A Bandwidth Adaptive Path Selection Scheme in IEEE 802.16 Relay Networks

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Abstract

The IEEE 802.16 mobile multi-hop relay (MMR) task group ‘j’ (TGj) has introduced the multi-hop relaying concept in the IEEE 802.16 Wireless MAN, wherein a relay station (RS) is employed to improve network coverage and capacity. Several RSs can be deployed between a base station and mobile stations, and configured to form a tree-like multi-hop topology. In such architecture, we consider the problem of a path selection through which the mobile station in and outside the coverage can communicate with the base station. In this paper, we propose a new path selection algorithm that ensures more efficient distribution of resources such as bandwidth among the relaying nodes for improving the overall performance of the network. Performance of our proposed scheme is compared with the path selection algorithms based on loss rate and the shortest path algorithm. Based on the simulation results using ns-2, we show our proposal significantly improves the performance on throughput, latency and bandwidth consumption.

Keywords: Path selection, IEEE 802.16, wireless multi-hop relay networks

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1. Introduction

The recent years have witnessed a massive growth of the services such as voice over IP (VoIP), media streaming, video conferencing and interactive games etc., offered by broadband access networks. At the other end, a variety of personal devices such as laptops, palmtops, smartphones, personal digital assistants (PDA) and hand-held multimedia players has been creating an extensive consumer base due to features such as portability, flexibility and low-cost. Wired broadband networks such as digital subscriber line (DSL) and cable modem technology lack flexibility and mobility features provided by wireless networks and thus are not suitable for the personal devices. Although cellular networks and the IEEE 802.11 based wireless local area networks (WLAN) are two fast growing alternatives, the former lacks the high data rate transfer required by such services and the latter's high rate transmission capability is limited within only few hundred meters range. Therefore, the uprising IEEE 802.16 [1] based broadband wireless access network has been considered as the most viable networking technology that bridges this gap to provide ubiquitous broadband access service.

The IEEE 802.16 family of standard specifies the medium access (MAC) and physical (PHY) layer features for both a base station (BS) and mobile station (MS) that provides a broadband wireless access (BWA) in the metropolitan area and rural networks. The IEEE 802.16e-2005 [2] provides a point-to-multipoint (PMP) single-hop communication between BS and subscriber station (SS or non-mobile MS) and service provisioning in terms of quality of service (QoS). Since the PMP mode can only support a single-hop network, it severely limits the coverage area. Moreover, the possibility of MS location in far-away or shadowed regions (due to topographical features such as high-rise buildings, hills and trees) with poor reception range enforces the use of low data transfer rate and reduces the network capacity. To overcome such problems of low throughput and coverage, the IEEE 802.16a [1] presented mesh networking specification among the SSs. However, this requires modification at the MAC and PHY layers of SS, arising compatibility issues with existing SS devices and with added complexity of addressing subscriber mesh and PMP mode. Additionally, the links among MSs are constrained due to limited transmission power and mobility. Another solution would be to deploy new BSs however, at the high cost of installation and operation. Therefore, as a better alternative the concept of a relay based multi-hop mesh network garnered more attention. The IEEE 802.16jtask group[3] was established in order to support multihop relaying by introducing relay station (RS) dedicated to transfer data between MR-BS (Multihop-relay BS) and the MSs. Relays aggregate traffic from both end-points and transmit data using higher rates so as to increase throughput and overcome limited coverage, potential dead spots and shadows. Since the specification only deals with the MR-BS and RS, the operation remains transparent to the MSs, which suffices to maintain the backward compatibility with the existing MSs.

Fig. 1 shows the topology of the IEEE 802.16j network. MR-BS is a fixed base station at the root of the topology and connected to the access network. RSs in general are divided into three types: "Fixed RS (FRS)" installed in the specific location for a long time period, "Nomadic RS (NRS)" installed for a temporary duration around the location where events occur, and "Mobile RS (MRS)" installed in vehicles such as buses or trains etc. These RSs can be deployed either in planned or unplanned manner, therefore several paths from MR-BS may be available to MSs. Referring to **Fig. 1**, MS2 can be served either by NRS or FRS through either of three unique paths (MR-BS→FRS1→FRS2, MR-BS→FRS1→NRS and MR-BS→NRS).

In such a case, at least one path from MR-BS to MS should be selected for forwarding data packets between two endpoints. For this purpose a naive way would be to randomly choose some paths or include all RSs in the path. However, relaying by all or randomly selected RSs might be prohibitive in terms of the performance and resource utilization [4]. For example, an RS serving a large number of MSs might become a bottleneck, eventually denying further connections in the network. This leads to unnecessary consumption of bandwidth and higher latency. Moreover, the selected paths would not be able to fulfill the required QoS for the connections that demands such kinds of services. In this paper, we present a path selection algorithm considering both link property and the available radio resources for enhancing the network performance. Our path selection algorithm is centralized that can be implemented within the framework of MAC specification for MR-BS and RS. Although there can be distributed approaches, they may require RS of higher complexity with similar features to that of MR-BS. We assume RSs that are simple and controlled by MR-BS (e.g., for scheduling and resource allocation) such that the installation and operational costs are minimal compared to installing new MR-BSs.

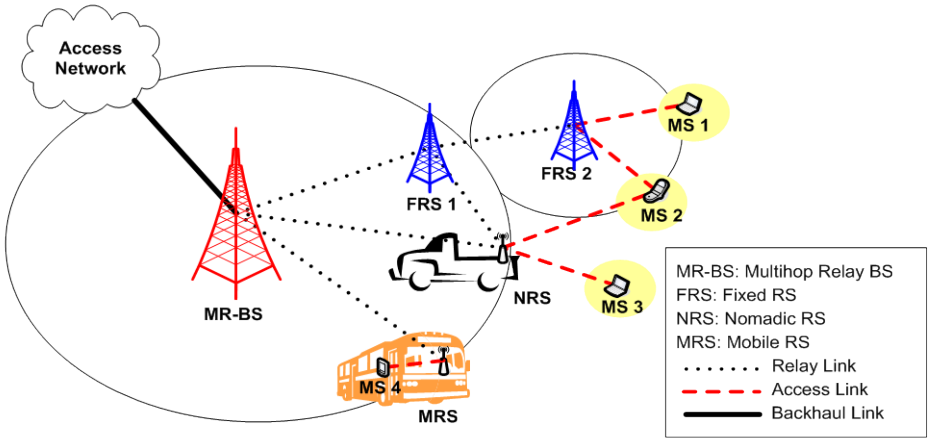


Fig. 1. The IEEE 802.16j network topology with several types of RSs and multiple paths for MSs.

This paper extends our previous work [5] that suggested a selection metric named *expected link throughput* (ELT) based on the physical layer data rate to maximize the throughput of the network. For the better utilization of bandwidth resource, we propose a new path selection algorithm with the two sub-schemes here: in the first scheme, we select the path that provides the highest expected throughput associated with SNR of the links and in the second, we attempt to balance the load of RSs by computing the available bandwidth and performing re-selection each time a new connection is added. We show that this new dimension of load balancing by path reselection in the network marginalizes the excessive bandwidth throttling at some RSs and shows better performance in terms of throughput and latency. For the performance analysis we extended the IEEE 802.16 module of the network simulator (ns-2) to support multi-hop relaying. We compare our proposed path selection schemes with the path selection based on link quality and shortest path algorithm. We show that our schemesachieve30~150% enhancement in the throughput and up to 40% gain in latency and additionally reduce overall bandwidth consumption.

The rest of the paper is organized as follows. Section 2 gives an overview of the IEEE 802.16j standard and the related works on path selection for multi-hop relaying systems. The proposed path selection schemes and metric are presented in Section 3. In Section 4, the simulation environment, analysis and results are discussed. Finally, in Section 5 we conclude our work.

2. Background and Related Works

2.1 Background: An Overview of the IEEE 802.16

The path selection algorithm designed for the IEEE 802.16 based multihop relay networks should closely consider the advances in [3]. In [3], two modes of operations are presented: (1) *Transparent mode* in which only two-hop relaying is possible and (2) *Non-transparent mode* in which multi-hop relaying is supported. Each mode treats frame structure, relay path management, neighborhood discovery and preambling distinctly. All stations including MR-BS and RSs must be configured in the same mode during the operation of the network. In this paper, as we consider a path selection algorithm for n-hop multi-hop networks, we briefly describe the PHY and MAC features in [3] pertaining to the non-transparent relaying mode.

The PHY layer in the IEEE 802.16 [1][2][3] incorporates the orthogonal frequency division multiple access (OFDMA). In OFDMA, a channel is multiplexed into a number of sub-carriers dedicated to the data streams for multiple MSs. Sub-carriers are further grouped to form a sub-channel consisting of bandwidth allocation unit called a slot. Multiple slots are combined to form a data burst that contains MPDUs for several users. Each burst is then transmitted according to the selected modulation and coding scheme depending upon the observed link quality. The higher rate modulation scheme such as 64 QAM (quadrature amplitude modulation) gives higher throughput gain provided that the users are in the higher SNR (signal to noise ratio) region. On the other hand, lower rate modulation scheme such as quadrature phase shift keying (QPSK) is used for the shadowed and faraway users for the better tolerance against error. In this paper, we utilize the physical data rate corresponding to the available modulation technique as a metric (details in Section 3) of the proposed path selection algorithm.

Fig. 2 depicts the frame structure proposed for the non-transparent relaying mode in [3]. MR-BS frame begins with a preamble transmission followed by sending error checking code (FCH), downlink map (DL-MAP) and uplink map (UL-MAP). Downlink (DL) portion of the frame includes one or more relay zones and at least one access zone for transmitting DL bursts toward RSs and MSs, respectively. Similar to MR-BS, for an RS, a frame is accordingly divided with relay and access zones to transmit DL bursts to the downstream nodes. Note that the transmissions of the management messages (for example DL-MAP and UL-MAP) are aligned with the MR-BS frame. Multi-frame grouping is applied such that the one or more RS and MR-BS frame is grouped with a repeating pattern of allocated relay zones. In this paper, we use 2-frame multi-frame in which, odd hop RSs transmit in the DL relay-zone of odd numbered frames, and the MR-BS and even hop RSs are assigned to transmit in the DL relay-zone of even numbered frames.

Embedded or explicit relay path management is considered for disseminating the path information to the RSs. In the embedded path management, initially the subsets of CIDs (connection identifiers that represent the connections) are systematically allocated by each parent node (e.g. MR-BS) to the child nodes (e.g. first-hop RSs) using partitioning technique. The explicit path management utilizes a control message called DSA-REQ to disseminate the CID information to all the RSs on the path. A selected path associated with a connection is assigned a unique path identifier (path-ID). Each RS builds a routing table that contains the binding between path-ID and the received CID from a DSA-REQ message. When the path is required to be removed, MR-BS sends DSD-REQ with the path-ID to request the removal of corresponding path information from the routing table. Two modes for forwarding MAC PDUs (MPDU) are proposed: in tunnel mode the MPDU is encapsulated in the relay-header, and in another mode transport-CID representing the established connection is placed in the MPDU header itself. Our proposed path selection schemes are designed in a centralized manner to effectively use the both modes for forwarding.

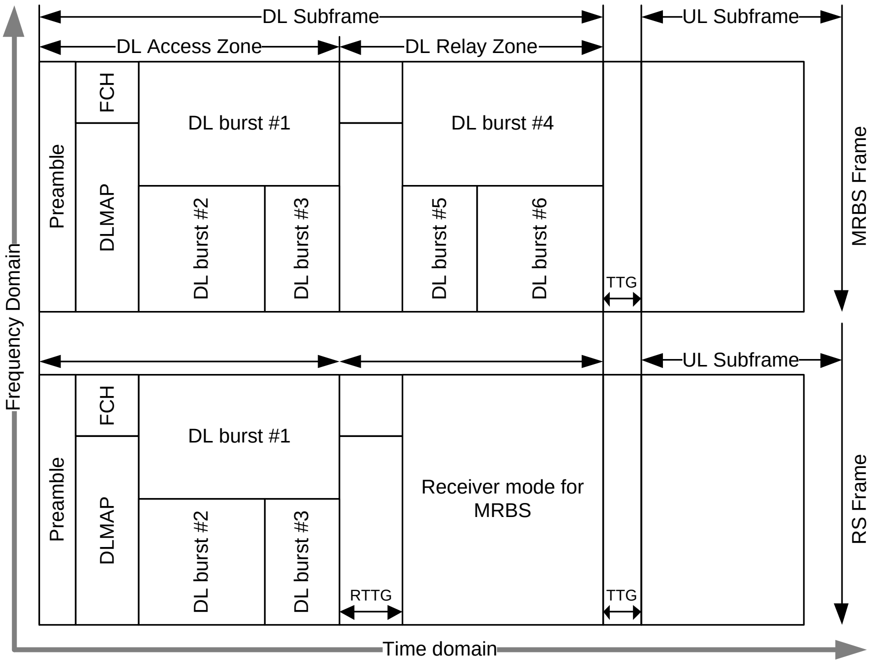


Fig. 2. Non-transparent frame for MR-BS and RS.

2.2 Related Work

How to make an efficient path selection in multi-hop wireless networks is a widely researched topic. [6][7] present the relay selection with peer-to-peer relaying. They propose the selection algorithms based on the distance, path-loss and the observed SINR. The coverage improvements obtained due to proper RS selection and transmit power selection is presented. They also show the throughput improvement due to relaying with performance order in terms of SINR, path-loss value and distance measurement. The algorithms in [6][7] are proposed purely from the perspective of cellular networks without considering bandwidth allocation issues. However, in our proposed scheme we show that the path selection considering both bandwidth and link quality for IEEE 802.16 based multi-hop network shows better performance.

In [8], authors suggest an expected transmission time (ETT) metric to optimize end-to-end QoS in cellular network that supports rate-adaptive relaying. The path is selected based on the links reporting higher SINR through fast-feedback channel which results into selecting higher rate and thus reduces the expected transmission time. [9][10] proposes a path selection metric and algorithm considering the effectiveness of radio resource of a link used to transmit data. The ERRI (effective radio resource indicator) metric in [9] is defined as the bandwidth unit required for transmitting a data using a fixed modulation and coding. In their following work [10], they propose a centralized symmetric path selection algorithm based on the ERRI metric. Compared to these works, we utilize both rate-adaptive relaying and bandwidth information as a part of a metric for the purpose of path selection. Our algorithm first selects all available paths to do away with the paths having low-rate bottleneck links. Among the paths with better links, we re-compute the bandwidth availability based on the current load at RS and other connection parameters.

There are the other researches about the route metric for the relay network. [11] proposes a path selection metric which focuses on the situation when a new RS joins the network. The authors focus on balancing between the loss rate and the link bandwidth. However, it does not consider the distribution of mobile stations, so the path is selected based on the topology information only including RSs. In [12], the authors propose a route metric including load balance factor in other to prevent such a situation that some RSs suffer from heavy traffic load. Their proposed scheme helps the fair bandwidth consumption among RSs, but it does not mean the smallest bandwidth consumptions to be achieved by the highest available data rate. On the other hand, our proposed scheme utilizes the best throughput path based on the physical data rate whenever the available bandwidth remains.

Several path management schemes have been contributed during the development of the IEEE 802.16j. These contributions [13][14][15][16][17] mainly propose signaling mechanisms required for path selection, removal and other management task required for the data forwarding. [13] proposed the link quality as a metric of multi-hop path selection, which is reported on the fast-feedback channel by the stations using a REP-RSP management message. [14][15] considers routing path to be established either during the network entry of RS or MS. Similar to these contributions, our previous work [5] proposes the signaling mechanism during the network entry process for MS and when the normal communication is in progress for path selection. However, in this work we adopt the signaling mechanism in [3] for compatibility with the standard development. The simulation performed in [5] did not consider any bandwidth parameter and the non-transparent relaying, but here we extend our simulation for non-transparent relays and bandwidth adaptation.

3. Proposed Scheme: Bandwidth Adaptive Path Selection Algorithm

As mentioned in the introduction section, the IEEE 802.16j network is expected to provide an extra coverage and gain in throughput by allowing multi-hop communication among the relaying infrastructure. However, randomly distributed radio resource in such settings might reduce the actual capacity of the network. Therefore, our path selection scheme allows load distribution among RSs such that bandwidth can be effectively distributed for the increasing connection requests in the network.

In this paper, we propose two path selection schemes. First, we select a high throughput path among the possible link disjoint paths based on the data rate of each link belonging to multiple paths. The SNR of each link is reported during the network topology discovery. For each reported link, the SNR is mapped to the respective physical data rate to estimate the link throughput. Next, we propose an advanced scheme which selects a path to distribute the load of RSs by considering the available bandwidth. The available bandwidth of each RS is measured by computing the difference of the allocated bandwidth from the consumed bandwidth to support existing connections. Based on this we select a high throughput path with sufficient bandwidth such that the service provisioning can immediately proceed. Two proposed schemes are designed to work with the OFDMA PHY structure defined in the IEEE

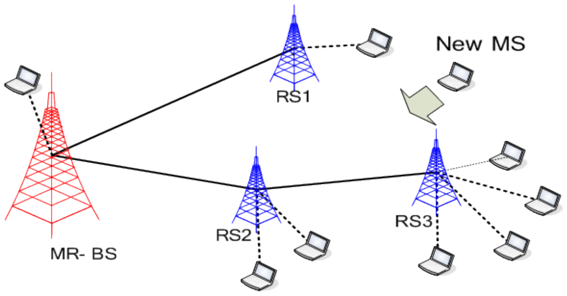
802.16j standard. The proposed path selection schemes are inherently decoupled with the underlying scheduling algorithm for the bandwidth allocation in the MR-BS, and thus they can be applicable with various scheduling algorithms. We thought this type of the loosely coupled approach is more useful and practical because each scheduling algorithm has its own pros and cons. For example, the maximum-CIR scheduler may give high throughput to a few users, but has a fairness problem. On the other hand, the proportional-fair (PF) scheduler provides even throughput for each user, but the system throughput is less than the maximum-CIR scheduler [20].Consequently, the proposed schemes try to fully utilize the allocated bandwidth by the underlying scheduling algorithm.

3.1 Path Selection Metric

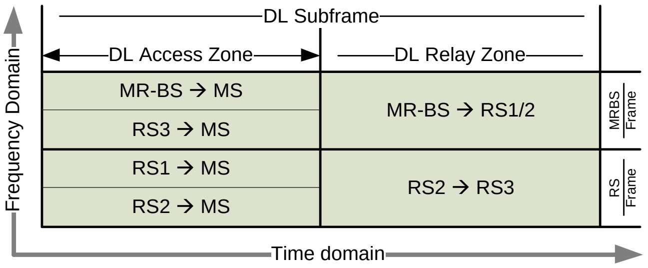
The SNR of each link between RSs and MSs is one of the metric used in our proposal, which is reported in MR_NBR_INFO message and the measurement reports are sent to MR-BS by RS_NBR-MEAS-REP message periodically or upon request. A rate-adaptation protocol selects the modulation and coding for each link based on the received SNR as shown in **Table 1**.The cost of the link is determined according to the corresponding physical layer data rate that is supported by the selected modulation and code rate. The expected throughput (*Th*) metric which is the maximum throughput in the physical layer is applied in the proposed scheme 1 as described in the next subsection.

Table 1. PHY throughput VS SNR for DL PUSC [18]

Modulation /code rate	Max. PHY throughput (Mbit/s)	SNR@0.01 CBLER (dB)	Cell range with fade margin(m)
QPSK-1/2	7.14	6.0	512
QPSK-3/4	10.71	9.2	421
16-QAM-1/2	14.28	10.3	392
16-QAM-3/4	21.42	14.9	290
64-QAM-2/3	28.56	19.0	222
64-QAM-3/4	32.13	21.2	192



(a)



(b)

Fig. 3. **(a)** Example topology and **(b)** DL sub-frame allocations.

3.2 Path Selection Scheme 1: Remove Low-Rate Link (RLR)

The path selection scheme is initiated when a new connection is requested or when MS moves to another location. The algorithm begins with MR-BS enumerating all the candidate paths (p_1...p_n), where n is the number of available paths. In the network, since several access links for an MS might be possible with RS/MR-BS, alternative paths can be approached for data forwarding. For example in **Fig. 3-(a)**, the new MS joining the network can have access link with the MR-BS, RS1, RS2 and RS3 with four possible paths: 1-hop path with MR-BS, 2-hop path with RS1 or RS2 and 3-hop path with RS3. These candidate paths are obtained I intermediate result in our algorithm to select a best path among them.

Notations

$\mathbf{P}$ is a set of candidate paths

$\mathbf{L}$ is a list of nodes in a path

$\mathbf{R}$ is a set of candidate access RSs

$\mathbf{U}_i$ is a set of candidate upstream nodes of RS_i

$\mathbf{Th}$ is a set of expected throughput of each link in a path

Algorithm 1: find_all_path()

```
$P \leftarrow \varphi$
for each $RS_i \in R$, I = 1,2,…,|R|
    $L \leftarrow \{RS_i\}$
    call enum_rec($RS_i$, $L$)
```

Algorithm 2: enum_rec(k, L)

```
for $node_j \in U_k$, j = 1,2,…, $|U_k|$
    if $node_j$ is MR-BS
        insert MR-BS into list L
        insert list L into set P
    else
        $L' \leftarrow$ copy list L
        insert $node_j$ into list $L'$
        call enum_rec($node_j$, $L'$)
```

Algorithm 3: order_path()

```
for list $L_i$ ε$P$, I = 1,2,…,|P|
    $Th \leftarrow \varphi$
    for each $RS_j$ ε$L_i$, j = 1,2,…,$|L_i|$
        get PHY throughput for $RS_j$
        insert the result into set Th
    find min throughput in set Th
```

```
insert result into $Th_{min}(i)$
call select_path()
Algorithm 4: select_path()
find $\max^m T_{min}(i)$, i=1,2,…,|P|
select path $L_i$ with $\max^m Th_{min}(i)$
$RS_{selected}$ (last hop RS in $L_i$)
```

Fig. 4. Proposed algorithms for path selection that avoids bottleneck throughput.

First, we select a path with maximum among the minimum throughput expected in the links. For each path, we first establish the throughput for each link based on the physical data rate derived from the observed SNR. Paths are then enumerated in descending order in terms of minimum throughput corresponding to the link that has the least throughput. $Th_{min}(i)$ is the minimum throughput for some link in the i^{th} path. Thus, the selected path p_{sel} is the one with maximum among the minimum $Th_{min}(i)$ as represented by Eq. (1).

$$p_{sel} = \arg\max_{n} \{Th_{\min}(1), Th_{\min}(2), ... Th_{\min}(n)\} \tag{1}$$

In other words, p_{sel} is the path that has the highest throughput that avoids the bottleneck link. Thus, this scheme is named as *Remove Low-Rate Link (RLR)*. **Fig. 4** shows the proposed algorithm for path selection that avoids the minimum throughput link. Algorithm 1 and Algorithm 2 compute all possible paths, recursively reaching out all RSs in the path until MR-BS. Algorithm 3 enumerates the path-ids with regard to the minimum available throughput link. Finally Algorithm 4 selects the path with maximum among the minimum throughput using Eq. (1).

3.3 Path Selection Scheme 2: Bandwidth Adaptation (BWA)

The example for the intuition of the path selection based on bandwidth is depicted in **Fig. 3-(b)**. We consider a frame structure in [3], in which the access and relay zones are defined as a portion of the frames used for MR-BS/RS to MS and RS transmissions respectively. As shown in **Fig. 3-(a)**, RS2 has two and RS3 has four access connections respectively. Assuming that each connection consumes similar bandwidth, RS2 and RS3 already have many MSs connected with active connections with limited available bandwidth. Therefore, RS2 and RS3 might not support more connections due to exhausted bandwidth.

To solve this problem, we propose an advanced scheme named as *Bandwidth Adaptation (BWA)*. It distributes the load of RSs by considering the available bandwidth. Bandwidth allocation for each RS is pre-determined centrally by MR-BS. We define N_s be the total number of slots per frame allocated for a RS to transmit data towards the downstream nodes. Let B_i represent a bandwidth in terms of bit per second required by a service allocated to i^{th} connection. The number of consumed slots by each RS depends upon the transmission rate (r_i) used for that connection. r_i is defined as the number of bit carried in a slot. Therefore, we compute the number of slot per unit time for each connection based on B_i and r_i. Let t_f be the frame length which is a fixed value representing a time interval required to transmit a frame. For example, in Section 4.1, we use the frame length of 10*ms* for the simulation. Thus, after the connection is admitted and while service is being utilized, the available bandwidth (A_s) in terms of the number of slots in a frame is given by the following Eq. (2):

$$A_s = N_s - t_f \times \sum_{i=1}^{n} \left\lceil \frac{B_i}{r_i} \right\rceil \tag{2}$$

The BWA scheme involves the path selection procedure in the previous scheme. For the selected path from RLR, we compute the available bandwidth (A_s) for each RS in the path. If A_s is negative for any RS in the selected path, the next best path is considered for selection. In case if it is impossible to allocate any bandwidth for the connection, the requested connection is dismissed. The MR-BS keeps track about the type of connection and the consumed bandwidth on all its subordinate RSs in the path. Since the number of connections might keep on varying in the network, the updated A_s qualifies whether the path is resourceful for accepting the connection or not.

Revisiting the example in **Fig. 3-(a)**, BWA finally selects the path from RS1 for the new MS that has joined the network even though the physical data rate might be lesser compared to the path selected by the proposed scheme 1. The shortest hop algorithm will select direct path to MR-BS, while RLR shall select the multi-hop path across both RS2 and RS3.

4. Performance Evaluation

In this section we report the simulation results based on performance evaluation conducted in *ns-2 simulator*. We implemented the non-transparent relaying, signaling mechanism for neighbor discovery and explicit path management features for forwarding the data packets over the IEEE 802.16 MAC implementation available from [19]. We compared our proposed schemes with the shortest path algorithm (SPA) and balanced algorithm (BAL). The SPA algorithm selects the path based on hop-count between MR-BS to MS. The BAL algorithm which is proposed in [11] focuses on balancing between the loss rate and the link bandwidth and thus smaller hops and more robust channels are favorable. Our RLR represents the path selection scheme that considers data rate as a metric. The path with the link that has maximum of the minimum associated rate is selected. In the proposed BWA scheme, we compute the available bandwidth at each RS and reconsider selecting a disjoint path with sufficient bandwidth resource. The performance is assessed in terms of average throughput, latency and bandwidth consumption on the downlink traffic from MR-BS to the MSs on the multi-hop path.

Table 2. System specific MAC parameters

Parameters	Value
Spectrum	5.0GHz
Bandwidth	10 MHz
Number of OFDMA symbol per frame	48
Number of sub-channels	60
Ranging and bandwidth request opportunity per frame	12 OFDMA symbols
Initial ranging CID	0
Basic CID / Primary CID	1-1000/1001-2000
Transport and secondary management CID	2001-65278
Broadcast CID	65535
SFID range	1-4292967295

Table 3. Time parameters

Parameters	Value
OFDMA Symbol Time	100.84 μs

OFDMA Frame length	10 ms
DCD/UCD period	10 sec
Ranging Interval	1210.08 μs
Bandwidth Request Interval	1210.08 μs
TTG / RTG / RRTG	29.4 μs (each)

4.1 Simulation Environment

The deployment scenarios consist of 10 to 90 MSs, 1 to 9 RSs and one MR-BS placed at the center of the $1000\times1000m^2$ area. Placements of RSs are predetermined to construct a maximum 3-hop tree topology originating at MR-BS, while MSs are randomly deployed in the region. **Fig. 5** illustrates the deployment of MR-BS and RSs. The modulation versus distance model is used for achieving physical transmission rate according to **Table 1**.

We generated downlink UGS traffic from MR-BS for each MS after initial ranging among the nodes are accomplished. The CBR traffic associated with each UGS agent generates packet size of 1024 bytes at the rate of 128 Kbps. The traffic is generated for each connection throughout 50 seconds duration of the simulation. Centralized bandwidth allocation and scheduling is performed for each requested connection after it is activated at the start of the simulation. Required downlink bandwidth is computed in terms of bytes according to the QoS property such as peak data rate of the requested connection. Scheduling for the burst transmission is performed in the round-robin manner. Result of each experiment is repeated and averaged over 10 different scenarios. In this simulation, we do not consider uplink traffic for simplicity. However, our algorithm can easily accommodate traffic both-ways since the adaptation is performed centrally at MR-BS. The system specific MAC layer and the relevant time parameters are presented in **Table 2** and **3**. The transmit power of each node is uniform (i.e. 15dB) and 2-ray ground path-loss model is used. The total frame size is fixed at 10ms and divided into downlink and uplink. An alternate downlink frame for odd and even leveled MR-BS and RSs is used to transmit both control and data packets towards the downlink. 48 OFDMA symbols (i.e. equivalent to approximately 8ms of the total frame duration) are dedicated for transmitting data to the downstream neighbors. The number of symbols required for transmitting towards MS (access zone) and RS (relay zone) is adaptively adjusted depending upon the connections allocated for each zone.

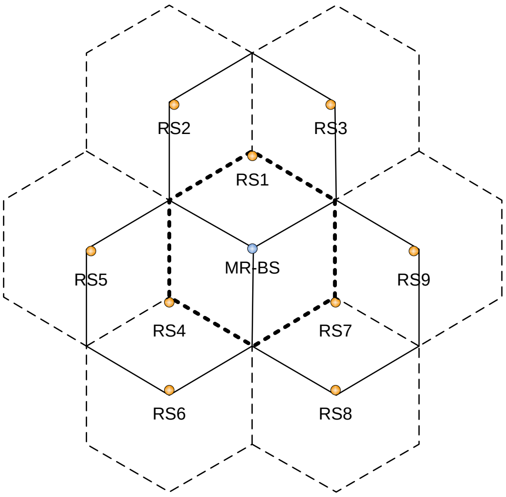
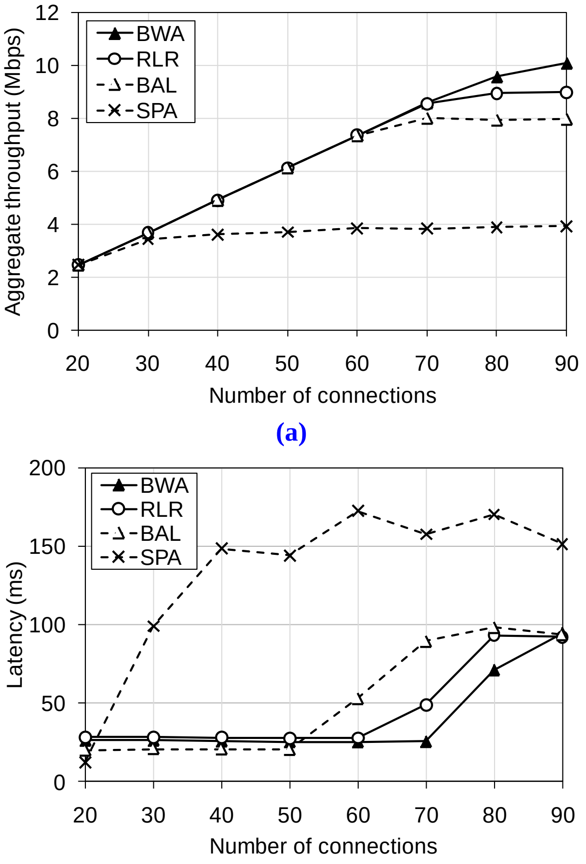


Fig. 5. MR-BS and RS topology

4.2 Simulation Results

Fig. 6-(a) shows that for all schemes throughput increases as the connections grow in the network. Aggregate throughput is defined as the average amount of bytes per unit time that is received at all MSs. This means the end-to-end throughput at the application layer. SPA tries to select the minimum hop path, so the geographical distance between the transmitter and the receiver node in the link tends to be longer than other schemes. It degrades the data rate of the link due to the reduced signal quality. Therefore, SPA consumes more bandwidth than the other schemes. As a result, SPA shows the worst performance and it is almost maximum throughput when the number of connections is 30. However, in all the other schemes, throughput continuously increases as the number of connections grows. This is obvious because they consider SNR related to multiple modulation and code rates. However, the performance of the proposed RLR and BWA overwhelm BAL after about 70 connections are provisioned through the RS. Analyzing the traces of the simulation result, we can see that the established connections are kept on hold for transmission on the best selected path by BAL or RLR. Note that since RLR insists on using the best path with maximum set of rates assigned to each link, bandwidth gets exhausted faster and the connections cannot be provisioned on that path. Therefore, BWA shows in average 150%, 26% and 12% throughput gain compared to SPA, BAL and RLR respectively.

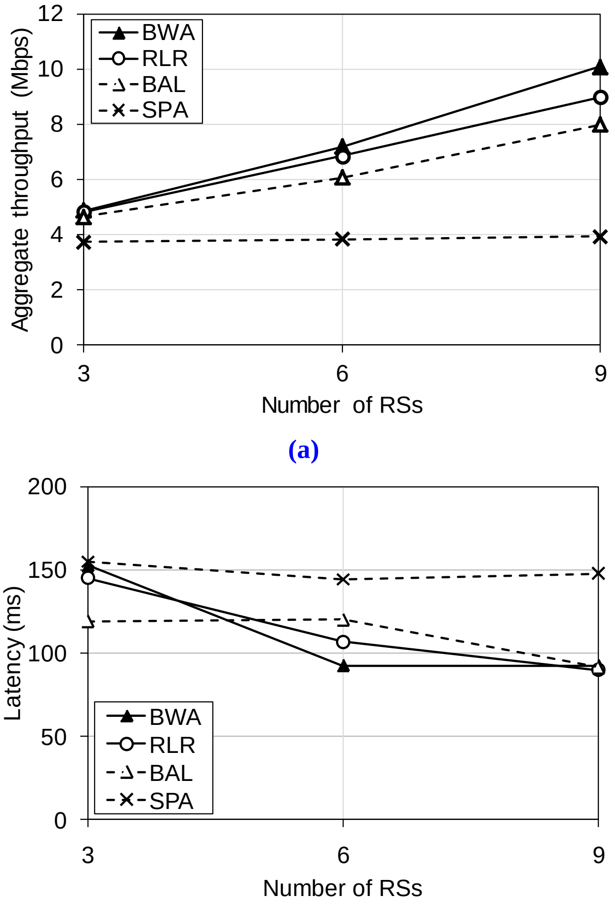


(a)

(b)

Fig. 6. **(a)** Aggregate throughput and **(b)** latency with 9 RSs placed between MR-BS and MS.

In **Fig. 6-(b)** we depict end-to-end latency results for the four schemes. The packet is time-stamped when generated at MR-BS and received at the stations. The difference is computed to reflect the amount of time required to transmit the packet from the source to the destination. In the every scheme, the average latency starts to increase when the throughput reaches the bottleneck point. As a result, the proposed schemes maintain the minimal latency with more connections than SPA and BAL. In the case of previous analysis, we see that the average latency for SPA is much higher compared to the other schemes. This happens due to the selection of links with low-rate that sends lesser amount of bytes while forwarding towards the station, even if the propagation delay for transmission is relatively less. The bandwidth adjustment in our proposed scheme BWA comes to rescue while comparing BWA with the RLR. Due to proper sharing of bandwidth, more connections are provisioned on the paths that use higher rates, thus reducing the average latency. Therefore, BWA shows that it is in-average 40% faster compared to SPA.



(a)

(b)

Fig. 7. **(a)** Aggregate throughput and **(b)** latency with increasing number of RSs and 90 connections.

To analyze the effect of RS on throughput and latency of our proposed scheme, in the next scenario, 90 connections are generated as the number of RSs varies from 3 to 9 in the x-axis. RSs constitute maximum 3-hop paths from MR-BS to MSs. According to the result presented in **Fig. 7-(a)**, throughput increases drastically when the new RSs are added for extended coverage in the path. BWA still shows best performance due to efficient bandwidth distribution.

Fig. 7-(b) shows the performance of end-to-end latency across the increasing number of RSs for 90 active connections. As expected, latency decreases with the increasing number of RSs because many connections are provisioned through higher transmission rate by the intermediate RSs. With only 3 RSs, the latency of RLR and BWA is higher than BAL as it selects longer hop paths with higher transmission rates. Since the intermediate RS forwards the received burst in the next RS frame, the latency increases. BAL tends to select shorter hop paths than the proposed schemes. Again, since the path selection in BWA is based on available bandwidth across the multi-hop path it shows consistently superior performance compared to other schemes. We note that as the number of RSs closes to 9, latency for both RLR and BWA becomes similar with BAL since the network capacity is fully exhausted.

We analyze bandwidth distribution and consumption by the three schemes. Bandwidth consumption in **Fig. 8** is computed as the number of connections each RS in the network is serving at each frame. The bar shows the total number of connections at RSs for BAL, RLR and BWA, respectively. We do not include the case of SPA because almost 85% of connections are served by MR-BS and the only remaining 15% of connections are served by RSs in SPA scheme. It is obviously skewed in terms of the bandwidth consumption and distribution. In general, for all the schemes it is expected that as the number of connection increases total bandwidth consumption also increases. The sum of the served connections in all RSs is same to the number of connections provisioned. At each bar we show the distribution of connections at 9 RSs and MR-BS. Regardless of increase in the number of connections the bandwidth consumed by each RS is relatively uniform in case of BWA than BAL and RLR. It confirms that the proposed BWA scheme efficiently distributes the load to each RS, and bandwidth consumption is minimized.

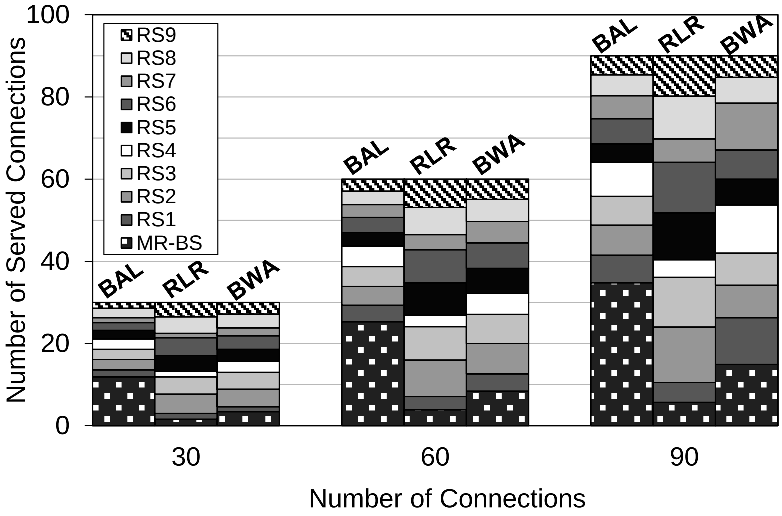


Fig. 8. Bandwidth consumed by 9 RSs with respect to the increasing number of connections

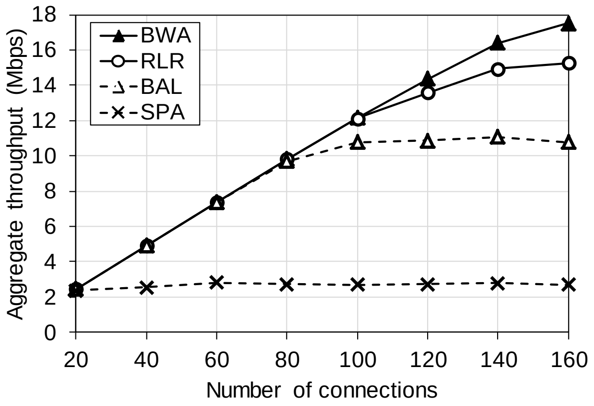
In the previous simulations, granted connections are continued during the entire simulation time. We have performed extra simulations in order to verify availability of proposed schemes under the situation that birth and death of connections frequently happen. In the simulation environment, total 90 connections are randomly started and retained during 5 seconds. When a connection ends, the connection starts again after 1 second pause time. As shown in **Table 4**, the proposed BWA still offers more throughput than any other schemes due to its effective path selection method. Consequently, we can conclude that the proposed schemes are still valuable in such environment that birth and death of connections frequently happens.

Table 4. Simulation results

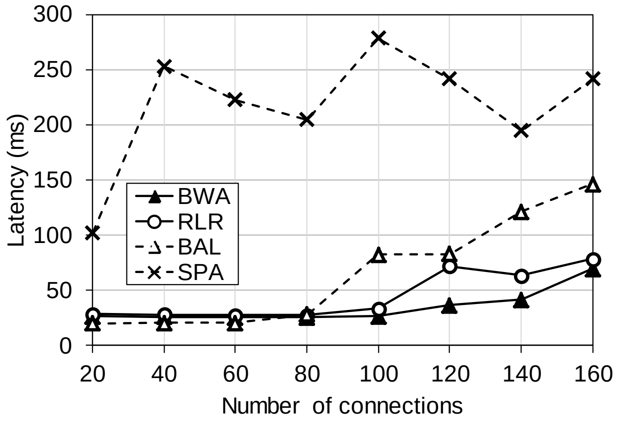
	SPA	**BAL**	**RLR**	**BWA**
Aggregate Throughput (Mbps)	4.12	7.80	8.07	9.14

In the previous simulations, each MR-BS and RS uses different DL bursts which are not overlapped with each other. However, in the next simulations, we evaluate the performance of the proposed schemes when the frequency reuse is applied in the MR-BS cell. Frequency reuse should be done carefully in a controlled manner to prevent any co-channel interference. This means that RSs and MR-BS that have no overlapping coverage region are only allowed to share the bandwidth. Based on our simulation scenario of RSs' deployment as shown in **Fig. 5**, we believe three cases of frequency reuse are possible. In the first case when MR-BS transmits data to MSs in the DL access zone, a group of RSs located at the second hop away from the MR-BS (i.e., RS2, 3, 5, 6, 8 and 9) can simultaneously transmit data to MSs with no interference. The second case is when the first hop RSs which are RS1, 4 and 7 can share the bandwidth in the DL access zone to transmit data to MSs. The third and last case is when the first hop RSs also can share the bandwidth similarly in the DL relay zone to transmit data to the second hop RSs.

As shown in **Fig. 9-(a)**, the maximum throughput of BAL, RLR and BWA schemes increase due to the bandwidth gain caused by frequency reuse, and thus more connections can be served. Throughput increases of the three schemes against the environment without frequency reuse are 35%, 70% and 74%, respectively. It means the proposed bandwidth adaptive path selection scheme is most efficient even in the environment that frequencies reuse is utilized. Similarly, the end-to-end latency of the proposed BWA scheme is much less than the others as shown in **Fig. 9-(b)**.



(a)



(b)

Fig. 9. **(a)** Aggregate throughput and **(b)** latency when the frequency reuse is applied.

5. Conclusions

We have presented efficient path selection algorithm for the IEEE 802.16 based multi-hop networks. The proposed schemes use selection metric that efficiently selects high throughput path with sufficient bandwidth. For compatibility and relevance, we considered utilizing messages and operations already presented in the existing standards. The performance result shows the increase in throughput and drop in the average latency with our path selection scheme compared to other rigid schemes that prefer to utilize the same path repeatedly for data forwarding.

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