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Technical Challenges in Mobile Multi-Hop Relay Networks

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Abstract

Broadband Wireless Access (BWA) has become very popular in recent wireless standards. Mobile Multi-Hop (MMR) networks are one of the suitable solutions to achieve the broadband internet access. There are various issues unsolved with MMR networks. In this paper, we have discussed the issues related to L1 (physical layer), L2 (Medium Access Control (MAC)) layers. Orthogonal Frequency Division Multiple Access (OFDMA), Multi Input Multi Output (MIMO), antenna selection are the major issues related to the physical layer. Scheduling, link adaptation, handover management, interference management, path selection are the issues related to the MAC layer. This paper also highlights the importance of optimal Base Station (BS) and Relay Station (RS) deployment.

Keywords: MMR; Radio Resource Utilization Index (RRUI); Adaptive Modulation and Coding (AMC); Quality of Service (QoS)

Introduction

Most of the conventional cellular networks work in point-to-multipoint (PMP) mode. In PMP architecture, there exist two nodes namely BS and MS. At any time, BS will be transmitting the signal to multiple mobiles simultaneously. The main drawback of PMP architecture is limitations in terms of coverage and capacity [1, 2]. There are situations in which many of the MSs nearer to the BS will not get proper signal strength, because of the shadowing effect. Because of the poor signal strength, the data rates of those mobile users become poorer. In wireless network, the received signal strength (p_r) is inversely proportional to the square of the distance (d) [3],

$$P_r \alpha \frac{1}{d^2} \quad (1)$$

Due to this there won't be proper coverage at the cell edge. To offer high quality services even for cell edge users, and the users in the shadow region within the cell, a new architecture called relay architecture is proposed in the third generation partnership project Long Term Evolution (3GPP-LTE) and IEEE 802.16 Wi-MAX (Worldwide Interoperability for Microwave Access) standards [4].

IEEE 802.16j is an amendment to IEEE 802.16e [1, 5]. To support the MMR specification, mesh architecture is removed from the IEEE 802.16-2009 standard. This scheme provides multi-hop wireless connectivity where the traffic between a BS and a MS can be relayed through a RS. The RS may be fixed in a particular location i.e. Fixed Relay Station (FRS) or movable i.e. Mobile Relay Station (MRS). A MS may directly receive the signal from the BS or can receive the signal relayed from a RS. The links initiating or terminating at MS is called access links and the links between BS and RS or between two RSs are called relay links. The basic relay architecture and the associated links have shown in fig.1.

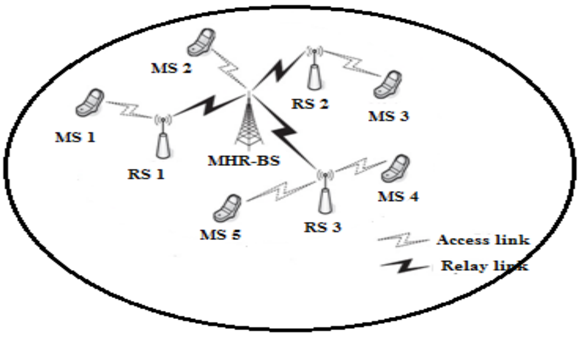

Figure 1: MMR networks

A. Relay Modes

Two different relay modes are defined in IEEE 802.16j standards, namely the transparent relay and the non-transparent relay [5-7]. In the transparent mode, the RS is deployed within the coverage area of the cell. This mode does not support coverage extension, rather it is used to increase the network capacity. It is operated in two hop network topology. It supports centralized scheduling and scheduling is carried out only by the BS. In non-transparent mode of operation RS is usually deployed at the cell edge to extend the coverage. These RSs will act like a separate BS. It generates its own control messages [7]. It operates in two or more hops topology. It uses centralized or distributed scheduling mode. Here scheduling is done at the BS and the RS. The concept of transparent and non-transparent RS is illustrated in fig. 2.

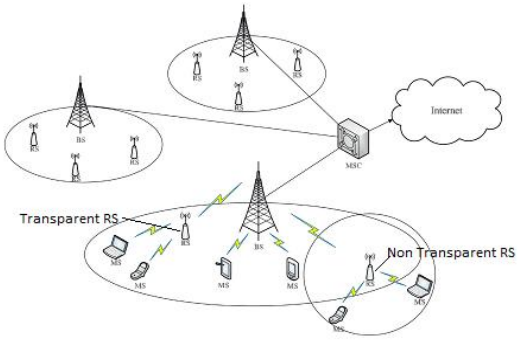

Figure 2: Types of Relay modes

B. Relay transmission schemes

IEEE 802.16j MMR network supports three transmission schemes, namely amplify and forward, decode and forward and demodulation and forward [1]. In amplify and forward scheme, the RS amplifies a signal received from the BS/MS in the first stage and forwards it to the MS/BS in the second stage. This scheme is very simple and it has short transmission delay. But the major problem is amplification of the noise. In decode and forward scheme, the relay decodes the received signal from BS/MS in the first stage; the decoded data is then checked for errors using Cyclic Redundancy Check (CRC).The decoded data is forwarded to MSs/BS in the second stage.

The rest of the paper is organized in the following way. The technical challenges related to L1 and L2 are discussed initially. Then the necessity of optimal BS and RS deployment is discussed. The paper ends with conclusion by highlighting the future works.

Technical Challenges Related To Layer L1

A. MIMO

MIMO techniques have been widely used in IEEE802.16j to improve cell coverage, capacity and the average number of users supported in the cell [8, 9]. MIMO techniques are used to increase the data rate and reliability of the system. Future Wi-MAX standards are expected to support eight transmitting antennas at the BS. MIMO works in 2 configuration modes, namely open loop and closed loop modes.

In open loop mode, the channel state information (CSI) is not required at the BS. In the closed loop mode, the CSI is required at the BS. But there exist problems in terms of obtaining the accurate CSI at the transmitter side. The channel estimation error is one of the main reasons for imperfect CSI at the BS [10, 11]. The estimator used in the receiver and the time varying nature of the channel introduces channel estimation errors.

Another major reason is channel information feedback delay [10, 11]. In Frequency Division Duplex (FDD) systems, a separate feedback channel is allocated to carry the feedback information. The limited bandwidth nature of the feedback channel, introduces the delay in feedback transmission. This non-zero feedback delay will cause outdated CSI at the BS. The precoding done based on the outdated CSI will introduce severe quality loss.

Another major problem in MIMO scheme is the complexity in terms of hardware and signal processing [12-14]. The system complexity increases along with the number of transmitting antennas. More number of Radio Frequency (RF) chains will increase the cost of the system. When MIMO is operated in diversity mode, the increase in number of transmitting antennas will reduce the rate of the system. Accurate synchronization of multiple transmitting antennas with one receiver antenna also increases the complexity of the system.

The feedback signaling used for synchronization causes wastage of bandwidth. In [12], a reduced MIMO system is proposed which offers performance similar to full MIMO system. Instead of using all transmitting antennas, the best two antennas are selected for every coherence period. It has been proved that, the antenna selection schemes offers better spectral efficiency performance than the conventional system with no antenna selection. In literature, there exist some antenna selection algorithms like subcarrier by subcarrier antenna selection, frobenious norm based antenna selection. These are the major issue which has to be incorporated while using MIMO for MMR network.

B. OFDMA

OFDMA is very popular among 4G standards [11, 15]. Wi-MAX uses OFDMA in both Uplink (UL) and Downlink (DL). Scalable OFDMA is specified in the IEEE 802.16j-2009 standards. Each OFDMA symbols consist of multiple subcarriers. Different subcarriers are given for different users. The subcarrier allocation for each user is a scheduling issue, which will be addressed on the later section of this paper. The major advantage of OFDMA is that each subcarrier experiences a flat-fading. This flat-fading nature avoids the usage of complex equalizers at the receivers. The usage of Cyclic Prefix (CP) causes zero Inter-Symbol-Interference (ISI) system and thus one tap equalization is sufficient to combat the effect of fading. Each subcarrier can be modulated by different modulation scheme, since each subcarrier experiences different amount of fading.

OFDMA is more sensitive to Doppler shift .The mobility of the user will introduce the Doppler shift, which causes the orthogonality loss among the subcarriers. This problem is called Inter-Carrier-Interference (ICI), which causes severe quality loss in MMR networks. There are various schemes proposed in the literature to mitigate the effect of ICI in OFDMA based system. The schemes like self-cancellation causes wastage of bandwidth. Most of the ICI mitigation algorithms are iterative and complex in nature. A simple ICI mitigation algorithm called Adaptive subcarrier bandwidth (ASB) is proposed in [16] to mitigate the effect of ICI. Since ICI power is inversely proportional to the subcarrier bandwidth, increasing the subcarrier bandwidth will reduce the effect of ICI. This method relieves the receiver from implementing the complex ICI cancellation algorithms. But increasing the subcarrier bandwidth will reduce the active number of subcarriers. This cause heavy spectral efficiency loss for OFDMA based MMR network. A simple low complex high performance optimal ICI mitigation algorithm has to be identified to address the above issue.

Technical Challenges Related To Layer L2

A. Path Selection Algorithm

In MMR networks, several RS support the communication between the BS and the MS, leading to the existence of multiple paths between BS and MS [17]. This idea is explained in fig. 3. In DL, each MS has to select proper path from the available paths. Improper path selection may lead to disappointing network throughput. The BS makes the centralized decision as data transmission can be achieved either in direct or in multi-hop relaying. The path selection depends on various constraints such as network topology, available radio resource, load condition of RS etc.

Effective path selection is a major issue in mobile ad-hoc, sensor, cellular and vehicular ad-hoc networks. Path selection schemes are not mentioned in the standards like IEEE802.16j, LTE and Long Term Evolution-Advanced (LTE-A). Different routing metrics like hop-count, Round-Trip Time (RTT) per hop, Expected Transmission Count (ETC) are the popular path selection metric proposed in the literature.

Different burst profiles have been proposed in IEEE 802.16j.Each burst profile is the combination of a specific modulation and coding scheme. RRUI based path selection algorithms is very popular in the literature [18]. Here optimum path is selected based on the burst profile of each link. They used link cost as the path selection metric which is derived from the Link Spectral Efficiency (LSE) of a particular burst profile. The spectral efficiency generally indicates the channel capacity of the link for a given burst profile and indicates the amount of radio resource utilized on a link. A higher spectral efficiency indicates higher throughput and link gain. The cost of each path is calculated by summing up the cost of each link available in that path. RRUI scheme selects a path with minimum path cost. There are situations in which each relay station has to support multiple mobile stations. When the traffic load exceeds the link capacity, link overloading issues occurs. This is a severe issue which degrades the overall network throughput performance.

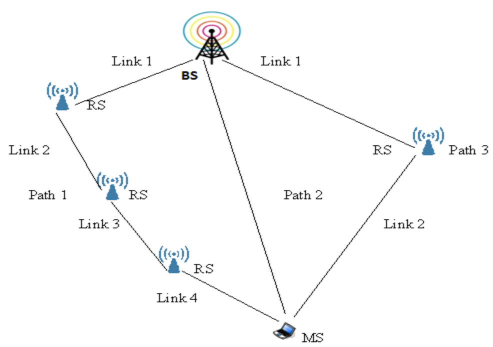

Figure 3: The path selection scheme

Most of the path selection algorithm including RRUI does not consider the link overloading algorithm. A Load-Aware Spectral Efficient Routing metric (LASER) path selection algorithm includes link overloading issue in path selection [17]. It has been proved that LASER scheme offers better network throughput performance than the RRUI scheme. The concept of link overloading and the solution with LASER is explained in fig. 4. Suppose MS(1) is in the coverage area of Multi hop Relay BS (MHR-BS) and RS(1) and the MS(2) is within the coverage area of the RS(1)and RS(2). If the downlink traffic to both the MSs select RS(1) as its relay point, sometimes RS(1) will be unable to forward the traffic in the same frame due to the constraint in channel capacity. Then the data transmission to both the MS will be dropped if the traffic is time-bounded, thus resulting in the failure of the QoS requirements for the data transmission. This problem can be avoided if the data transmission to MS (2) can be carried out through RS(2) instead of RS(1). This increases the network throughput.

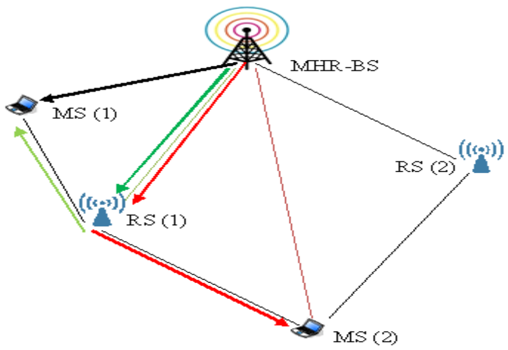

Figure 4: Link overloading problem

There are some unsolved issues with the LASER scheme. They have not considered scheduling techniques thoroughly. The effect of link error on the path selection is not considered in the paper. It is also assumed that RSs are permanently installed at the vertices of the cell. But in practical, RS positioning is a real-time issue which affects the network throughput performance if left uncared. The buffers available at the RS are assumed to hold sufficient data traffic. The authors have not considered the practical queuing related issues related to the buffer. The path selection algorithm for DL is considered in the paper. Thus an appropriate path selection algorithm for bi-directional transmission has to be developed by considering the above issues.

B. Link adaptation based on AMC

MMR network uses AMC scheme to offer dynamic data rates as per the varying channel conditions [11]. As per the free space propagation model, the Signal to Noise Ratio (SNR) of each link can be calculated by [3],

$$\mathrm{SNR(dB)} = 10\log_{10}\left(\frac{p_t}{p_n}\left(\frac{\lambda}{4\pi d}\right)^2\right) \tag{2}$$

where p_t is the transmitter power, p_n is the thermal noise power, λ is the wavelength and d is the distance between two communication node.

Since the distance between two nodes changes with time, the received SNR also changes with time [2]. The received SNR is divided into seven regions. AMC scheme related to SNR, data rate and distance is displayed in table 1. The concept of AMC is also explained in fig. 5. When the SNR of a communication node 'x' falls in the i^{th} range,

(i.e.) $\mathrm{SNR}(x) \in [\mathrm{SNR}_i, \mathrm{SNR}_{i+1}]$ (3)

The i^{th} transmission mode is allocated for that node x. When SNR(x) >= SNR_7, the highest transmission mode is allocated for that link. When SNR(x) < SNR_1, no transmission mode is allowed for that link since it has poor received signal strength. The link adaptation plays a crucial role in path selection algorithms and network throughput improvement.

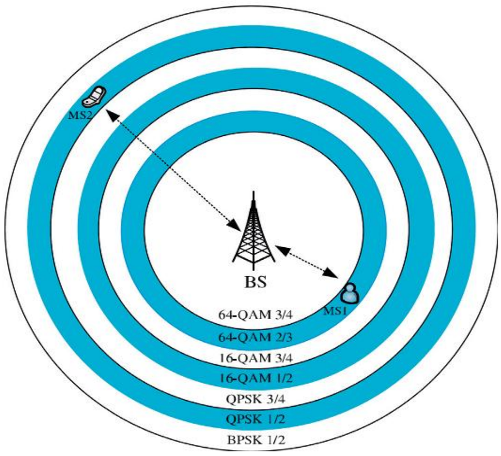

Figure 5: AMC as function of distance [2]

Table 1: AMC Transmission Mode [2]

Mode	**Modulation**	**Coding rate**	**Receiver SNR (dB)**	**Data rate (Mbps)**	**Distance (km)**
1	BPSK	1/2	3.0	1.269	3.2
2	QPSK	1/2	6.0	2.538	2.7
3	QPSK	3/4	8.5	3.816	2.5
4	16-QAM	1/2	11.5	5.085	1.9
5	16-QAM	3/4	15.0	7.623	1.7
6	64-QAM	2/3	19.0	10.161	1.3
7	64-QAM	3/4	21.0	11.439	1.2

C. Scheduling schemes

Radio resource management is the set of functions that control the use of radio resources in the system. It is nothing but an optimum solution for the allocation of time slot, frequency and antenna port to MSs with the required QoS and also ensuring the minimum usage of radio resources. Resource allocation for both DL and UL is done by the BS. Scheduling issue of IEEE 802.16j network has become a hot research topic [19]. The resource allocation scheme for OFDMA based system is discussed in [20].This scheduling algorithm uses wireless channel status and packet queue information. In [21], opportunistic scheduling scheme for OFDMA based network is proposed. This scheduling scheme considers the time varying nature of the physical channel. In [22, 23], suitable subcarrier and power allocation scheme for multiuser OFDMA system is proposed. This scheme considers CSI. Weighted Fair Queuing (WFQ) technique provides a fair allocation of resources among the users by considering the bandwidth request of the user [19]. This algorithm works in two steps. In the resource allocation step, the amount of resources per user is calculated and the subcarriers are allocated in the second step. The users could have a lack or excess of allocated slots. This introduces unfairness in allocation. This issue is solved in the second phase of the WFQ algorithm. There is another scheduling algorithm called maximum throughput algorithm (MTA) proposed in [19]. This scheduling scheme aims to maximize the network throughput without considering the fairness in resource allocation. The scheduler allocates the required number of slots to the users having favorable channel conditions. After this step, if resources are still available, they are assigned to the users with bad channel conditions. Always there exist a trade-off between maximum throughput and fairness scheduling schemes. An optimum scheduling algorithm should be proposed to address the above trade-off.

Optimum Deployment of BS and RS

To achieve high data rate transmission in MMR network, suitable deployment of BS and RS is required. By enabling optimal deployment, the overall network throughput and the coverage ratio of the system can be improved in a more cost effective manner. The cell edge users will receive stronger signals if a RS is deployed close to the cell boundary. But the longer hop distance between the BS and RS will result in lower system capacity. Similarly placing a RS close to the BS will cause a decrease in signal strength for the cell edge users. Thus optimum deployment of BS and RS is very important in MMR networks. Various RS deployment schemes have been discussed in the literature [24-27]. The proposed scheme in [24], suggest deploying RSs on the boundary between two adjacent cells. This deployment scheme reduces the service interruption time caused by inter cell-handover. The paper [25] proposes a dual relay mode for IEEE 802.16j network. In this mode, the MSs can connect with two RSs at the same time. An algorithm to select two RSs from the predefined candidate positions have been discussed here. In [26], an optimum RS location is identified using throughput-oriented and signal strength-oriented selection rules. Here the system achieves its maximum capacity when the RS is placed at the originally identified optimum location. A three phased Cost Aware Relay Deployment (CARD) algorithm is proposed in [27].The algorithm deploys the RS efficiently so as to reduce the hardware cost and transmission delay.

In MMR networks, improper deployment of BS and RS affects the system capacity and communication reliability [1]. Although the deployment cost of RS is less than BS, deploying a large number of RS increases the total budget [28].BS and RS has to be placed at sufficient far distance so that the interference is kept minimum. Positioning of more number of RS in a particular geographic area causes co-channel interference [1]. As interference increases, the Signal to Interference plus Noise Ratio (SINR) decreases and thus the system uses a low burst profile leading to reduction in network throughput. Also, if the distance between communication nodes is large, it will result in a higher transmission delay [29], which is an undesired effect in time bound applications. The other issue with improper placing of BS and RS is coverage holes. It's unlike to place a RS in areas that are already well covered with other BS or RSs. On the other hand, more number of RS leads to path selection problem [29]. Since each MS is having multiple paths, selecting an optimum path will require certain duration of time. Another major issue to be considered while selecting BS and RS position is link overloading [17]. The RS capacity is limited compared to BS. When a single RS supports more number of users, a severe issue called link overloading occurs. The link overloading reduces the data transmission rate which causes the queuing of packets. Eventually this results in data transmission failure.

Only a very few articles have studied the problem of deployment of BS and RSs simultaneously by considering the network throughput, deployment budget as well as the coverage ratio [30, 2]. A Joint Base Station and Relay Station placement (JBRP) algorithm is proposed for IEEE 802.16j in [30] where the authors suggest a two stage deployment algorithm to improve the network throughput under some budget constraints. But this scheme suffers from network load balancing issues and does not discuss about the coverage ratio. The authors also assume that the candidate positions of RSs are the locations of MSs and the candidate position for the BS is the corners of MSs which is unreasonable and impractical. Also, while determining the location of BS, the traffic distribution within the network (which changes with time) is not considered. In [2], a uniform clustering based algorithm is proposed for BS and RSs deployment by considering the traffic demands. It describes two algorithms based on coverage and budget constraints. This scheme offers a reasonable throughput and coverage ratio by balancing the network load among the clusters .But in this work, the link overloading and path selection problems are not taken into account which would have resulted in much higher throughput and coverage ratio. Thus to satisfy the network demands of future wireless standards, improved BS and RS deployment algorithms are required with high throughput, coverage ratio and low deployment cost.

Conclusions

The technical challenges involved in MMR networks have been discussed in this paper. This paper concentrates on the physical layer issues like OFDMA,MIMO and MAC layer issues like scheduling, path selection, AMC. This paper also discusses about the BS and RSs optimal deployment schemes to maximize the QoS. In this work, we have mainly concentrated on issues related to IEEE 802.16j WiMAX networks. But the same technical challenges holds good for 3GPP LTE standard. In this review paper, the practical issues like interference management and handover are not considered.

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