4.5 is also used for the max-min fairness simulation. Based on Equation 14, Figure 22, 24, and 26 show the result of the proposed adaptive allocation algorithm and a non-adaptive allocation scheme with respect to max-min fairness as we increase the number of total subscriber stations in the MMR network. In general, the proposed algorithm shows better max-min fairness because it can use all of the sub-frame to allocate slots to SSs regardless of what superior station (the BS or the nt-RS) they are associated with. As the number of SSs in the access zone increases (more number of SSs than the SS in the relay zone), the fairness index of the proposed scheme decreases. This is because the throughput increases as the number of SSs in the access zone increases, which means that the SSs in the access zone can obtain OFDMA slots that they request. So, fairness index is determined by the data rate of each SS when it is created. Figure 23, 25, and 27 show the throughput of the proposed adaptive allocation algorithm and a non-adaptive allocation scheme in terms of max-min fairness. The graphs indicate that the non-adaptive allocation scheme is a little better than the proposed adaptive scheme only in a symmetric distribution of subscriber stations between access zones and relay zones. This is because the non-adaptive allocation scheme can select the best sub-channel in the fixed time domain. In any asymmetric distribution of subscriber stations, the proposed scheme is always much better than the non-adaptive scheme, because the proposed scheme always uses all the OFDMA slots regardless of the distribution of subscriber stations between access zones and relay zones.

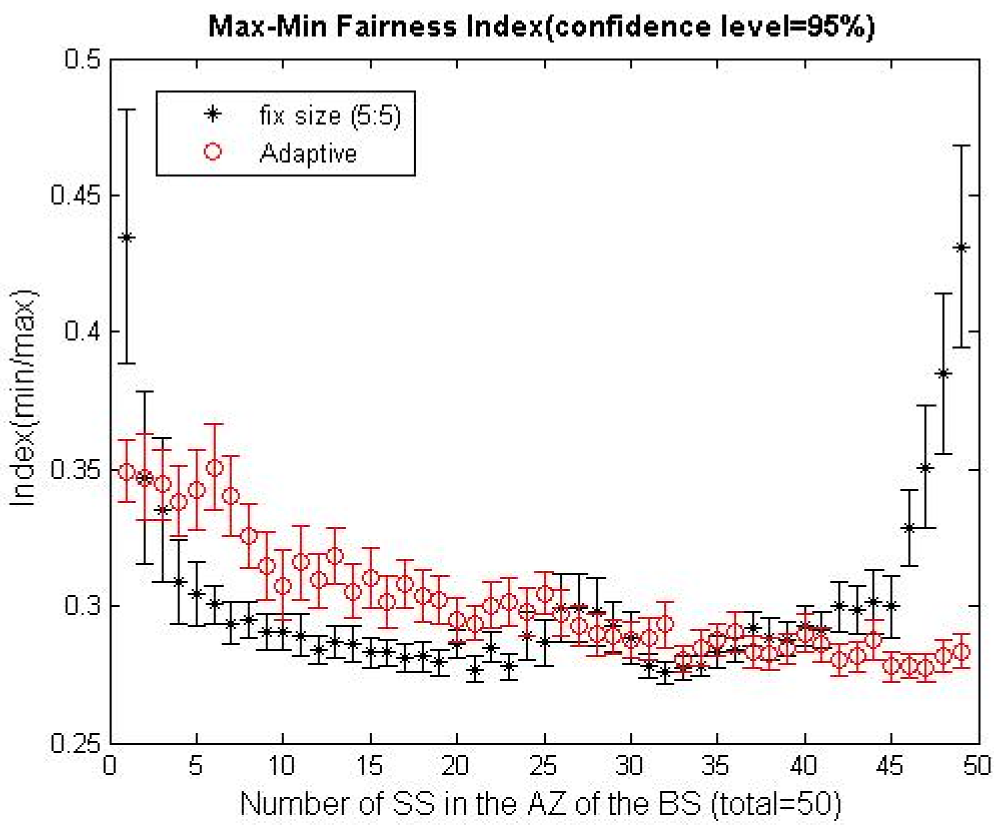

Figure 22. Max-min fairness index in the case of 50 SSs.

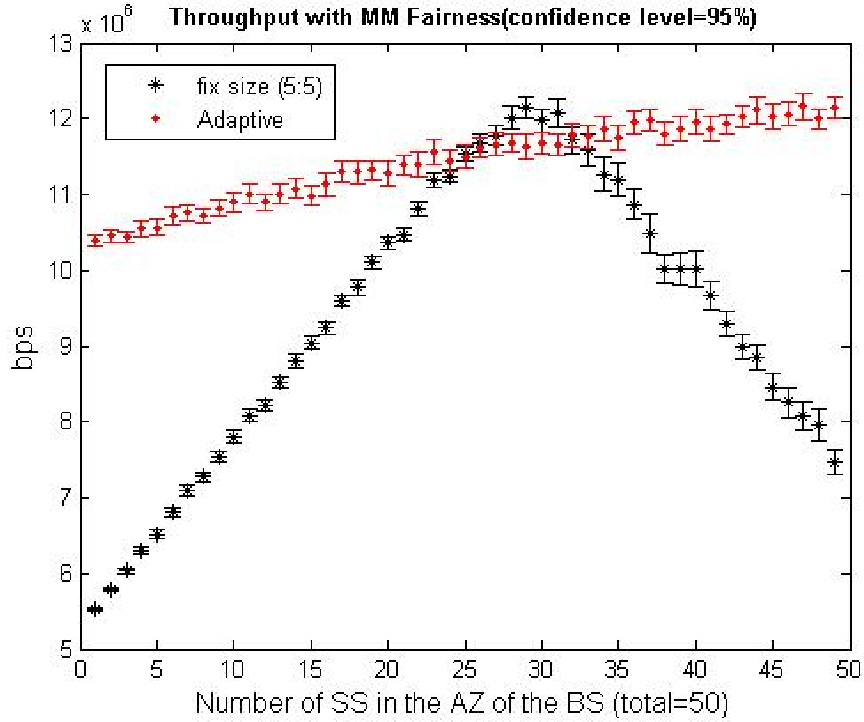

Figure 23 Throughput with max-min fairness in the case of 50 SSs.

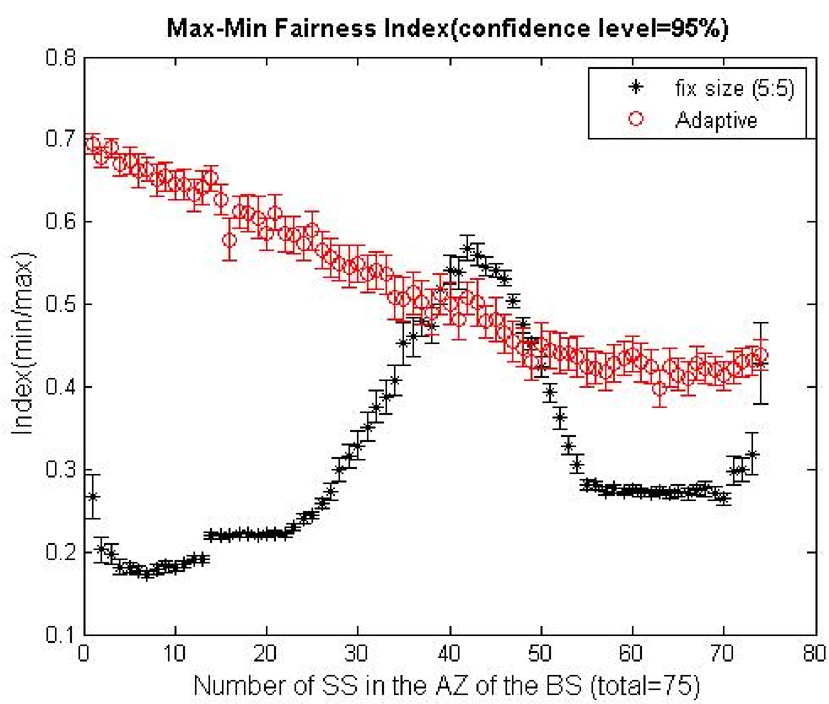

Figure 24. Max-min fairness index in the case of 75 SSs

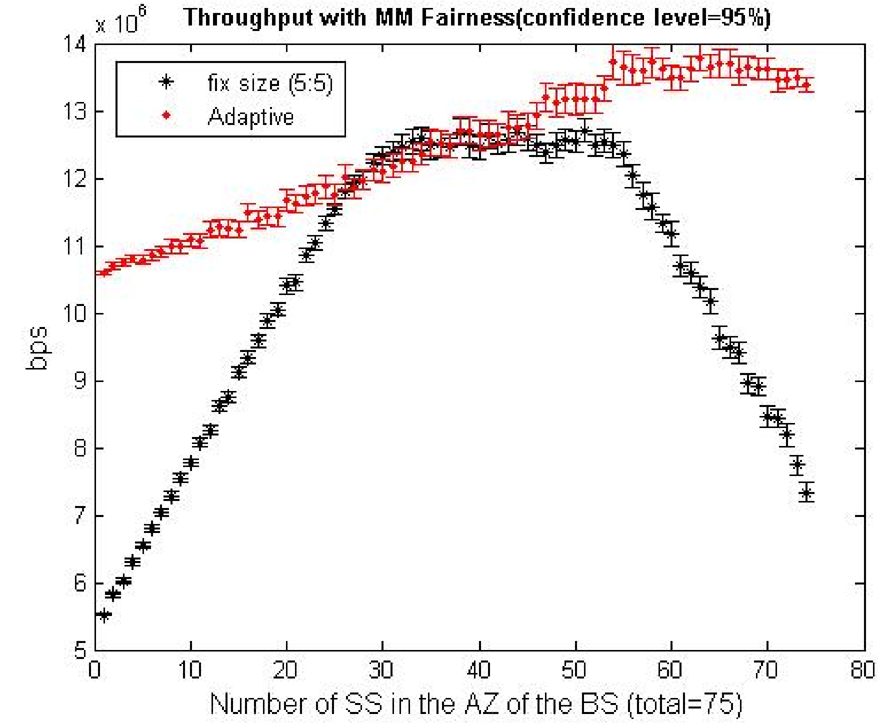

Figure 25. Throughput with max-min fairness in the case of 75 SSs.

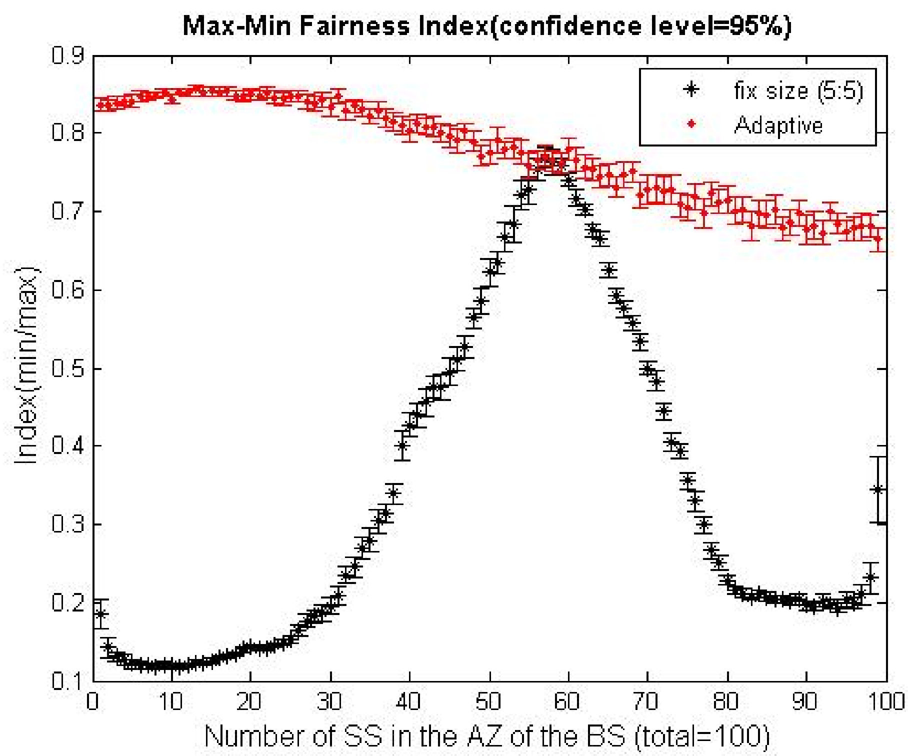

Figure 26. Max-min fairness index in the case of 100 SSs.

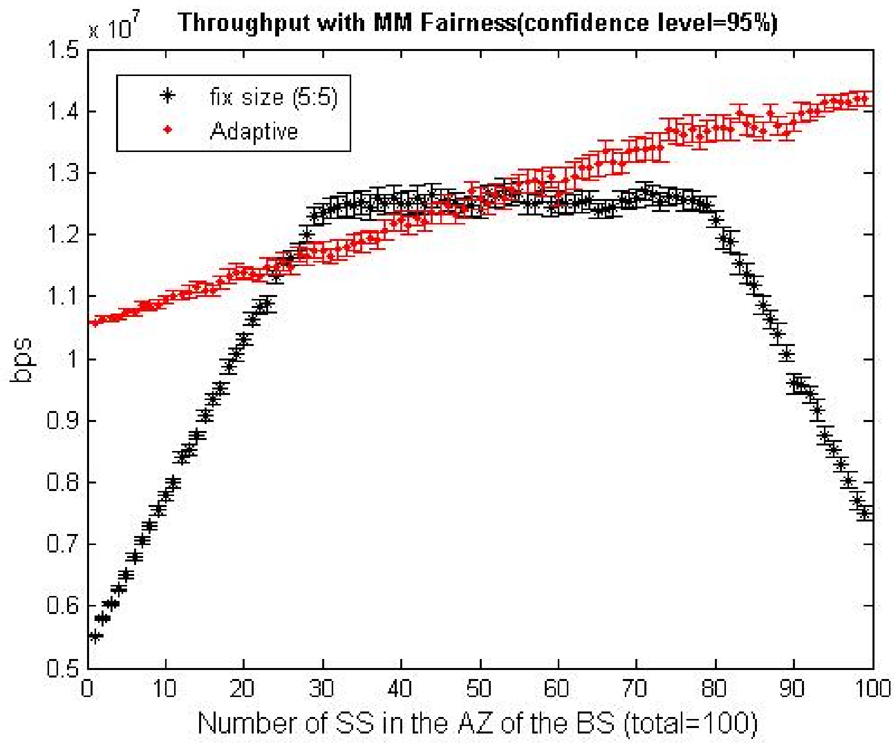

Figure 27. Throughput with max-min fairness in the case of 100 SSs.

Figure 28 and 29 shows the throughput of the proposed allocation algorithm with proportional and max-min fairness. In this simulation, we change the data rate when each subscriber station is created. Based on the distance between a subscriber station and its superior station, the data rate of each subscribe station is different. In other words, the short of distance is between a SS and its superior stations, the more data rate the SS has. This is to see how the proposed proportional fairness performs. The results indicate the proposed algorithm with proportional fairness is better than the one with max-min fairness regardless of the weight value assigned to the access zone of the BS. It also shows that the throughput performance increases with the higher weight on the access zone as the number of SSs associated with the BS increases. The proposed max-min fairness scheme shows the same throughput regardless of the distribution of subscriber stations. This is because the proposed scheme does not care about the signal strength between SSs and their superior station.

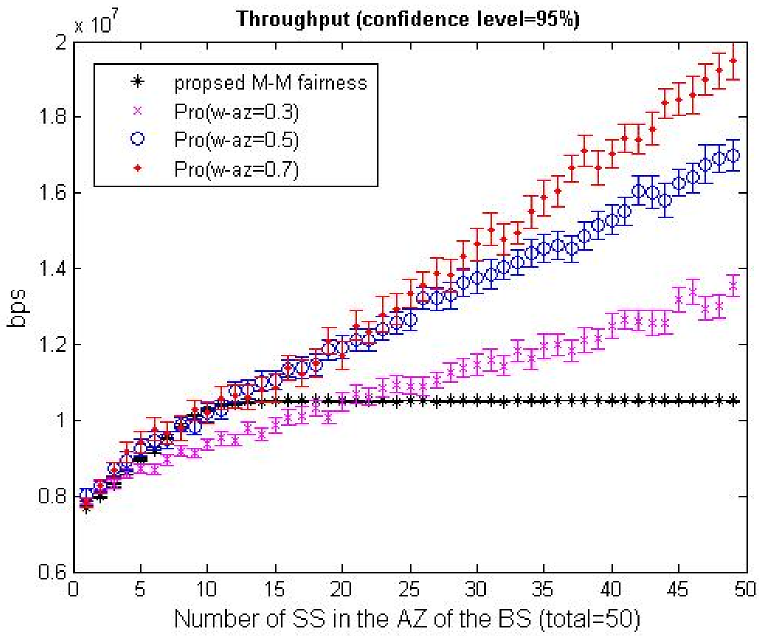

Figure 28. Throughput between proportional and max-min fairness in the case of 50 SSs

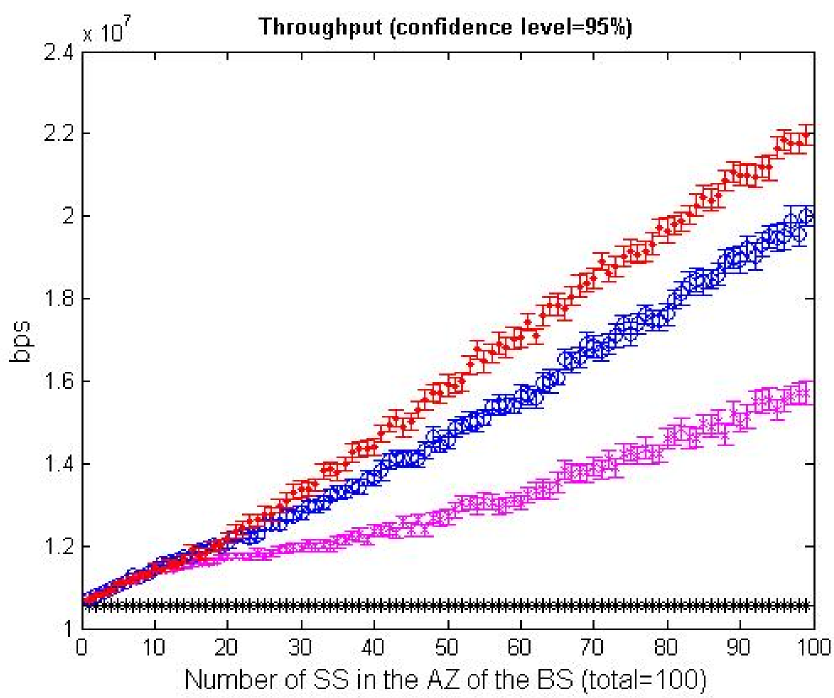

Figure 29. Throughput between proportional and max-min fairness in the case of 100 SSs

CHAPTER 5

BACKHAUL AND LOCAL TRAFFIC

5.1 Backhaul traffic and local traffic

In Section 3.1 and 3.2, we show the proposed adaptive frame structures for nt-RSs to increase the cell coverage of the BS. However, the extension of the cell coverage of the BS by placing nt-RSs causes a drawback: less bandwidth utilization. The reason for the lower bandwidth utilization is that the access zone of the DL/UL sub-frame in nt-RSs cannot be fully utilized because only some portion of the access zone allocated by a superior station can be relayed to their associated SSs and the superior station. For example, the nt-RS_1^1 in Figure 12 serves its SSs by using only some portion of its access zone (the shadow region of the first stage in Figure 13. What is worse, the portion of access zone that nt-RSs cannot use becomes larger as the nt-RSs are more hops away from the BS.

To handle this drawback, we introduce the concept of the backhaul and local traffic. The backhaul traffic is the data traffic that should originate from a BS or terminate at the BS, and the local traffic is the traffic that originates from nt-RSs, terminates at their subordinate nt-RSs ,or their associated SSs. Examples of the local traffic are communication among SSs within a specific nt-RS and multimedia data streams from the nt-RS to its associated SS. Using the rest of the access zone that is assigned by a superior station, we assign OFDMA symbols to the local traffic. Figure 26 shows a new frame structure by which nt-RSs can use some portion of their access zone for the local traffic. In the first stage of Figure 13, the nt-RS_1^1 cannot use some OFDMA resources of access zone in the DL/UL sub-frame (white region) because of the size of OFDMA resources assigned by a BS. However, the nt-RS_1^1 in Figure 30 can use them in the DL/UL sub-frame (light shadow region) for the local traffic. In the second stage, the nt-RS_1^2 has more remaining OFDMA resources than the RS_1^1 because of the size of OFDMA resources assigned by its superior station. Figure 31 shows the proposed frame structure in the same MMR network shown in Figure 12.

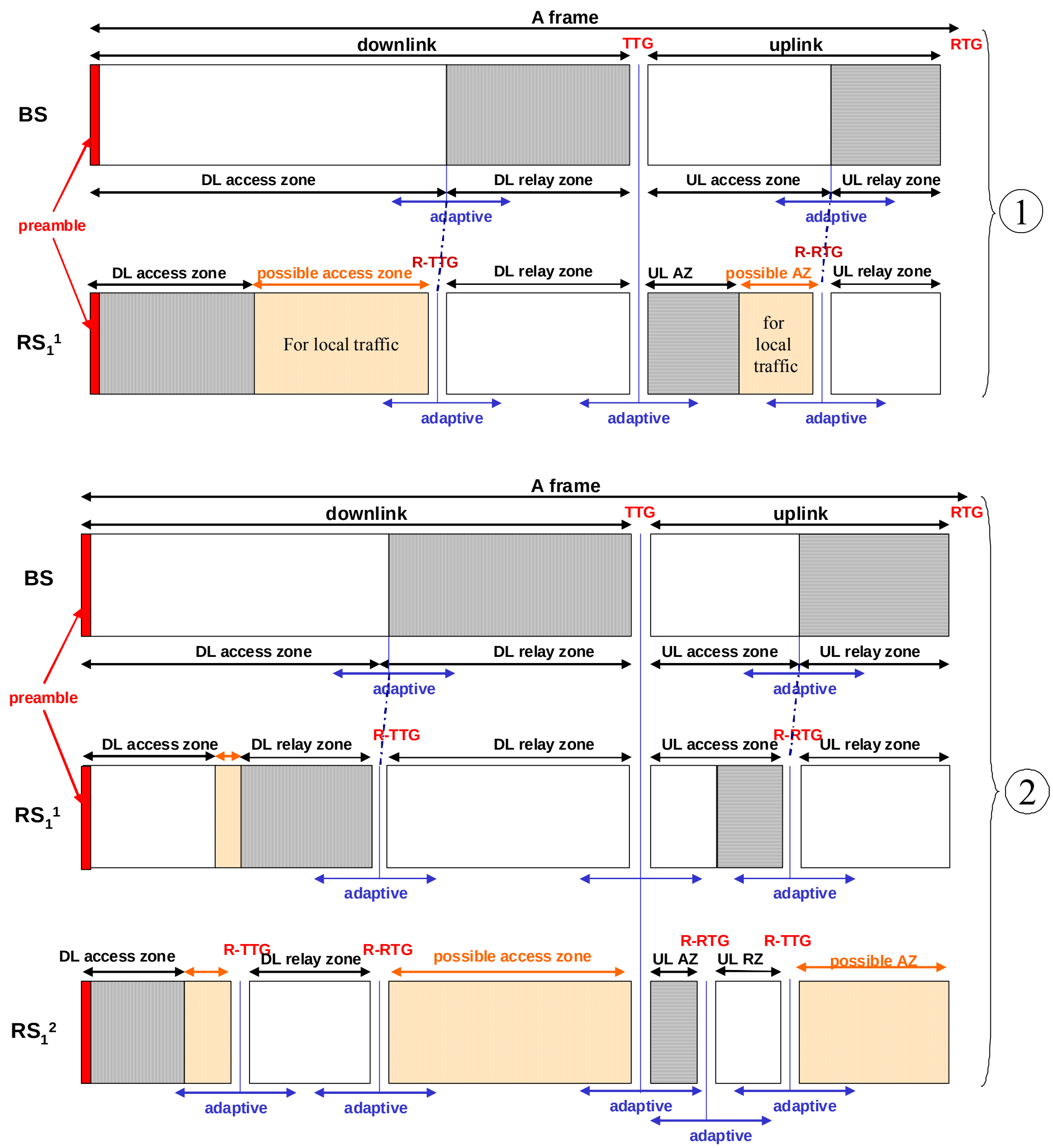

Figure 30. OFDMA resources of the AZ for the local traffic with a relay direction.

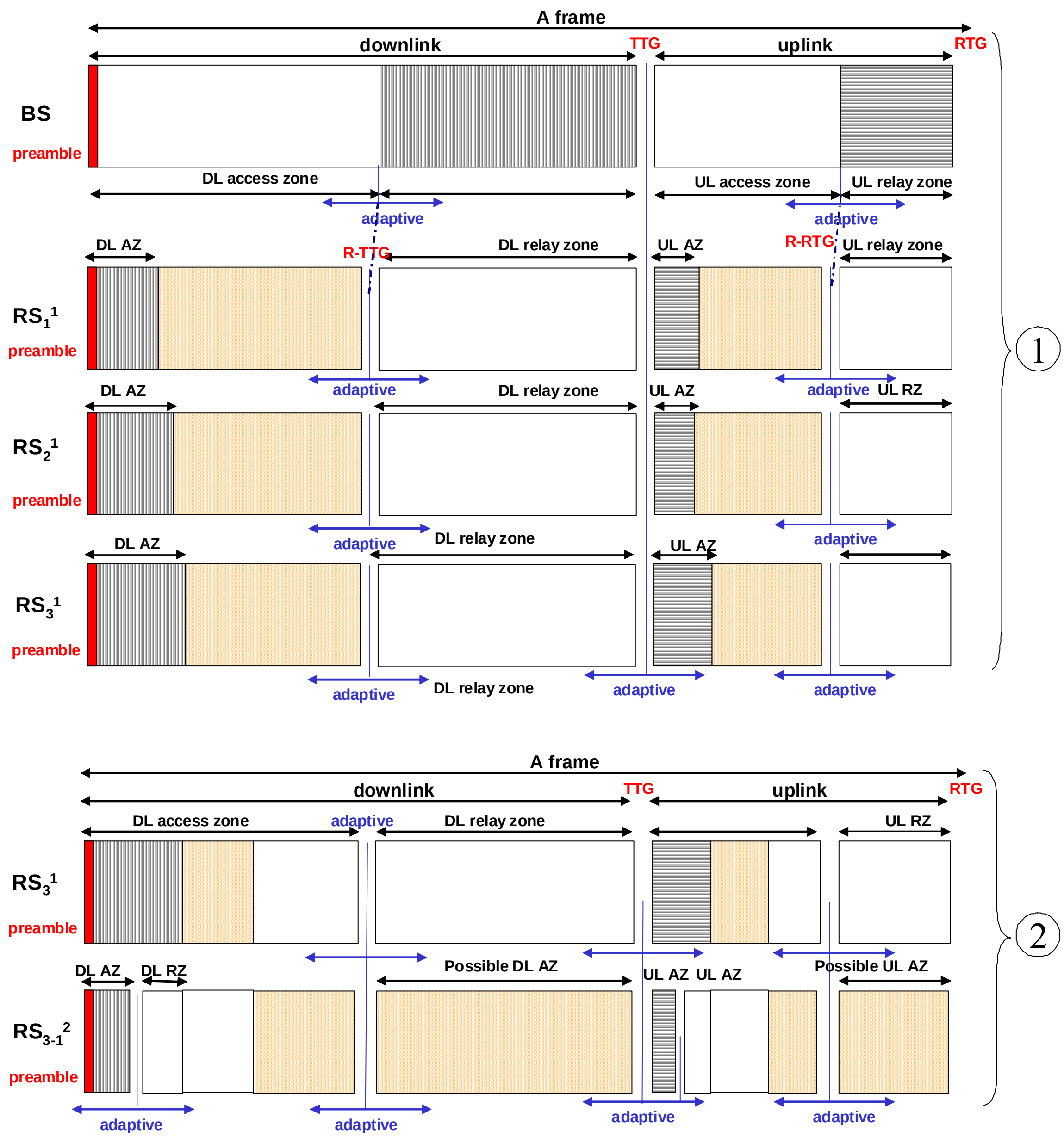

Figure 31. OFDMA resources of the AZ for the local traffic with multiple relay directions.

5.2 OFDMA Resource Allocation Scheme for Local Traffics

Because we introduce the backhaul and local traffic to increase bandwidth utilization of nt-RSs, the proposed three properties in Chapter 3 need to be changed such that the properties are only applied to the backhaul traffic. Table 4 shows the notations for the backhaul and backhaul traffic.

Table 6. Notation for the local traffic

Notations	Explanation
$R(DL\_AZ_{nt-RS_k^i}^{back})_{\mathrm{req}}^{nt-RS_x^{i+1}}$	data rate of backhaul traffic assigned to the access zone of the i-th hop relay station *k*
$R(DL\_AZ_{nt-RS_k^i}^{back})_{\mathrm{asgn}}^{nt-RS_x^{i+1}}$	data rate of local traffic assigned to the access zone of the i-th hop relay station *k*
$R(DL\_AZ_{nt-RS_k^i}^{local})_{\mathrm{req}}^{nt-RS_x^{i+1}}$	Requested the data rate of the relay zone from the first hop k-th nt-RS associated with a BS
$R(DL\_AZ_{nt-RS_k^i}^{local})_{\mathrm{asgn}}^{nt-RS_x^{i+1}}$	Requested the data rate of the relay zone from the first hop k-th nt-RS associated with a BS
$R(DL\_AZ_{nt-RS_k^i}^{local})_{\mathrm{req}}^{SS_k}$	Requested the data rate of the relay zone from the first hop k-th nt-RS associated with a BS
$R(DL\_AZ_{nt-RS_k^i}^{local})_{\mathrm{asgn}}^{SS_k}$	Requested the data rate of the relay zone from the first hop k-th nt-RS associated with a BS

The proposed relay property is changed by the following:

$$\sum_{k=1}^{n} R(DL\_AZ_{nt-RS_k^1}^{back}) \leq R(DL\_RZ_{BS}), \quad \text{(C4-1)}$$

$$\sum_{k=1}^{n} R(DL\_AZ_{nt-RS_k^i}^{back}) \leq R(DL\_RZ_{nt-RS^{i-1}}), \text{ where } i > 1 \quad \text{(C4-2)}$$

$$\sum_{k=1}^{n} R(UL\_AZ_{nt-RS_k^1}^{back}) \leq R(UL\_RZ_{BS}), \quad \text{(C4-3)}$$

$$\sum_{k=1}^{n} R(UL\_AZ_{nt-RS_k^i}^{back}) \leq R(UL\_RZ_{nt-RS^{i-1}}), \text{ where } i > 1 \quad \text{(C4-4)}$$

The proposed maximum balance property is also changed into the following:

$$\max C_{DL\_RZ_{BS}} \approx \max \sum_{r=1}^{N_{nt-RS^1}(BS)} C_{DL\_AZ_{nt-RS_r^1}}, \qquad \text{(C2-1)}$$

$$\max \sum_{r=1}^{A} C_{DL\_RZ_{nt-RS_r^{i-1}}} \approx \max \sum_{r=1}^{A} C_{DL\_AZ_{nt-RS_r^{i}}}, \quad where, 2 < i < \max hop, A = N_{nt-RS^i}(nt-RS^{i-1}) \qquad \text{(C2-2)}$$

$$\max C_{UL\_RZ_{BS}} \approx \max \sum_{r=1}^{N_{nt-RS^1}(BS)} C_{UL\_AZ_{nt-RS_r^1}}, \qquad \text{(C2-3)}$$

$$\max \sum_{r=1}^{A} C_{UL\_RZ_{nt-RS_r^{i-1}}} \approx \max \sum_{r=1}^{A} C_{UL\_AZ_{nt-RS_r^{i}}}, \quad where, 2 < i < \max hop, A = N_{nt-RS^i}(nt-RS^{i-1}) \qquad \text{(C2-4)}$$

The following allocation schemes explain how an nt-RS assigns OFDMA slots for the backhaul and local traffic. Generally speaking, slot allocation for the backhaul traffic is followed by slot allocation for the local traffic. The RS-L-1 algorithm shows an initialization phase to prepare slot allocation of the backhaul traffic. In addition, it obtains the group of subordinate nt-RSs and SSs that have the local traffic. After the initialization, the algorithm first allocates OFDMA slots to subordinate nt-RSs for the backhaul traffic and then to associated SSs. The RS-L-4 and RS-L-5 show that the nt-RS allocate OFDMA slots to subordinate nt-RSs and SSs that have the local traffic.

[RS-L-1] Initialization phase in an nt-RS$_k^{i\text{-}th}$

Follow the RS-A-1 algorithm in Section 3.4

Obtain $G_{nt-RS_k^i}^{local}\{nt-RS_k^{i+1})$ and $G_{nt-RS_k^i}^{local}\{SS_k)$

[RS-L-2] slot allocation for the backhaul traffic of nt-RS$_k^{i+1}$

Follow the RS-A-2 algorithm in Section 3.4

[RS-L-3] slot allocation for the backhaul traffic of SS$_k$

Follow the RS-A-3 algorithm in Section 3.4

[RS-L-4] slot allocation for local traffic of the nt-RS_k^{i+1}

$G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\}) = G_{nt-RS_k^i}^{avail}\{index(N(_{t\_slot}^{DL\_AZ})\})$

If $G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\}) \neq 0$

while $G_{nt-RS_k^i}^{local}\{nt-RS_k^{i+1}) \neq 0$

If $N_{slot}\{G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\})\} ==$ $N_{slot}\{G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\})\}$

breaks

find the subordinate nt-RS

such that $R(DL_{nt-RS_k^i})_{req}^{nt-RS_x^{i+1}} < R(DL_{nt-RS_k^i})_{req}^{nt-RS_y^{i+1}}$ (y ≠ x and y =1,2,..k)

// start point is the maximum number of slot index in the access zone of the nt-RS_k^i

j_init = $\max\{G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\})\}$

// assign slots to meet $R(DL\_RZ_{nt-RS_k^i}^{local})_{req}^{nt-RS_x^{i+1}}$

$R(DL_{nt-RS_k^i}^{local})_{\text{asgn}}^{nt-RS_x^{i+1}} = 0$

for j = j_init; j < 1; j-- :

// checking limitation of relay zone

If $N_{slot}\{G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\})\} ==$ $N_{slot}\{G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\})\}$

breaks

for i = i_init; i < $\max(N_{f\_slot}^{DL})$; i++

$R(DL_{nt-RS_k^i}^{local})_{\text{asgn}}^{nt-RS_x^{i+1}} =$

$slot(i,j) \times M_{nt-RS_k^i-nt-RS_k^{i+1}} \times CR_{nt-RS_k^i-nt-RS_k^{i+1}} + R(DL_{nt-RS_k^i}^{local})_{\text{asgn}}^{nt-RS_x^{i+1}}$

if $R(DL_{nt-RS_k^i}^{local})_{\text{asgn}}^{nt-RS_x^{i+1}} \geq R(DL_{nt-RS_k^i}^{local})_{req}^{nt-RS_x^{i+1}}$

update $\max\{G\{N_{nt-RS^{i+1}}^{UL\_AZ}(t\_slot)\}\}$

breaks

if $G_{nt-RS_k^i}^{local\_avail}\{index(N(_{f\_slot}^{DL\_AZ})\} = 0$:

i_init = 0

$G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\} = G_{nt-RS_k^i}^{local\_avail}\{index(N(_{t\_slot}^{DL\_AZ})\} - index(j)\}$

else : i_init = i

[RS-L-5] slot allocation for the local traffic of SS_k

while $G^{local}_{nt-RS^i_k}\{SS_k\} \neq 0$

find the SS_k such that $R(DL^{local}_{nt-RS^i_k})^{SS_x}_{req} < R(DL^{local}_{nt-RS^i_k})^{SS_y}_{req}$ (y ≠ x and y =1,2,..k)

// assign available slot range in the time domain for the access zone of a BS

j_init = $\min(G^{local\_avail}_{nt-RS^i_k}\{index(N(^{DL\_AZ}_{t\_slot})\})$

j_max = $\max(G^{local\_avail}_{nt-RS^i_k}\{index(N(^{DL\_AZ}_{t\_slot})\})$

//assign slots to meet $R(DL\_AZ^{local}_{nt-RS^i_k})^{SS_k}_{req}$

$R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{asgn}} = 0$

for j = j_init; j < j_max ; j++ :

if $R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{asgn}} \geq R(DL^{local}_{nt-RS^i_k})^{SS_k}_{req}$:

breaks

for i = i_init; i < $\max(N^{DL}_{f\_slot})$; i++

$R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{asgn}} = slot(i,j) \times M_{nt-RS^i_k-SS_k} \times CR_{nt-RS^i_k-SS_k} +$
$R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{asgn}}$

if $R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{asgn}} \geq R(DL^{local}_{nt-RS^i_k})^{SS_k}_{\mathrm{req}}$:

breaks

if $G^{local\_avail}_{nt-RS^i_k}\{index(N(^{DL\_AZ}_{f\_slot})\} = 0$:

i_init = 0

$G^{local\_avail}_{nt-RS^i_k}\{index(N(^{DL\_AZ}_{f\_slot})\} = G^{local\_avail}_{nt-RS^i_k}\{index(N(^{DL\_AZ}_{f\_slot})\} - index(j)\}$

else :

i_init = i

CHAPTER 6

ADAPTIVE FRAME STRUCTURE FOR nt-RSs and t-RSs

In Chapter 5, we introduced a drawback of extending the cell coverage of a BS and proposed the concept of the local traffic to reduce the drawback. In this chapter, we also introduce another drawback: a decrease in the MMR network capacity. The reason for the decreased network capacity is that the first hop nt-RSs are located near the cell boundary, where the signal strength between them and the BS is not sufficient and does not generate an efficient modulation scheme or a coding rate. To overcome this issue, we place transparent RSs (t-RSs) to bridge between the BS and nt-RSs at the expense of having time delay of one more frame time. To have nt-RSs as well as t-RSs in the same wireless MMR network, we need a new frame structure. To the best of our knowledge, no papers mentioned this type of frame structure.

6.1 Adaptive Frame structure with one relay direction

Figure 32 shows that a t-RS is placed between a BS and an nt-RS. In this configuration, Figure 23 shows the proposed frame structure. The t-RS_1[1] sends downlink traffic to the nt-RS by using the transparent zone of its DL sub-frame (the shadow region). During the transparent zone, the BS should be silent, and the t-RS sends traffic. As compared to Figure 12, even though the nt-RS receives the same number of OFDMA slots from the t-RS, it can support more data rate because of the signal strength between the t-RS and the nt-RS. However, data from the BS should pass through the t-RS, which causes the time delay. The main difference from the adaptive frame structure only for nt-

RSs (Chapter 3) is the location of the access zone and relay zone of nt-RSs., The nt-RS_1^1 in Figure 13 uses the last portion of the uplink sub-frame to relay its data to the BS whereas the nt-RS_1^2 in Figure 33 uses the first portion of the uplink sub-frame because the t-RS_1^1 uses the last portion of the sub-frame in the time domain to relay data to the BS. Using the time period of the relay zone of t-RS_1^1, the nt-RS_1^2 receives data from its subordinate nt-RSs and SSs.

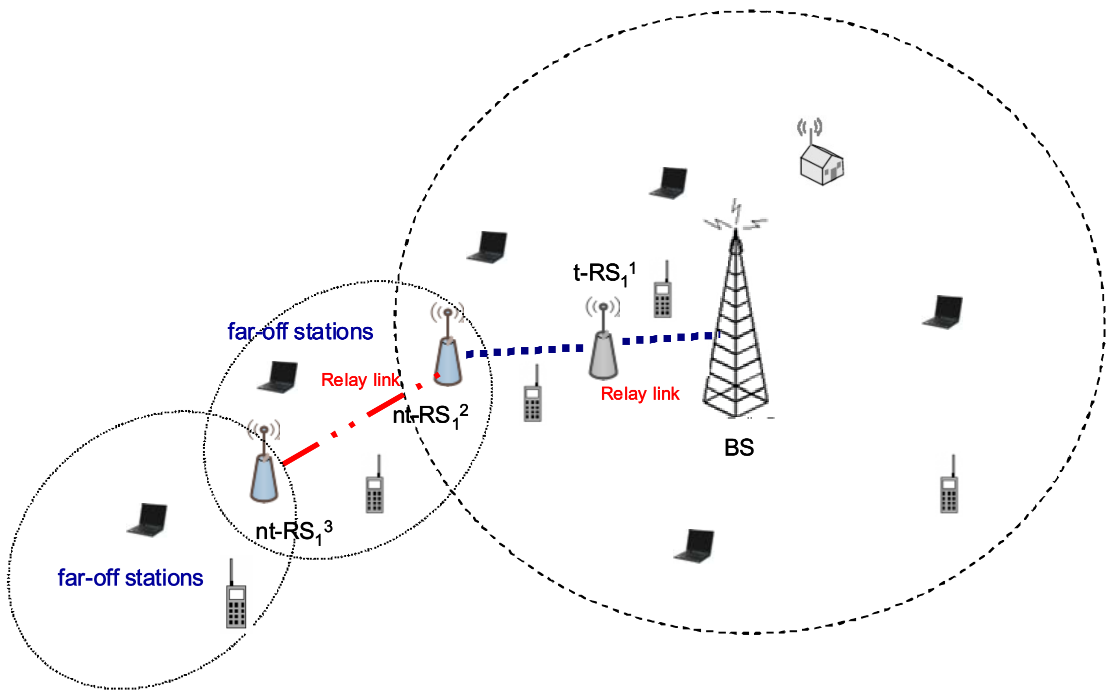

Figure 32. An MMR network with the t-RS and the nt-RSs.

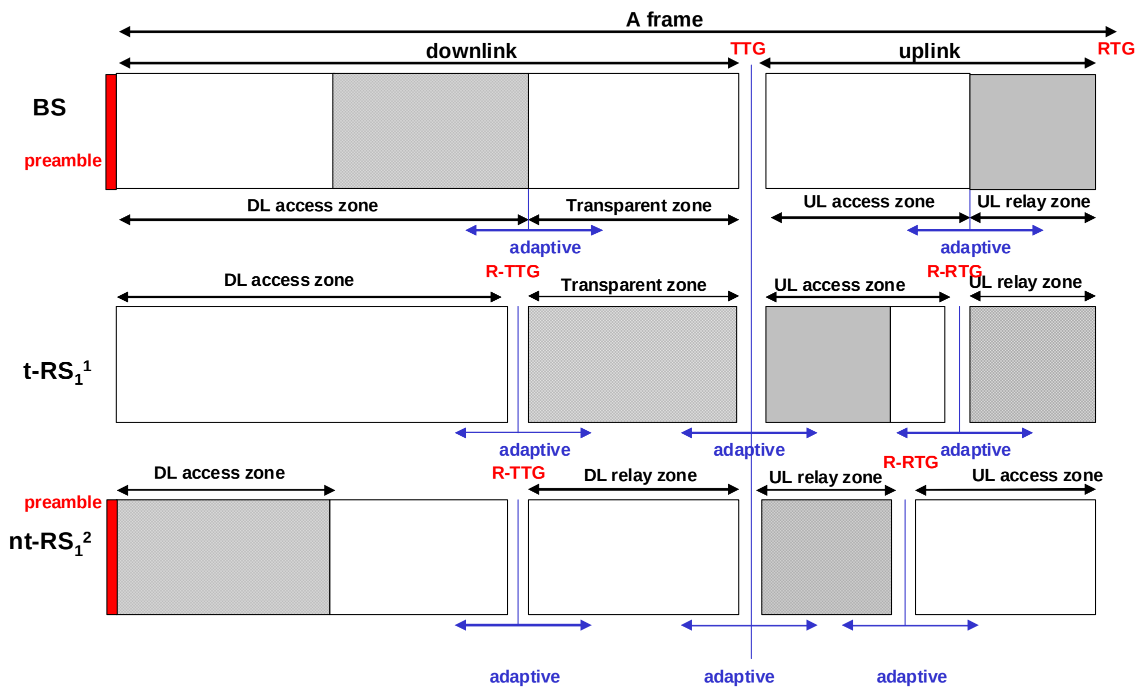

Figure 33. OFDMA frame structure for the t-RS and the nt-RS.

6.2 *Adaptive Frame Structure With Multiple Relay Directions*

Figure 34 shows the same network configuration shown in Figure 13 except that three first hop t-RSs locate between a BS and three nt-RSs. The three first hop nt-RSs are exclusively independent one another. In this configuration, Figure 35 shows the proposed frame structure for the three t-RS and nt-RSs. In terms of downlink traffic, the three t-RSs shares OFDMA resources depending on the traffic load of their subordinate nt-RSs by using the transparent zone of the BS, t-RS_1^1, t-RS_2^1, and t-RS_3^1. Using this amount of data rate, three t-RSs serve their designated nt-RS, and the three nt-RS provide their associated SSs with data rate by using access zone. In terms of uplink traffic, three t-RSs share the relay zone of the BS in the UL sub-frame. Same as Figure 23, three nt-RSs

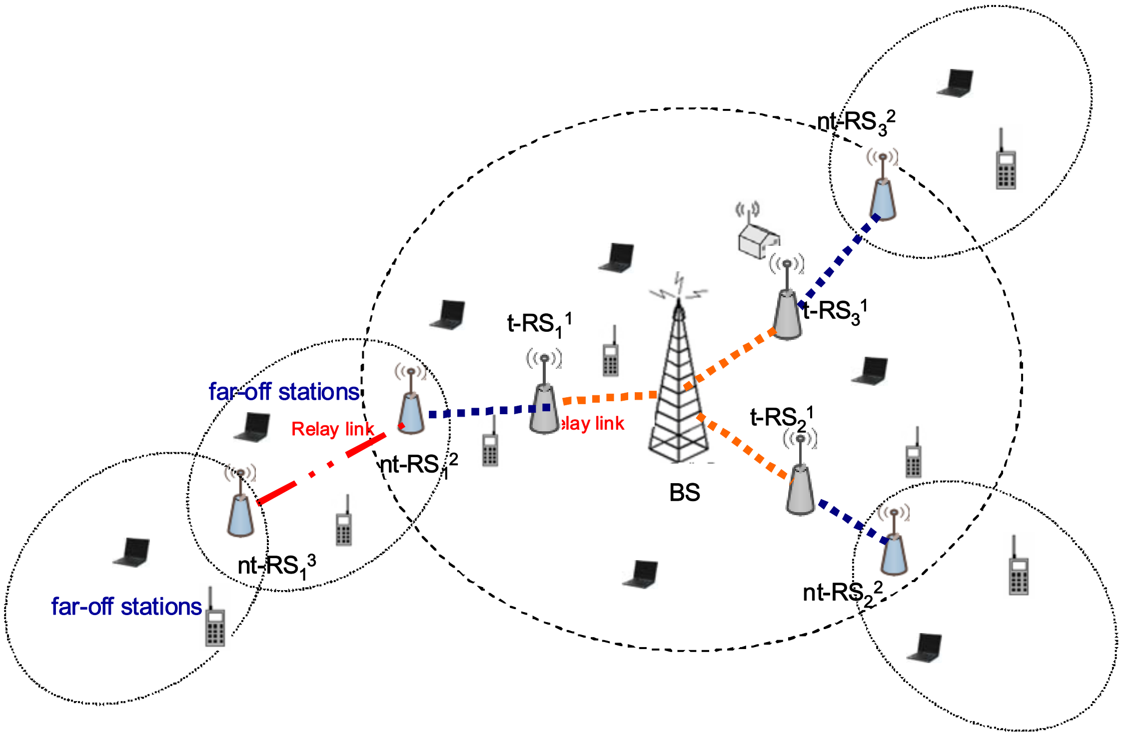

Figure 34. Placement of three t-RSs for three nt-RSs.

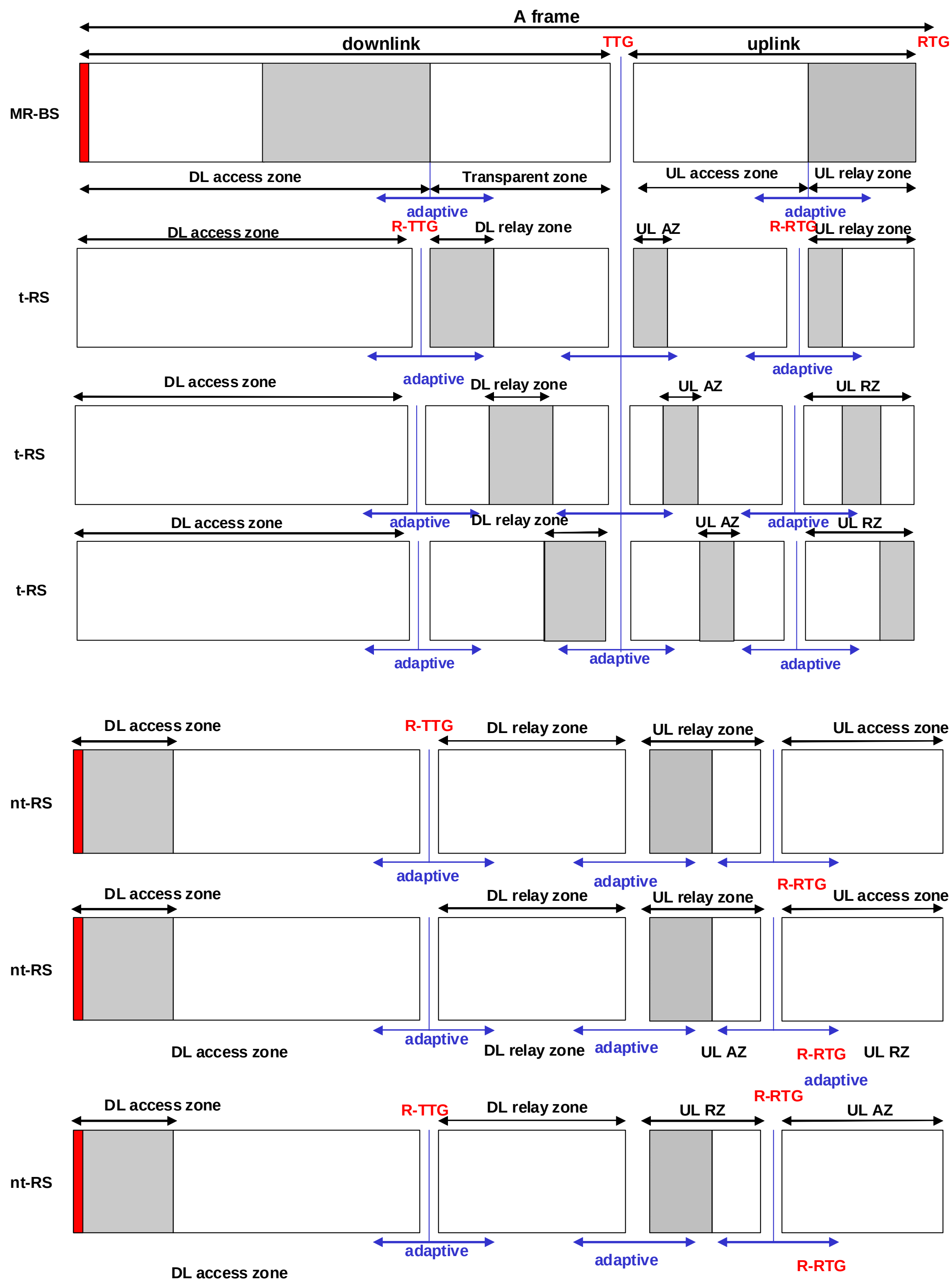

Figure 35. Frame structure for three t-RSs and three nt-RSs.

CHAPTER 7

SUMMARY AND FUTURE RESEARCH

This thesis focuses on MMR networks that use OFDMA and TDD as a multiple access scheme and a duplex communication technique, respectively. The use of OFDMA resources and how they are shared in current schemes can reduce system capacity and network throughput in certain scenarios. To increase the capacity of the MMR network, we propose a new protocol that uses an adaptive OFDMA frame structure for BSs and RSs. We also propose adaptive OFDMA resource allocation for SSs within a BS or RS. We derive the maximum OFDMA resources that RSs can be assigned and synchronize access zones and relay zones between a superior station and its subordinate RSs. This is bounded by three properties defined in this thesis: a data relay property, a maximum balance property, and a relay zone limitation property. Finally, we propose max-min and proportional fairness schemes that use the proposed adaptive frame structure. The proposed scheme is the first approach that incorporates the adaptive technique for wireless MMR networks. We evaluate our scheme using simulations and numerical analysis. Results show that our technique improves resource allocation in wireless MMR networks. Further, in asymmetric distributions of SSs between access zones and relay zones, the proposed OFDMA allocation scheme performs two times better than the non-adaptive allocation scheme in terms of average max-min fairness and 40% better in terms of average throughput.

We also pointed out that the extension of the cell coverage of the BS by placing nt-RSs has two drawbacks: less bandwidth utilization of the nt-RSs and a decrease of the

MMR network capacity. To overcome the less bandwidth utilization, we introduce a local traffic concept, and to overcome the decrease of the MMR network capacity, place transparent RSs (t-RSs). The reason of these is that the local traffic of nt-RSs is independent of their superior stations and the t-RSs can enhance the signal strength between the BS and the first-hop nt-RSs.

For the future work, we will consider a communication algorithm between an nt-RS and its associated SS and nt-RSs to discriminate the local traffic from the backhaul traffic.

REFERENCES

[1] IEEE 802.16-2004, “IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems,” IEEE Press, 2004.

[2] IEEE 802.16-2005, “IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems,” IEEE Press, 2005.

[3] IEEE Draft 802.16j-06/026r4, “Baseline Document for Draft Standard for Local and Metropolitan Area Networks —Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems,” 2007.

[4] B. Kwon, Raheem A. Beyah, and John Copeland, “Key Challenges in Securing WiMAX Mesh Networks,” Wiley’s Security and Communication Networks Journal, 2009.

[5] Grahame Lynch, “www.commsday.com/node/228,” Mar, 2008.

[6] Sen David Twiddy, “http://biz.yahoo.com/ap/080507/-sprint_nextel_clearwire.html”, May 2008.

[7] Michael Kassner, “http://blogs.techrepublic.com.com/networking/?p=499&tag=nl.e102,” May 2008.

[8] WiMAX Forum, "Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation,” 2006.

[9] WiMAX Forum, “Mobile WiMAX – Part II: A Comparative Analysis,” 2006.

[10] Juliana Freitag and Nelson L. S. da Fonseca, “WiMAX Module for the ns-2 Simulator,” PIMRC, 2007.

[11] Masato Okuda, Chenxi Zhu, and Dorin Viorel, “Multihop Relay Extension for WiMAX Networks – Overview and Benefits of IEEE 802.16j Standard,” FUJITSU Tech Journal, vol 44, no 3. pp 292-302, 2008.

[12] H. Lei, R. Mengtian, W. Lan, Yisheng Xue, and E. Schulz. "Resource Scheduling for OFDMA/TDD Based Relay Enhanced Cellular Networks," WCNC 2007.

[13] Lin Xiao and Laurie Cuthbert, "Improving Fairness in Relay-Based Access Networks," MSWiM, 2008.

[14] Tao Liu, Mengtian Rong, Ping Li, Dan Yu, Yisheng Xue, and Egon Schulz, 'Radio Resource Allocation in Two-hop Cellular Relaying Network",

[15] Hakan Bolukbasi, Halim Yanikomeroglu, David D. Falconer, and Shalini Periyalwar, "On the Capacity of Cellular Fixed Relay Networks,"

[16] Eunhyun kwon, Jaiyong Lee, Mi-Sun Do, and Kyunghun Jung, "Comparison of Symmetric and Asymetric Routing for Fixed Two-Hop Cellular Relaying Network," IEEE Communication Letters, vol 11, no 5, 2007.

[17] Yong Li, Qingyu Miao, Mugen Peng, and Wenbo Wang, "Frequency Allocation in Two-Hop Cellular Relaying Networks,"

[18] Liu Erwu, Wang Dongyao, Liu Jimin, Shen Gang, and Jin Shan, "Performance Evaluation of Bandwidth Allocation in 802.16j Mobile Multi-hop Relay Networks," VTC, 2007.

[19] Amir Salman, Suhas N. Diggavi, and David N C. Tse, "A Deterministic Approach to Wireless Relay Networks,"

[20] Zhifeng Tao, Anfei Li, Koon Hoo Teo, and Jinyun Zhang, "Frame Structure Design for IEEE 802.16j Mobile Multihop Relay (MMR) Networks," GLOBECOM, 2007.

[21] Vasken Genc, Sean Murphy, and John Murphy, "Performance Analysis of Transparent Relays in 802.16j MMR Networks,"

[22] B. Kwon, Yusun Chang, and John Copeland, "A Network Entry Protocol and OFDMA Symbol Allocation Scheme for Non-transparent Relay Stations with Distributed Scheduling," MILCOM, 2008.

[23] Bin Lin, Pin-Han, Liang-Liang Xie, and Xuemin Shen, "Relay Station Placement in IEEE 802.16j Dual-Relay MMR Networks," ICC, 2008.

[24] Yu-Jung Chang, Feng-Tsun Chien, and C.-C. Jay Kuo, "Delay Analysis and Comparison of OFDM-TDMA and OFDMA under IEEE 802.16 QoS Framework," GLOBECOM, 2006.

[25] Michael Einhaus, "Dynamic Resource Allocation in OFDMA Systems," ComNets, 2006.

[26] Andrea Abrardo, Paolo Detti, Gaia Nicosia, Andrea Pacifici, and Mara Servilio, "Radio Resource Allocation in OFDMA Cellular Network," CTW, 2008.

[27] Seung-Won Keum and Jeong Gon Kim, "Decision of Frame Size and Radio Resource Allocation for OFDMA/TDD-based Next Generation Cellular Systems," ICCIT, 2007.

[28] Natalia Y. Ermolova and Boris Makarevitch, "Low Complexity Adaptive Power and Subcarrier Allocation for OFDMA," IEEE Trans. Wireless Communications, vol. 6, no. 2, pp. 433-437, 2007.

[29] Howon Lee and Dong-Ho Cho, "Combination of Dynamic-TDD and Static-TDD Based on Adaptive Power Control,"

[30] Karthikeyan Sundaresan and Sampath Rangarajan, "On Exploiting Diversity and spatial Reuse in Relay-enabled Wireless Networks," MobiHoc, 2008.

[31] Alessandro Biagioni, Romano Fantacci, and Dania Marabissi, "Adaptive Subcarrier Allocation Schemes for Wireless OFDMA Systems in WiMAX Networks," IEEE JSAC, vol. 27, no. 2, pp 217-225, 2009.

[32] Ivan Marsic, "Max-min Fair Share Algorithm, "http://www.ece.rutgers.edu/~marsic / Teaching/CCN/-minmax-fairsh.html," 1998.

[33] Jangeun Jun and Mihail L. Sichitiu, "Fairness and QoS in Multihop Wireless Networks,"

[34] Bassam Aoun and Raouf Boutaba, "Max-Min Fair Capacity of Wireless Mesh Networks,"

[35] Holger Boche, Marcin Wiczanowski, and Slawomir Stanczak, “Unifying View on Min-Max Fairness, Max-Min Fairness, and Utility Optimization in Cellular Networks,” EURASIP Journal on Wireless Communications and Networking, 2007.

[36] Chakchai So-In, Raj Jain, and Abdel-Karim Tamimi, “Scheduling in IEEE 802.16e Mobile WiMAX Networks: Key Issues and a Survey,” IEEE JSAC, vol. 27, no. 2, pp 156-171, 2009.

[37] Gautam. Kulkarni, Sachin. Adlakha, and Mani. Srivastava, “Subcarrier Allocation and Bit Loading Algorithms for OFDMA-based Wireless Network,” IEEE Trans. Mobile Computing, vol. 4, no. 6, pp. 652-662, 2005.

[38] Chih-He Chiang, Wangjiun Liao, Tehuang Liu, Iam Kim Chan, and His-Ku Chao, "Adaptive Downlink and Uplink Channel Split Ratio Determination for TCP-Based Best Effort Traffic in TDD-Based WiMAX Networks,” IEEE JSAC, vol. 27, no. 2, pp 182-190, 2009.

[39] R. Pries, D. Staehle, and D. Marsiso, "IEEE 802.16 Capacity Enhancement Using an Adaptive TDD Split,” VTC, 2008.

[40] Christian Hoymann, Karsten Klagges, and Marc Schinnenburg, "Multihop Communication in Relay Enhanced IEEE 802.16 Networks,” PIMRC, 2006.

[41] Chakchai So-In, Raj Jain, Abdel-Karim, and Al Tamimi, “General Weighted Fairness and its support in Deficit Round Robin with Fragmentation in IEEE 802.16 WiMAX,” Computer Communications, vol. 23, no 2, pp. 149-161, 2000.

[42] Haitang Wang, Bing He, and D.P. Agrawal, “Admission control and bandwidth allocation above packet level for IEEE 802.16 wireless MAN,” ICPADS, 2006.

[43] Sahar Ghazal, Lynda Mokdad, and Jalel Ben-Othman, “Performance Analysis of UGS, rtPS, nrtPS Admission Control in WiMAX Networks,” ICC, 2008.

[44] Haidar Safa, Hassan Artail, Marcel Karam, Rawan Soudan, and Samar Khayat, “New Scheduling Architecture for IEEE 802.16 Wireless Metropolitan Area Network,” AICCSA, 2007.

[45] Debalina Ghosh, Ashima Gu[ta, and Prasant Moha-patra, "Admission Control and Interference-Aware Scheduling in Multi-hop WiMAX Networks,” MASS, 2007.

[46] Hamed S. Alavi, Mona Mojdeh, and Nasser Yazdani, " A Quality of Service Architecture for IEEE 802.16 Standards," APC on communications, 2005.

[47] Lin Xiao and Laurie Cuthbert, "Improving fairness in relay-based access networks," MSWiM, 2008

[48] Yang Yu, Sean Murphy, Liam Mirphy, "Planning Base Station and Relay Station Locations in IEEE 802.16j Multi-hop Relay Networks," CCNC, 2008.

[49] Zhifeng Tao, Koon Hoo Teo, and Jinyun Zhang, "Aggregation and Concatenation in IEEE 802.16j Mobile Multihop Relay (MMR) Networks," Mobile WiMAX Symposium, 2007.

[50] Shiang-Jiun Lin, Wern ho Sheen, I-Kang Fu, and Chia-chi Huang, "Resource Scheduling with Directional Antennas for Multi-hop Relay Networks in Manhattan-like Environment," Mobile WiMAX Symposium, 2007.

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