Chapter 4

JOINT ROUTING AND BANDWIDTH ALLOCATION

PROTOCOL FOR IEEE 802.16 WIMAX MESH NETWORKS

4.1 ROUTING IN WiMAX

In the recent years, the web and VoIP services has motivated the development of new broadband access technologies due to the increased demands for faster connection [12]. For the upcoming generation, IEEE 802.16 standard, WiMAX (Worldwide Interoperability for Microwave Access Forum) has become the most potential wireless access technology. WiMAX uses a common MAC protocol to incorporate the set of air interfaces but physical layer specifications are included depending upon the frequency range [29].

A base station (BS) and multiple Subscriber Stations (SSs) are included in the IEEE 802.16 network. In a certain geographical area, from each SS the traffic is aggregated and from the end users and is sent to BS which serves as the gateway for external network [12]. WiMAX has a transmission rate of 75Mbps and it can reach upto a distance of 50 km. the transmission speed is higher and the transmission coverage is larger for the WiMAX when compared to other wireless networks. High transmission rate can be achieved due to greater coverage and enhanced mobility support. The QoS scheduling in the network supports the heterogeneous traffic. Few remote areas which does not have accessibility for cable or DSL internet connection, this WiMAX provides efficient support [30].

Mobile service, mobile entertainment, mobile commerce, mobile learning and mobile healthcare are the areas in which WiMAX is applied extensively [19].

The point-to-multipoint (PMP) mode and mesh mode are the two modes which are supported by the IEEE 802.16 MAC protocol. In the PMP mode, the
organizations of stations are in the form of a cellular network. In this the BSs connects all the SSs directly with it. The coverage range of the network can be minimized in this mode, when each SS is within the communication range of its associated BS. In mesh mode, the stations are structured in ad hoc manner. The traffic is transmitted from each SS to its neighbors since it acts as an end point or router. Due to this, SS doesn’t require direct link to its associated BS. Rate of transmission is higher from SS to the parent SSs or BS and with a minimum deployment cost, a wider area can be covered by the BS [10].

In WiMAX, the routing has been carried out extensively in order to increase the throughput, minimize delay and provide more robustness over wireless channel [12]. The routing protocols proposed here should be efficient in finding the routes between any two nodes, should consider the nobility factor and the topology [29]. Long-term route stability and short term opportunistic performance can be guaranteed using a good wireless mesh routing algorithm. For a wide spectrum of soft and hard failures, which range from transient channel outages, the wireless routing ensures robustness.

Also for the links which has intermediate loss rate from numerous channel disconnections, the nodes under denial of service attacks, and failing nodes, the wireless routing ensures robustness [12]. The Dynamic Source Routing (DSR), Temporally-Ordered Routing Algorithm (TORA), Ad hoc On-demand Vector Routing (AODV) which come under traditional routing algorithms does not support distributed services in WiMAX efficiently. This is due to the fact that the similar types of nodes are engaged for routing between source and destination. But the routing in WiMAX occurs through the base station and the mobile nodes and thus the
reconfiguration of the base station is essentially required to support the routing in WiMAX [30].

4.1.1 Existing Routing Protocols

4.1.1.1 Centralized Queue Aware Routing – CQAR

The network congestions can be reduced by utilizing the potential paths for departing traffic using a routing scheduling algorithm known as CQAR. In CQAR, there are two nodes: potential parent node and pseudo parent node in an SS. The pseudo parent node is the second potential parent node selected. The routing of the internet traffic is changed from parent node to the pseudo parent node using SS, when congestion occurs in the centralized Scheduling (CS). There is a decrease in the centralized link usage of node’s internet traffic, since the distributed link is present in between SS and pseudo parent node.

Hence, the system does not suffer from congestion, since there is a decrease in total traffic introduced to the CS. When no more congestion occurs in CS, the internet traffic is switched back from pseudo parent to parent node by SS, so that the intranet traffic is not delayed unreasonably [32].

4.1.1.2 MAC-based Routing Protocol for Triton (MRPT)

The routing information between the land station and ships can be disseminated by MRPT which uses WiMAX mesh MAC control messages for its proactive approach. Since the routing information is based on the existing MAC control messages, overhead can be reduced in this approach. In a tree structure, multiple routes are available without difficulty due to this proactive approach. Initial packet delay can be reduced when there is immediate arrival of a new node in the network. When there is a failure in the existing link, alternative routes are available for backup and this increases the network robustness. A unique method is proposed
which uses Bitmap for efficient encoding of the routing tree discovered in the reserved direction so that the land station reaches a ship [33].

4.1.1.3 Adaptive Routing algorithm using Disciplined Flooding and Proxy Setup (ARDFPS)

When the destination moves across the cell, the route along the mobile nodes are maintained by a new routing algorithm. Due to that the base stations become the intermediate nodes, they are stationary. The mobility of the source and destination can be efficiently managed by routing. The route request message from the source is received by the base station and all the nearby base station receives this so that the route to destination is found. Additional overhead is created in the base stations which directs to the destination. In order for the request message to traverse across the base stations, a TTL initial value is set and this has to be incremented until a threshold value is reached. Disciplined flooding can also be used to achieve this [30].

4.1.1.4 Cost-Based WiMAX Adaptive Routing Approach

In WiMAX mobile multi-hop relay (MMR) networks, the optimal routing path can be determined using a cost-based approach. In IEEE 802.16j MMR network, load balancing and network revenue maximization can be achieved by determining the alternative routing path using the distributed competitive on-line routing algorithm for a Mobile Station (MS). Relay link residual bandwidth is used by the competitive on-line algorithm for defining the link cost. In a selected path, the total cost of all the links is defined as the carrying path cost. Optimal results can be achieved and individual impact factor doesn’t require different weights in this proposed approach. This is due to the fact that residual bandwidth, hop-count and Adaptive Modulation and Coding (AMC) channel coding rate, are considered concurrently [34].
4.1.1.5 Quality of service with Admission control Routing(QUART)

The best workable route can be found using the QoS aware routing where the admission control and route discovery is joined together for path setup. The card with second signal for QUART-DD collects the related information which the node wants in order to find a feasible route for the destination. The route discovery and the route setup processes needs admission control system for all the variant versions (QUART-DD, QUART-SD, QUART-SS) the packages are transmitted out by the system after some time interval in order to obtain the suitable route [35].

4.1.2 Routing Issues in WiMAX Networks

• The multiple simultaneous transmissions causes too much of interference in mesh networks which in turn reduces the total capacity [12].

• Chances of congestion and unbalanced network in centralized routing are due to the shortest path routing. This is because the shortest path is selected by all the nodes in the network [12].

• The areas near the cell boundary, hiding areas including skyscrapers, hills, and narrow alleys faces reduction in transmission quality and data rate due to Signal fading, attenuation, and path loss [34].

• The fixed type BSs provides high reliability routing for QoS metrics but the transmission coverage is not so efficiently improved. Unfair results are produced since the impact factor doesn’t consider the normalization operation [34].

• In a multi-hop fixed relay network, on averaging the path loading, overloading on routing paths can be prevented. IEEE 802.16j Mobile-hop relay (MMR) networks differ greatly from IEEE 802.16j due to their mesh type
network and thus averaging of path loading cannot be applied on IEEE 802.16j Mobile-hop relay (MMR).

- The path determination in the centralized schemes uses the relay stations which extends the network service in WiMAX relay network. The selected routing path is the path with highest access/relay link transmission rate from MR-BS to MS. This increases polling delay in centralized schemes but distributed wireless network is not capable of determining the path.

- Distributed services in WiMAX are not supported effectively by the conventional routing algorithms like Dynamic Source Routing (DSR), Temporally-Ordered Routing Algorithm (TORA), Ad hoc On-demand Vector Routing (AODV). Other wireless networks use same type of nodes for routing between source and destination. Since routing in WiMAX is through the base station and mobile nodes it is necessary for the reconfiguration of base station [34].

4.2 BANDWIDTH ALLOCATION IN WiMAX

In the time-sensitive multimedia applications, the growing bandwidth demand has led to inadequate bandwidth in the wireless environment. In addition to service classes and parameters such as minimum reserved rate, maximum sustained rate and maximum latency, the BS requires bandwidth allocation algorithm so the better quality can be achieved [36]. Stable network transmission can be obtained by improving the high power consumption and reducing the collision of the packet for which the channel allocation mechanism is used. Channel allocation mechanism is classified into reservation and dynamic channel. In the reservation channel, the resources are not fully utilized for low requirements. But in dynamic channels, the channel utilization can be improved since it adjusts itself according to the
requirements. For users who require channel for the first time, some part of the channel is reserved and the remaining channels are shared for resource utilization [19]. Grant per Connection (GPC) and Grant per Subscriber Station (GPSS) are the two ways for allocating bandwidth in IEEE 802.16 [37].

The communication between BS and SS are of unidirectional connection which is controlled by the base station in a point-to-multipoint architecture of IEEE 802.16 networks. From BS to SS a downlink connection (DL) is established and from SS to BS a uplink connection (UL) is established. For DL data the centralized BS maintains transmission queue and for UL data it maintains bandwidth request queue. For UL connection, a bandwidth request message has to be sent from SS to BS in order to allocate the bandwidth. The UL and DL connection are scheduled by the BS based upon the QoS requirements including tolerable delay and minimum reserved rate which are specified for each scheduling class. A two dimensional (time and frequency) channel allocation frequency consisting of DL/UL map message is generated by the BS after scheduling. In a specified time and frequency, SS transmits UL data on receiving UL MAP. SS can request bandwidth using several standard ways based upon the scheduling class.

Both centralized scheduling and distributed scheduling occurs in packet scheduling of WiMAX mesh mode. The bandwidth request is sent to the BS in the centralized scheduling and the bandwidth is allocated by the BS. Available bandwidth and the bandwidth demands for each SS are the basis for bandwidth allocation. Since the two communicating SSs in the distributed scheduling confer about the bandwidth allocation, mini-slot determination requires time in order to forward the packet at each side [39].
Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), extended real-time Polling Service (ertPS, defined in 802.16e), non-realtime Polling Service (nrtPS) and best-effort (BE) which come under service type WiMAX standard needs to be supported by the bandwidth allocation algorithm since users are mostly serviced through WiMAX part of the network [40].

Real time data streams are supported by UGS in order to generate fixed size packets during periodic intervals. Eg. Voice over IP without silence suppression. Similar to VoIP with silence suppression, eRTPS is designed in order to support real-time service flows. These can generate variable sized data packets periodically. Periodically generated real time data streams are supported by RTPS which generates variable size packets. Eg: MPEG-multimedia format. The delay tolerant data streams are supported by nRTPS which generates variable size data packets, like FTP. The data streams which doesn’t require any service level can be supported by BE. Eg: Web browsing, email etc [41].

4.2.1 Existing Works on Bandwidth Allocation in WiMAX

4.2.1.1 Path Bandwidth Calculation Algorithm

The bandwidth requirement is measured as the number of timeslots in one frame. It assumes that a connection only uses a single path for transmission. To provide a bandwidth B on a given path, it is necessary that every node along the path find at least B timeslots to transmit to its downstream neighbor, and these timeslots do not interfere with other transmissions. Path bandwidth between two nodes, termed BW(P), is defined as the number of available timeslot between them. If the two nodes are in neighborhood, path bandwidth is link bandwidth.

The calculation of bandwidth is NP-complete problem. The paper adopts heuristic bandwidth computation. Its principle is described as follows: calculate a set
of non conflicting timeslots on three adjacent links which locally maximizes the bandwidth from source node, and to propagate this calculation along the path to destination node [42].

The number of timeslots in one frame is précised as the bandwidth requirement. It has been assumed that single path is used for transmission connection. For a given path, bandwidth B can be provided by finding at least B timeslots by each node in order to transmit to the downstream neighbor. The supplementary transmissions are not interrupted by these timeslots. The number of available timeslot between the two nodes is their path bandwidth, BW (P).

4.2.1.2 Highest Urgency First

Latency guarantee and fairness are taken into account for scheduling all requests in the Highest Urgency First (HUF) algorithm. This uses Urgency parameter divides the allocation procedure into two phases. Bandwidth of DL/UL sub-frame is determined in the first phase and the bandwidth for data/bandwidth requests from MSs is allocated in the second phase. Metrics like high throughput, latency guarantee and fairness are directed in each phase [36].

4.2.1.3 Fair End-To-End Bandwidth Allocation

At the Medium Access Control (MAC) layer of single-radio, multiple channels IEEE 802.16 mesh nodes which are operated in a distributed coordinated scheduling mode, implementation of FEBA is done. Fair share is assigned for each end-to-end traffic flow when FEBA negotiates its bandwidth among the neighbors. Initially the heavily loaded links are provided with higher amount of service than lightly loaded links by arranging the bandwidth in a round-robin fashion. Then the Deficit Round Robin (DRR) scheduling algorithm buffers different traffic flows in separate queues. The network capacity can be increased using frequency reuse in a
network containing multiple channels. These channels are evenly distributed so that the capacity can be increased [43].

**a) Service Class Based Bandwidth Allocation**

First come first serve concept is the basis for allocating bandwidth based on the service class [19]. The required bandwidth is given by the service classes of different SS for all the service flows. The type of service class determines the bandwidth allocation in the BS. i.e the bandwidth allocation is according to the following order: UGS, RTPS, ertPS, nrtPS, BE service flows.

**b) User Based Bandwidth Allocation Mechanism**

The User based bandwidth allocation technique (DBAM) [37] classifies the users into three: high priority users, regular users and low priority users. Better QoS and higher cost for improved QoS are given to high priority users. Lower QoS for delay sensitive classes with lower cost are given to low priority users. The priority levels have nothing to do with the regular users since there requirements is between higher and lower priority levels.

When all three types of data request for a bandwidth, bandwidth allocation is processed first for the high-priority users, then the regular users and at last low-priority users. While considering a normal network, there are no added advantages in this algorithm. Bandwidth is limited for the network which has intense traffic. Here, bandwidth is allocated for high priority RTPS first, then for regular RTPS and at last for the low-priority RTPS [41].

**4.2.2 Issues in Bandwidth Allocation**

- During transmission of uplink TCP acknowledgement in 802.16, there occurs a delay in bandwidth-request. This leads to the degraded performance in the downlink TCP flow [38].
• Transmission of uplink TCP ACK may lead to collision in the contention-based bandwidth request process [38].

• Additional delay, increased round trip time of downlink TCP flow and decreased throughput occur during centralized scheduling since the ACK packets are served with a separate uplink connection in IEEE 802.16BWA network.

• Though higher transmission performance can be achieved for adaptive uplink and downlink bandwidth adjustment in 802.16, the frame structure and bandwidth requesting/granting procedures restricts the improvement in packet queuing delay and radio link utilization [4]

• The preferred QoS performance requirements cannot be achieved in 802.16, though physical (PHY) layer and medium access control (MAC) signaling mechanisms are clearly defined. This is because the radio resource scheduling and management are not rectified yet [44].

4.3 JOINT ROUTING AND BANDWIDTH ALLOCATION

The IEEE 802.16 standard [12], commonly known as WiMAX, is targeted for broadband wireless access and is best suited for multi-hop wireless backhaul. Such multi-hop (mesh) property, incorporated in the IEEE 802.16 standard, enables high speed multimedia applications, extended service coverage and supports high data rates [45]. WiMAX mesh networks can be an interesting solution for offering connectivity to rural areas, hard-to-wire zones and large cities. They can also be used as backups for the existing infrastructure networks. Moreover, WiMAX mesh is especially useful for extending the coverage of the BS to provide access for further areas. The need for WiMAX mesh network, arises from a real application requirement. In the context of an on-board video-surveillance system, WiMAX is
used for ensuring seamless and ubiquitous connectivity to trains, where it is assumed to have a BS connected to the backhaul wired network, and several SSs are used to extend its coverage all over the train trajectory. WiMAX mesh is especially important for providing QoS, since the access is contention-free dislike Wi-Fi based meshes [26].

WiMAX mesh mode uses two scheduling methods for allocating network resources and controlling network access: Centralized and Distributed. When using centralized scheduling, the BS gathers the requests of different SSs that are connected to it forming a mesh tree and allocates resources locally. Nevertheless, in distributed scheduling requests and grants are exchanged in the extended neighborhood that comprises the neighbors and their direct neighbors [26]. A joint routing and scheduling algorithm, maximizes the utilization of network capacity and also ensures fairness among SSs [26].

4.4. PROPOSED JOINT ROUTING AND BANDWIDTH ALLOCATION PROTOCOL

4.4.1 System Model

We consider a wireless metropolitan area mesh network in which the infrastructure/backbone is built using IEEE 802.16 technology. The mesh network consists of fixed wireless mesh routers and end mobile clients. The wireless mesh routers form a multihop wireless backbone to relay traffic to and from mobile clients. An IEEE 802.16 cell consists of a base station and one or more mobile stations based on point-to-multipoint (PMP) network topology. Wireless mesh routers also serve as base stations to mobile stations within their coverage area. An IEEE 802.16-based wireless mesh network as a set of nodes $N = \{1, \ldots, N\}$ that includes all the mobile clients and mesh routers and a set of wireless links $L = \{1, \ldots, L\}$ that includes all the
backhaul links as well as the links between mobile stations and base stations is considered. Assume the bandwidth requirement for the new arrival is $\text{REQ}_{\text{bw}}$. Each node and each link along the chosen route must have at least $\text{MIA}_{\text{bw}}$ units of bandwidth available for the new connection.

The routing problem is to decide a QoS route with bandwidth constraint for each source node and an assignment of its flow to all links in the network. For this, the paper proposes a joint routing and bandwidth allocation protocol in which a bandwidth estimation technique is combined with route discovery and setup in order to find a best route.

### 4.4.2 Bandwidth Estimation

Direct range is the area within transmission range and indirect range is the area between transmission range and interference range. The number of competitive nodes is the total numbers of these two areas. So, two tables are maintained by the nodes, the Direct Range Members (DRM) which are found from the first hop nodes and Indirect Range Members (IRM) table which are found from two or more hops nodes or hidden nodes. Neighboring nodes’ bandwidth can be obtained proactively or reactively. Proactive approach is chosen by our proposed scheme to obtain bandwidth information at neighboring nodes. To decrease collision and to deliver bandwidth information, every node issues a signal at its own defined intervals which are coordinated with the neighboring nodes. All neighboring nodes send their own bandwidth data by one-hop with double power to collect neighboring nodes information.

In the proposed scheme, each node within the interference range ensures that it has enough bandwidth to transmit data without causing congestion. And so, identification of local and the neighboring nodes within the interference range is done
accurately. Local bandwidth and the bandwidth of all interference range nodes should be considered by a node to transmit data. In our proposed system, special signals are sent out by the nodes with double power in predefined interval and signals are collected from neighboring nodes and finally the DRM and IRM tables are updated. The local bandwidth and neighboring nodes’ bandwidth are determined as below.

Since bandwidth is shared among neighboring nodes, a node listens to the channel and estimates bandwidth based on the ratio of idle and busy times for a predefined interval.

The local bandwidth $L_{BW}$ is estimated as follows:

$$L_{BW} = C_{BW} \times \frac{idle}{int},$$  \hspace{1cm} (1)

Where $C_{BW}$ denotes the channel capacity, $idle_i$ denotes the idle time in a predefined interval $int_i$.

The neighboring nodes bandwidth is given by $NM_{BW}$ which is collected from the neighboring nodes.

So the residual bandwidth $R_{BW}$ is calculated as

$$R_{BW} = NM_{BW} - L_{BW}$$  \hspace{1cm} (2)

4.4.3 Route Discovery Process

The proposed bandwidth allocation scheme can be applied to any on-demand routing protocols such as AODV and DSR. We apply our scheme to the AODV routing protocol by modifying the route request (RREQ) and route reply (RREP) packets.

4.4.3.1 Route Request

In addition to the standard RREQ header, the route request packet contains the following
<table>
<thead>
<tr>
<th>RREQ header,</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQbw</td>
</tr>
<tr>
<td>V(Idk, ck, i, d)</td>
</tr>
</tbody>
</table>

Where,

REQbw is the Requested bandwidth

V is a vector comprising combined IDs of the nodes in the interference range from source node s up to node i for the destination node d and their corresponding counts.

Idk - id of the nodes in the interference range

c_k - counter for the node n_k

i - intermediate node

d - destination node.

Steps:

1. If node n_j has no one hop neighbor, then
   Drop RREQ

   Else
   Send RREQ

2. If node n_v receives RREQ, If REQbw > R_bw, then
   Drop RREQ

   Else
   Calculate < (n_k, c_k), i, d>
   Forward RREQ

End if.

End if.
4.4.3.2 Route Reply

A route reply packet contains the following

| RREP header, | REQBW | MIA_{BW} | V(I_{dk}, c_{k}, i, d) |

Where,

- REQ_{BW} is the requested bandwidth,
- MIA_{BW} is the minimum available bandwidth,
- V is a vector comprising combined IDs of the nodes in the interference range from source node s up to node i for the destination node d and their corresponding counts.

| Id_{k} | - id of the nodes in the interference range |
| c_{k} | - counter for the node n_{k} |
| i | - Intermediate node |
| d | - Destination node. |

Steps:
1. Destination node sends the modified RREP packet.
2. Intermediate node n_{j} receives RREP.
3. n_{j} calculates MAX_{BC} = max (c_{k})
4. If R_{BW} < (MAX_{BC} * REQ_{BW}) then
   MIA_{BW} = (MAX_{BC} * REQ_{BW}) - R_{BW}
   Forward RREP to n_{j-1}
   Else
   Send failure message to source
End if.

Source chooses the RREP with maximum MIA_{BW} as the best path.

Here MAX_{BC} is the maximum value of bandwidth counter for a node which is around node n_{j} within its interference range.
The system performance mainly depends on the correctness of bandwidth estimation.

**Figure 4.1: Route Request Process**

Flows below the capacity of network are rejected by the AP if the estimated bandwidth is less than that of network capacity. AP admits a flow whose bandwidth consumption is beyond the capacity of network when the estimated bandwidth is
greater than that of network capacity. This will degrade the whole system performance. Difference of estimated bandwidth and capacity of the network should be minimized for better results.

4.5 SIMULATION RESULTS

4.5.1 Simulation Model and Parameters

To simulate the proposed scheme, network simulator (NS2) is used. The proposed scheme has been implemented over IEEE 802.16 MAC protocol. In the simulation, clients (SS) and the base station (BS) are deployed in a 1000 meter x 1000 meter region for 50 seconds simulation time. All nodes have the same transmission range of 250 meters. In the simulation, the video traffic VBR and CBR traffic are used.

The simulation settings and parameters are summarized in table 2.

<table>
<thead>
<tr>
<th>Table 4.1 Simulation settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Size</td>
</tr>
<tr>
<td>Mac</td>
</tr>
<tr>
<td>Clients</td>
</tr>
<tr>
<td>Radio Range</td>
</tr>
<tr>
<td>Simulation Time</td>
</tr>
<tr>
<td>Traffic Source</td>
</tr>
<tr>
<td>Video Trace</td>
</tr>
<tr>
<td>Physical Layer</td>
</tr>
<tr>
<td>Packet Size</td>
</tr>
<tr>
<td>Frame Duration</td>
</tr>
<tr>
<td>Rate</td>
</tr>
</tbody>
</table>

4.5.2 Performance Metrics

The proposed Joint Routing and Bandwidth Allocation (JRBA) algorithm is compared with the Interference-aware Multi-path Routing and Bandwidth Allocation (IMRBA) algorithm [18]. The performance is evaluated according to the following metrics:
Channel Utilization:

It is the ratio of bandwidth received into total available bandwidth for a traffic flow.

Throughput:

It is the number of packets received successfully

Average End-to-End Delay:

The end-to-end-delay is averaged over all surviving data packets from the sources to the destinations. The performance results are presented in the next section.

4.5.3 Results

In the experiments, the rate of all the CBR and VBR flows are varied from 2Mb to 10Mb.

![Rate Vs Utilization](image1)

**Figure 4.3: Rate Vs Utilization**

![Rate Vs BandWidth Received](image2)

**Figure 4.4: Rate Vs Throughput**
When the rate of the flow is increased, it increases the amount of traffic in the network resulting in increased throughput and bandwidth utilization. Due to this increased traffic flows, the end-to-end delay will also increase.

Figure 4.4 and 4.4 show that the bandwidth utilization and throughput are more for the proposed JRBA when compared with the IMRBA scheme, this is because of the fact JRBA considers both local and neighboring bandwidth while estimating the bandwidth.

![Rate Vs Delay](image)

**Figure 4.5: Rate Vs Delay**

From Figure 4.5 it is clear that the delay for the proposed JRBA scheme is less when compared with the IMRBA scheme, this is due to the efficient route selection of JRBA which selects resource efficient routes, when compared with IMRBA.