A Multi-Rate Based Router Placement Scheme for Wireless Mesh Networks

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Abstract

Mesh router (MR) placement is one of the fundamental issues that need to be addressed carefully to achieve a desired performance of a wireless mesh network (WMN). The objective of the MR placement schemes is to systematically determine the minimal number of MRs and their positions while satisfying various constraints, such as coverage, connectivity, traffic demand, etc. This paper explores the solution for placing the MRs with multiple transmission rates, which influence both transmission range and wireless link capacity. In the paper, we first formulate the problem with a mixed integer programming model. We then present a heuristic placement algorithm called ILSearch which takes into account both multiple transmission rates and co-channel interference. The ILSearch consists of two components: (1) Coverage MR determination which greedily exploits the capability of each selected MR to cover mesh clients (MCs); and (2) Relay MR determination that incrementally chooses the additional MRs for traffic relaying through the local search. Our simulation has not only shown that ILSearch can effectively obtain the MR placement that meets all the constraints, but also demonstrated that a MR placement which considers the variable transmission rates outperforms those don't.

1. Introduction

A Wireless Mesh Network (WMN) consists of static Mesh Routers (MRs) and mobile Mesh Clients (MCs). A small number of MRs with Internet access act as Internet Gateways (IGWs) to connect a WMN to the Internet and the others are used to forward traffic between MCs and IGWs. Each MR is equipped with multiple interfaces that generally operate on non-overlapped channels, interconnecting with each other to form a backbone in the network.

This paper addresses one of the key issues in building a mesh network: *MR placement — how many MRs are needed and where should they be placed*? A MR placement strategy should carefully examine all candidate positions and provide a MR deployment plan given various network parameters, traffic density or topology constraints (the candidate locations where MRs can be placed), for example, with the goal of minimizing the number of MRs and maximizing the network capacity. The prior work [1] has shown that the MR placement can significantly affect the performance of a WMN.

The MR placement problem has recently attracted much attention [2]–[4]. In this paper, we investigate one issue that has been left out unstudied in these prior works — the possibility to run MRs at different transmission rates. The impact of the multi-rate feature on MR placement is two-fold. One, allowing MRs to operate on higher transmission rates increases link capacities and thus potentially reduce the number of MRs needed to meet the throughput demand for MCs. On the other hand, however, higher transmission rates reduce the transmission range[1], and thus might lead to a placement scheme that needs more MRs to cover the entire network. When designing a mesh network, it is imperative for network administrators to be aware of these trade-offs.

We first formulate the multi-rate based MR placement after a mixed integer programming model [6] and show that it is in fact a NP-hard problem. We then propose a heuristic placement algorithm called *ILSearch* that takes into account both multi-rate and co-channel interference when placing MRs. A MR operates on the highest possible rate given its distance to its next-hop MR. If this rate is not able to sustain the traffic forwarded from its associated clients and other MRs, then additional MRs have to be deployed.

ILSearch is a two step process. The first step is to determine a set of MRs by greedily exploiting the capability of each selected MR to cover all MCs. These MRs are called *Coverage MRs* and some of them might not connect to any IGW (i.e., disconnected from the Internet). The second step is then to select another set of MRs, called *Relay MRs*, to relay traffic between coverage MRs and IGWs. Each Relay MR is selected locally to maximally reduce the distance

1. Increasing transmission rate from 6Mbps to 54 Mbps reduces the transmission range from 200 meters to merely 34 meters [5].

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between an isolated Coverage MR and an IGW, while having enough link capacity to forward all the traffic between them.

Our simulation results have demonstrated that ILSearch is capable of finding a MR deployment solution, in which the MRs are placed only at permitted locations and provide enough bandwidth to meet the traffic demand in the network. By comparing ILSearch to the other two fix-rate schemes, we show that ILSeach can strike the good balance between transmission range and transmission rate, and thus achieve a MR deployment scheme that uses fewer MRs.

The rest of this paper is organized as follows: Section 2 discuss the related work. The network model and problem formulation are introduced in Section 3. Section 4 details our heuristic placement algorithm. The simulation results are presented to show the effectiveness of our algorithms in Section 5. Finally, the paper is concluded in Section 6.

2. Related Work and Background

2.1. IGW Placement

Many earlier works on MR placement were trying to determine the positions of IGWs. Qiu et al. first proposed to select IGWs from an existing WLAN [7]. Bejerano [8] further studied this problem in a large-scale multi-hop network. They divide a network into disjoint clusters and each cluster is organized as a tree structure rooted at the IGW nodes. Prasad et al. [9] later modeled the IGW placement as an integer linear programming problem and proposed a heuristic algorithm that iteratively selects random locations until a predefined set of constraints are satisfied.

2.2. MR Placement

Ju et al. [10] are the first to study the MR deployment issue in a WMN and proposed a distributed algorithm to select some of the existing APs to constitute a connected backbone. In their architecture, however, MCs can be at most two-hop away from IGWs. Sirnivas et al. [11] then proposed a two-phase algorithm to construct a mesh backbone. In phase one, they use a strip-cover algorithm to decide the backbone nodes so that the other nodes can connect with at least one backbone node. In phase two, the backbone nodes are connected by establishing a Steiner tree with minimum number of Steiner points. Later work from Robinson et al. [2] showed that a regular MR placement provides better performance than a random MR placement. All these above approaches, however, did not consider practical deployment issues such as geographic constraints and traffic demand in the network. Sen et al. [12] formulated the MR placement as a cost optimization problem and took into account network topology, tower heights, antenna types and transmission power. But in their work, the traffic demand issue is still ignored and all MCs are required to reside within two-hop

Range(m)	Rate	Range(m)	Rate
$0 - 34$	54Mbps	$145 - 149$	11Mbps
$34 - 61$	48Mbps	$149 - 168$	9Mbps
$61 - 69$	36Mbps	$168 - 198$	6Mbps
$69 - 99$	24Mbps	$198 - 201$	5.5Mbps
$99 - 122$	18Mbps	$201 - 210$	2Mbps
$122 - 145$	12Mbps	$210 - 213$	1Mbps

Table 1: Map between Transmission Rate and Range for CISCO Aironet Wireless Cards

radio range from the IGWs. A more comprehensive integer linear programming model has been recently introduced in [3], and a heuristic algorithm is proposed to determine MRs/IGWs positions from a set of candidate locations.

2.3. Considering Multi-rate MRs

All the prior work has provided insightful theoretical guidelines when planing a WMN. However, they usually assumed each MR can transmit at the highest rate *and* with the maximum transmission range. This assumption is not realistic — a node's transmission range is adversely impacted by its transmission rate.

The multi-rate feature is supported by many standards such as 802.11 [13]. Ideally, when operating at a higher rate, a MR node can improve the link capacity to its next hop. However, packets sent at higher rate are encoded in a weaker modulation scheme and thus are more susceptible to external noise and so it is required to have a higher signal-to-noise ratio to successfully decode a packet sent at a higher rate. Therefore, when operating at a higher rate, the transmission range of a MR is also reduced. Table 1 lists the mapping information from transmission rates to transmission ranges for a commodity 802.11 NIC [5].

A MR placement without considering the multi-rate feature can suffer from poor network performance. If MRs are situated as far as possible from each other in order to reduce the number of the MRs, they can only operate on the lowest transmission rates. The traffic demand from the MCs could easily overload the mesh backbone, rendering the mesh network useless.

3. Network Model and Problem Formulation

Each Coverage MR node is equipped with at least three wireless interfaces in our model. One interface is used to communicate with its associated MCs, the other two are used to communicate with other MRs. Similarly, a Relay MR will need two interfaces for MR-MR communication. These interfaces work on non-overlapping channels. An example set-up like this is to use 802.11g for MR-MC communication and use 802.11a for MR-MR communication. Note that 802.11g offers 3 non-overlapping channels while 802.11a offers 19.

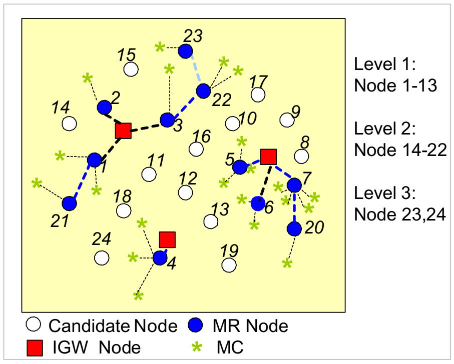

Figure 1: Network Model

Each MC generates one unit traffic to and from the IGWs. To simulate a MC with higher traffic demand, we position multiple MCs at the same location in the network. The maximum transmission rate achievable between two nodes is determined by many network parameters such as transmission power, propagation loss and distance, etc. In this paper we assume that the transmission power of MR nodes is fixed and the connected MRs are in line of sight of each other. Therefore, the maximum transmission rate is largely determined by the transmission range.

In the remainder of this section, we will first introduce our network and interference models in details and then formulate the multi-rate MR placement problem. Table 2 lists most of notations used in this paper for reference.

3.1. Network Model

Figure 1 represents a candidate network, $G(V, E)$, in a rectangle region where $V = \{0, 1, ..., m, m+1, ..., m+g\}$ is the node set including all the *candidate positions* for MRs and IGWs. These positions are pre-determined based on geographic constraints in the network, in which $1, ..., m$ are m candidate positions for MRs, $m+1, ..., m+g$ are g IGWs. The subsets of MRs and IGWs are referred as V_{MR} and V_{IGW} respectively. The positions of IGWs are assumed to be fixed in our model. Note that we use the specific number 0 to represent the Internet.

$E = \{e_{ij}\}$ is the adjacency matrix of G. e_{ij} is 1 if and only if the distance between node i and j, d_{ij}, is shorter than the maximum transmission range, R_{max}. Note that IGWs are connected to the node 0 (i.e., the Internet) via wired connections and so these links are assumed to have infinite network capacity.

$$e_{ij} = \begin{cases} 1, & (i = 0, j \in V_{IGW}) \text{ or } (j = 0, i \in V_{IGW}) \\ 1, & d_{ij} \leq R_{max} \text{ and } i \neq j \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Based on the adjacency matrix E, we define l_{ij} as an edge between candidate nodes i and j. l_{ij} is a valid edge if and only if $e_{ij} = 1$.

We define $V_{MC} = \{1, 2, ..., n\}$ as the MC node set. The MC nodes are non-uniformly distributed in the network. The traffic demand of a MC t is f_t. $W = \{w_{tj}\}$ is a $n \times m$ adjacency matrix between MCs and candidate MR nodes. It is used to indicate if a MC node t is in transmission range of a candidate node j.

$$w_t^j = \begin{cases} 1, & j \in V_{MR} \text{ and } t \in V_{MC} \text{ and } d_{tj} \leq R'_{max} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where R'_{max} is the maximal transmission range for MR-MC communication.

Let $\lambda = \{\lambda_1, \lambda_2, ...\lambda_K\}$ denote the rate set consisting of all K transmission rates defined by a standard. The value of K will change when adopting different standards. For instance, K is 4 for 802.11b and 12 for 802.11g. $C = \{c_{ij}\}$ is a capacity matrix, where c_{ij} represents the achievable capacity when a valid edge l_{ij} is used. The value of c_{ij} is approximated to maximal achievable transmission rate of l_{ij}, i.e., $|c_{ij}| \in \lambda$. As mentioned earlier, given that the transmission power and propagation model are fixed, the maximum transmission rate achievable for a given link l_{ij} is largely decided by its distance, d_{ij}. We use a function F_λ to map from link distance to link capacity, i.e., $c_{ij} = F_\lambda(d_{ij})$. In our work, we model F_λ after the CISCO Aironet card parameters shown in Table 1.

$G' = (V', E')$ is one *possible* MR placement solution. V' is a node set including all the positions where MRs are going to be placed. Note that the nodes in V' are selected from V_{MR}, i.e., $V' \in V_{MR}$. We use v_i as a binary variable to mark if a candidate location i has been selected,

$$v_i = \begin{cases} 1, & i \in V' \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$E' = \{\varepsilon_{ij}\}$ is the adjacency matrix of G', in which ε_{ij} is set to 1 if a wireless link between node i and j is assumed. Note that there are many MR placement alternatives and G' is only one of them. G' has to be validated to check if it is able to satisfy all the constraints.

$W' = \{\varpi_{tj}\}$ is the adjacency matrix between MCs and nodes in V',

$$\varpi_{tj} = \begin{cases} 1, & \text{MC } t \text{ is assigned to MR } j \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

f_{ij}^t denotes the traffic that originates from MC t, $t \in V_{MC}$ and goes through $l_{ij}, i, j \in V'$. If the traffic from MC t never goes through l_{ij}, $f_{ij}^t = 0$. f_{ij} denotes the aggregated traffic through l_{ij}. Thus $f_{ij} = \sum_{t=1}^{t=n} f_{ij}^t$.

Every candidate node is leveled by its minimum number of hops to IGWs, denoted by $h_i, i \in V$. Each MR node uses one interface for the transmission with upper level MRs and the other for lower level MRs. The corresponding

$G(V,E)$	Candidate network	$G'(V',E')$	One MR placement
m	Number of candidate nodes	n	Number of MCs
e_{ij}	Mark if candidate node i,j are neighboring	ε_{ij}	Mark if MR i,j are neighboring
w_t^j	Mark if MC t could be covered by candidate node j	ϖ_t^j	Mark if MC t is assigned to be associated with MR j
r_i^{up}	up-link transmission range of MR i	r_i^{down}	Downlink transmission range of MR i
v_i	Mark if candidate node i is placed with a MR	l_{ij}	An edge/link between candidate/MR nodes
I_{ij}	Interference set of l_{ij}	F_λ	Function mapping link distance d_{ij} to link capacity c_{ij}
f_t	MC t's traffic demand	f_{ij}	Traffic load in l_{ij}
f_{ij}^t	Traffic load in l_{ij} from MC t	$f_{I_{ij}}$	Overall traffic load in interference set I_{ij}
h_i	Level of candidate node	h_{ij}	Level of e_{ij}
d_{ij}	Euclidean distance between candidate node i,j	T_i	Tree rooted at MR node i
f_{T_i}	Traffic load of tree T_i	h_{T_i}	Level of tree T_i

Table 2: Notations

links are called *up-links* and *downlinks*, whose transmission range is r_i^{up} and r_i^{down} respectively for a MR node i. The candidate edges are leveled in the same way. Given any edge $l_{ij}, i,j \in V$ and $e_{ij} = 1$, its level is h_{ij}. $h_{ij} = h_i$ if $h_i > h_j$, otherwise, $h_{ij} = h_j$. For example as shown in Figure 1, Node 22 is at least two hop away from IGWs and node 23 is at least three hop away from IGWs. Therefore $h_{22} = 2$ and $h_{23} = 3$. Accordingly, $h_{3-22} = 2$, $h_{22-23} = 3$. Then Node 22 will use one interface to communicate with 3 and the other for 23 when they are sit with MRs.

In this paper, we use the channel assignment policy proposed in [14]. The links in the same level share one common channel, i.e., the up-links of MRs in the same level share one common channel and the downlinks share another common channel. The links in different levels are assigned with different channels and we assume the number of non-overlapped channels are enough to avoid co-channel interference between the levels.

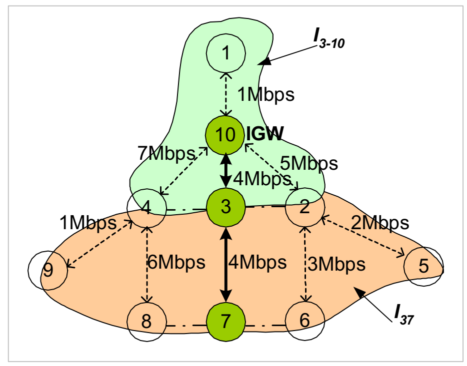

Figure 2: Interference Set

3.2. Interference Model

Given a wireless link l_{ij}, $i,j \in V'$ and $\varepsilon_{ij} = 1$, I_{ij} is the set made up of itself and all other links that could interfere the transmission between i and j. To avoid the collision, none of the links in its interference set should be active when l_{ij} is active. Different MAC protocols avoid interference and collision in different manners and I_{ij} varies as well. Figure 2 shows two interference sets I_{3-10} and I_{37}, based on CDMA/CA with RTS/CTS enabled. Note that due to the leveled architecture, links in I_{3-10} don't interfere those in I_{37} since they are in the different level and then operate on non-overlapped channels. I_{37} includes five links: $l_{25}, l_{26}, l_{48}, l_{49}$ and l_{37}. Before node 3 can send packets to node 7, it first needs to send RTS to node 7. Since node 2, 4 are within the transmission range of node 3, both nodes could recognize this RTS and will deactivate themselves as required. Note that no packets will be transmit between nodes 2 and 3 and so there is no wireless link between them. Similar things apply between node 3 and 4, 6 and 7, 7 and 8. When Node 7 receives RTS from Node 3, it sends CTS as a response. Similarly, Nodes 6, 8 could also get this CTS and then deactivate themselves too. Furthermore, when node 9 tries to send packets to node 4, it sends RTS request first as well. But node 4 is not active at this time and cannot respond CTS, the transmission between node 9 and node 4 could not start. Similar thing occurs at node 5. Thus, $l_{25}, l_{26}, l_{48}, l_{49}$ should not be active when l_{37} is active for a network employing CDMA/CA with RTS/CTS enabled MAC protocol. Based on the same principles, I_{3-10} is comprised of $I_{1-10}, I_{2-10}, I_{4-10}$ and I_{3-10}.

The links in a interference set operate on one common channel and so they have to share the capacity of the channel. We use $f_{I_{ij}}$ to represent the overall traffic load in I_{ij}. It is the sum of the aggregated traffic of all links in the interference set, i.e.,

$$f_{I_{ij}} = \sum_{l_{xy} \in I_{ij}} f_{xy} \quad (5)$$

Once $f_{I_{ij}}$ is greater than the channel capacity, packet dropping will be unavoidable and the throughput of the interference set will degrade rapidly [15]. Due to the leveled architecture, the interference for a link mainly comes from other links at the same level. Given a link l_{ij}, those links $\rho \times d_{ij}$ away can be treated as interference links and included into the interference set. ρ depends on the propagation environment. For example, it should be different for outdoor and indoor deployment. In many works, ρ can be set to two

[1].

3.3. Problem Formulation

Given a candidate network $G(V, E)$ with m candidate nodes, g IGW nodes, n MC nodes, a MR placement scheme tries to determine a WMN $G'(V', E')$ with a minimum number of MRs that cover all MCs and relay all the traffic between IGWs and MCs, while every link, which has variable transmission rate and then variable link capacity attributed to different link length, works under its capacity. The problem can be formulated as follows:

$$\min(|V'|), \tag{6}$$

$$\sum_{j \in V'} \varpi_t^j \times w_t^j \times v_j = 1, \forall t \in V_{MC}, \tag{7}$$

$$\varepsilon_{ij} \le v_i, \varepsilon_{ij} \le v_j, \varepsilon_{ij} \le e_{ij}, \forall i, j \in V', \tag{8}$$

$$\sum_{j \in V'} (f_{ij}^t \times \varepsilon_{ij}) - f_t \times \varpi_t^i = 0, \forall i \in V', t \in V_{MC}, \tag{9}$$

$$\sum_{j \in V_{IGW}} f_{0j}^t = f_t, \forall t \in V_{MC}, \tag{10}$$

$$\sum_{t \in V_{MC}} f_{ij}^t + \sum_{l_{xy} \in I_{ij}} \sum_{t \in V_{MC}} (f_{xy}^t \times \varepsilon_{xy}) \le c_{ij}, \text{ and} \tag{11}$$

$$c_{ij} = F_\lambda(d_{ij}) \tag{12}$$

The objective is to minimize the number of MRs as defined by Equ. (6). Equ. (7) requires each MC be covered by one and only one MR. Equ. (8) states that the wireless link in V' is a valid edge in the candidate network. Equ. (9)-Equ. (12) are the capacity requirement. Equ. (9) ensures that the flow into a MR should equal to the flow out of a MR. Equ. (10) requires that all the traffic from any MC reach the single destination: the Internet. Equ. (11) limits that the overall traffic of an interference set should not exceed the shared channel capacity. Otherwise, shorter link should be considered to reduce the total load of a interference set. Equ. (12) indicates that the achievable link capacity that is approximated to transmission rate is determined by link length, which lower-bounds the transmission range of related MRs.

The above mixed integer programming model indicates that the multi-rate based MR placement problem is a combinatorial optimization problem including two hard sub-problems: multi-commodity flow problem and Steiner-forest problem. When the positions of MRs are known, the problem becomes a multi-commodity flow problem as defined by Equ. (9) and Equ. (10). If all the capacity constraints are relaxed, it is reduced to a Steiner-forest problem which is NP-hard problem [16]. Therefore, the multi-rate based MR placement is NP-hard as well. Due to practically unbearable time complexity of NP-hard problems as the network size increases, it is imperative to find out some efficient approximating approaches for deploying large scale WMNs.

4. Incremental Local Search (ILSearch)

In this section, we propose a heuristic algorithm called ILSearch to determine the MR placement for a given candidate network. The MRs are classified into two groups: MRs without any associated MCs are Relay MRs and the others are Coverage MRs. ILsearch consequently consists of two components: (1) Coverage MR determination and (2) Relay MR determination. Coverage MR determination is first used to determine a set of Coverage MRs to cover all MCs. However, some of Coverage MRs might not be able to connect to any IGW and thus are not able to forward MCs' traffic from/to the Internet. Relay MR determination is then used to incrementally search for a number of relay MRs to connect these isolated Coverage MRs to IGWs. Coverage MRs and Relay MRs together form a WMN backbone.

4.1. Coverage MR Determination

Each MC associates with one and only one Coverage MR in a WMN. Each Coverage MR, on the other hand, may not able to support all MCs within its transmission range. When this situation occurs, a Coverage MR has to choose to serve only a subset of these MCs. The rest clients have to be offloaded to the other Coverage MRs nearby.

The Coverage MR determination algorithm also consists of two steps. It first selects Coverage MRs to cover all the MCs in the network, and then groups these Coverage MRs into clusters. Each cluster is organized as trees, aggregating traffic towards a nearby IGW.

4.1.1. Selecting Coverage MRs.

1) Sort the candidate nodes that have not been selected as MRs by the number of uncovered MCs in its maximum transmission range.
2) Choose the candidate node, e.g. node i, which has the largest number of uncovered MCs in its range.
3) Compute the maximal achievable up-link capacity of node i, c_i^{up}.

$$c_i^{up} = MAX(c_{ij}) \;\; for\ all\ j \in V\ and\ h_j < h_i \tag{13}$$

4) Associate one MC (e.g., t) with i and then update i's up-link capacity to $c_i^{up} - f_t$. This process iterates until the remaining up-link capacity of i reaches zero or there is no uncovered MC left within i's transmission range.
5) Repeat from step 1) until all MCs are associated.

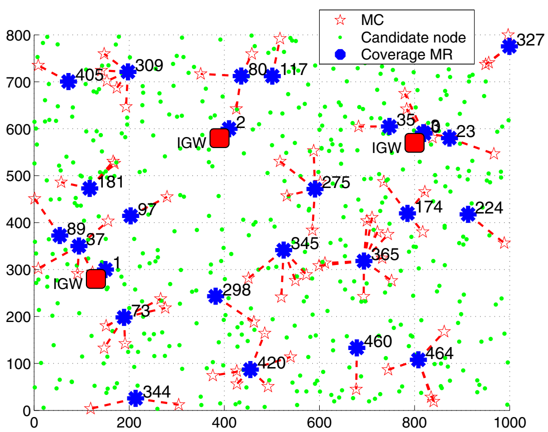

Figure 3: Selecting Coverage MRs

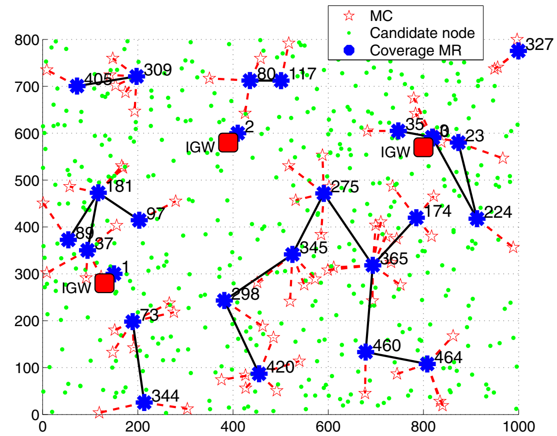

Figure 4: Initial Traffic Aggregation Trees

The time complexity of one iteration for the above algorithm is mostly decided by the step 1. Counting the number of uncovered MCs in each MR's range takes $O(mn)$, while sorting m candidate nodes is $O(m \log m)$. Therefore, the time complexity is $O(mn + m \log m)$ in step 1. The sorting process will iterate at most m time, when all the m candidate nodes are selected as the MR nodes. Therefore, the overall time complexity of is $O(mn + m^2 \log m)$.

We apply the above Coverage MR selection algorithm on a candidate network in which there are 500 candidate nodes and 70 MCs. The network setting will be detailed later in Section 5. Figure 3 illustrates the results — 23 Coverage MRs (blue stars) are selected to cover all these 70 MCs (red pentagrams). The dashed lines indicate the MC-MR association relationships.

4.1.2. Traffic Aggregation Tree. After Coverage MRs are selected, ILSearch will try to group these Coverage MRs into clusters. The MRs in a cluster are connected to each other via single/multi-hop wireless links. Each cluster is organized in a *tree* structure and a MR closer to an IGW will be selected as the root. The traffic is aggregated from the tree leaves to the tree root, and thus we call this tree as *traffic aggregation tree*. Note that this tree structure inherently allows each MR to use the shortest multi-hop path to communicate with the tree root so that it can reduce the total number of packet transmissions and therefore requires fewer MRs for traffic relay.

Let T_i denote a tree rooted at node i and the level of the tree h_{T_i} equal to the level of the root node i, i.e., $h_{T_i} = h_i$. Let f_{T_i} denote the total traffic load of T_i. It equals to the sum of the traffic from all the MCs associated with this tree. ILSearch uses the following algorithm to build traffic aggregation trees given Coverage MRs.

1) Initially, every Coverage MR node is a tree. ILSearch sorts the trees by tree level.
2) Starting from the source tree (e.g., T_i) with the highest level.
3) ILSearch searches for a neighboring node of i that is closest to the IGWs as the target node (e.g., j). The tree that j belongs to is called the target tree (e.g., T_x, rooted at the node x and $j \in T_x$).
4) The source tree T_i will join the target tree T_x by parenting node i with the target node j, if the following constraints can all be satisfied:
   a) $h_j < h_i$, j is closer to an IGW than i.
   b) $d_{ij} \le r_j^{down}$, the length of link l_{ij} should be less than j's downlink transmission range.
   c) $c_{ij} \ge f_{T_i}$, the achievable transmission rate of link l_{ij} can sustain the source tree's traffic load.
   d) $f_{I_{ij}} \le c_{ij}$, the interference level originated from link l_{ij}'s interference set is less than its link capacity.
   e) The remainder capacity of T_x is more than f_{T_i}. The remainder capacity is calculated by subtracting the current T_x's traffic load, f_{T_x}, from x's up-link capacity, c_x^{up}.
5) If any of the above constraints cannot be met, i deletes j from its neighbor list and jumps back to step 3).
6) Update the aggregate traffic of both the target node j and its ancestors in tree T_x, by adding f_{T_i}.
7) Repeat from step 2) until no two trees can be combined.

The above algorithm needs to traverse all Coverage MRs. Each time a MR node is selected, all its neighboring MRs have to be checked to see if tree combination can take place. Therefore, the time complexity of this traverse is $O(m^2)$.

Given the 23 Coverage MRs shown in Figure 3, we can see from Figure 4 that ILSearch is able to organize them into seven traffic aggregation trees. The nodes that are farther away from IGWs are grouped into trees rooted at nodes closer to the IGWs. For example, nodes 460, 464 are grouped

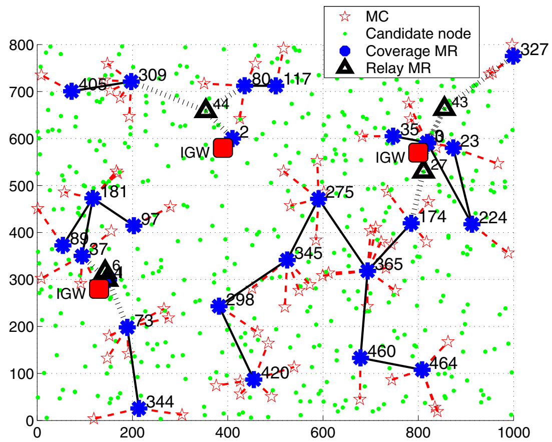

Figure 5: Relay MR Determination

into a tree rooted at node 174. Thus, instead of looking for Relay MRs for each MR, such as nodes $460, 464$, ILSearch only needs to determine Relay MRs for the tree root nodes such as node 174.

4.2. Relay MR Determination

As indicated by Figure 4 that not all traffic aggregation trees are connected to the IGWs, and therefore additional MRs have to be chosen to connect these isolated trees to the IGWs. The Relay MR determination component of ILSearch is designed to fulfil this connectivity requirement.

4.2.1. Selecting Relay MRs. ILSearch first sorts these trees by their levels (distance from IGWs). It then selects one additional MR to each of the trees, starting from the tree with highest level (i.e., farthest from IGWs), to connect the tree roots closer to the IGWs. A candidate Relay MR node (e.g. node j) is greedily chosen to maximally reduce a tree's (e.g. T_i) distance to the IGWs while satisfying all the following three network capacity constraints. Every time an additional MR is chosen, ILSearch checks to see if it is able to combine separate trees together. This process continues until all the trees are connected to IGWs directly, i.e., the levels of all the trees equal to 0.

- $f_{T_i} \le c_{ij}$, the achievable transmission rate of l_{ij} should be able to sustain the total traffic load of tree T_i. If $c_{ij} < f_{T_i}$, ILSearch needs to choose other candidate relaying nodes closer to the tree root node i so that the link l_{ij} is able to operate at an even higher rate.
- $f_{T_i} \le c_j^{up}$, the maximal achievable up-link capacity of node j should be greater than the total traffic of tree T_i. Otherwise, j is unable to relay all T_i's traffic to an IGW.
- $f_{I_{ij}} \le c_{ij}$, the overall interference level originated from l_{ij}'s interference set does not exceed the link capacity.

Finally, Figure 5 presents the final MR placement result for our example network. Five additional Relay MRs, represented by the black triangles, are chosen by ILSearch to connect all these trees to IGWs. For example, node 27 is selected to connect T_{174} with an IGW.

Algorithm 1 Relay MR Determination

Sort the trees by their level in descending order;
IsMoving = TRUE;
while IsMoving **do**
    IsMoving = FALSE;
    for each tree T_i rooted at i **do**
        If i is an IGW node or T_i has been combined, move to the next tree;
        for each neighbor candidate node of i **do**
            j = the node index of the candidate node;
            If $h_j > h_i$, search for the next candidate node;
            If $(c_{ij} = F_\lambda(d_{ij})) < f_{T_i}$, search for the next candidate node;
            If j has no uplinks whose capacity is larger than f_{T_i}, search for the next candidate node;
            If $(c_{ij} = F_\lambda(d_{ij})) < f_{I_{ij}}$, search for the next candidate node;
            Set j as the root and i's parent;
            IsMoving = TRUE;
            for each MR node that j is neighboring **do**
                k = the node index of the neighbor MR;
                x = the node index of the tree root that k belongs to;
                If $h_j < h_k$, $v_{Tgt} = j$, $v_{Src} = k$; otherwise, $v_{Tgt} = k$, $v_{Src} = j$;
                If $(r_{v_{obj}}^{down} < d_{ij})$, No combination;
                If $(c_{jk} = F_\lambda(d_{jk})) < f_{T_{Src}}$, No combination;
                If $(c_{jk} = F_\lambda(d_{jk})) < f_{I_{jk}}$, No combination;
                If the target tree doesn't have enough idle capacity, No combination;
                Set v_{Tgt} as the parent of v_{Src} and update the aggregated traffic load of the target tree;
            end for
        end for
    end for
end while

4.2.2. Traffic Aggregation Tree Maintenance. Once a relay MR j is determined for a tree T_i, j is set as the parent of i and the tree root becomes j. The newly selected relay node j could be neighbor node of MRs in other trees as well. These trees ought to be combined to further reduce the number of relay MRs. However, whether the tree combination could happens depends on if constraints a)-e) for tree combination listed in Section 4.1.2 are satisfied. For example, node 44 is directly connected to both node 80 which belongs to T_{80} and node 309 which is in T_{309} as shown in Figure 4. When node 44 is selected as a relay MR for T_{309}, it becomes the new root and also includes T_{80} into the tree after validating all the combination constraints. If any constraint is violated, the combination would not take place and other relay nodes are needed then to connect T_{80} with IGWs.

The procedure of selecting Relay MRs and maintaining trees continues until all trees are connected with IGWs. The more detailed information can be found in Algorithm 1. Similarly to the algorithm of creating the traffic aggregation trees, maintaining the trees also needs to traverse all the candidate nodes and their adjacent edges. As discussed earlier in Section 4.1.2, the time complexity is $O(m^2)$. Thus, the overall time complexity of our ILSearch algorithm is $O(mn + m^2 logm + 2m^2) \approx O(m^2 logm)$.

The final MR placement result for our example network is illustrated in Figure 5, in which a total of five Relay MRs and 23 coverage MRs are selected to cover all the 70 MCs in the network and deliver their traffic to/from the Internet.

4.3. Network Capacity Estimation

An important issue immediately following the MR placement scheme is how to estimate the network capacity of the resulted placement. Jun et.al [17] proposed a interference set based approach to estimate the WMN capacity. In brief, they choose the interference set with heaviest overall traffic load as the bottleneck collision domain of a WMN. Since MCs are assumed to share the network bandwidth equally in this work, the maximal capacity of each MC can get is $\frac{\text{Channel Capacity}}{MAX(f_{I_{ij}})}$. For example, $f_{I_{3-10}} = 17Mbps$ and $f_{I_{3-10}} = 16Mbps$ in Figure 2. Then the bottleneck collision domain is $f_{I_{3-10}}$. If the channel capacity is $10Mbps$, the maximal capacity available to each user is $10/17 = 0.59$.

The method for estimating network capacity in this paper is on the basis of the above proposed approach. In a WMN, traffic aggregates towards the IGWs. Therefore, the links in the first level, i.e. the links with one end at the IGWs, are most heavily loaded in comparison with other links in the network. These links need to relay the traffic of the entire network. According to the network model described in Section 3, only the links in the same level interfere each other. Thus, the interference sets made up with links in the first level have heaviest load in turn. Given g IGWs, there are g interference sets in the first level at least. We define the bottleneck interference set as the one with most overflowed traffic among these g interference sets. The network capacity c_{NW} is normalized as follows:

$$c_{NW} = \begin{cases} 1, \text{ If } f_{I_{ij}} < c_{ij} \text{ for } \forall j \in V_{IGW} \\ 1 - \frac{MAX(f_{I_{ij}} - c_{ij})^{\alpha}}{\sum_{t \in V_{MC}} f_t}, \end{cases} \tag{14}$$

If the overall traffic of every interference set in the first level is less than the corresponding wireless link capacity, the network capacity is one. Otherwise, some traffic will be dropped and the network capacity is below one. $MAX(f_{I_{ij}} - c_{ij})$ represents the overflowed traffic of the bottleneck interference set. Whenever the total traffic of a interference set exceeds the channel capacity, the overflowed part of traffic would be dropped. To be worse, the actual dropped traffic might be $(f_{I_{ij}} - c_{ij})^{\alpha}, \alpha \geq 1$, which could be far more than $f_{I_{ij}} - c_{ij}$ [15]. Then network capacity c_{NW} is normalized as the ratio between remaining part of traffic and the overall traffic of the network, i.e., $c_{NW} = 1 - \frac{MAX(f_{I_{ij}} - c_{ij})^{\alpha}}{\sum_{t \in V_{MC}} f_t}$. For example, in Figure 2, the bottleneck interference set is I_{3-10} and $f_{I_{3-10}} = 17Mbps$. If $c_{3-10} = 10Mbps$ and $\alpha = 1.2$, $(17-10)^{1.2} \approx 10Mbps$ traffic will be dropped. The overall traffic of the network is $17Mbps$. Thus, $c_{NW} = 1 - \frac{(17-10)^{1.2}}{17} = 0.41$

5. Evaluation

In this section, we study the effectiveness and performance of our proposed algorithm. The ILSearch algorithm presented in this paper is implemented by C++ and Matlab 6.5. Unless mentioned, we use the following settings in our simulation. The candidate network to be covered by a WMN backbone is a $1000m \times 800m$ rectangular region as shown in Figure 3. There are 497 candidate positions (nodes) (shown as green points in Figure 3), which are randomly generated and indexed from 1 to 497. The network has three pre-determined IGWs represented by red squares. 70 MCs are randomly generated as well (shown as pentagrams in Figure 3). The transmission power of MRs is identical and doesn't change dynamically. The data rates MRs could support are $\{6Mbps, 9Mbps, 18Mbps, 24Mbps, 48Mbps, 54Mbps\}$. The corresponding transmission ranges are $\{198m, 168m, 122m, 99m, 61m, 34m\}$ [5]. The transmission range between MCs and MRs are $100m$. Every MC generates a $512Kbps$ unit traffic averagely.

ILSearch determines 23 MRs to cover all MCs as shown in Figure 3. Figure 4 shows how these Coverage MRs are grouped into seven traffic aggregation trees. The solid lines illustrates how MRs are connected to form a tree. These links are validated by ILSearch so that they are within the valid transmission ranges to provide the required transmission rate and link capacity for the aggregated traffic. The largest tree, whose root is *Node 174*, consist of eight MR nodes while the smallest tree rooted at *Node 327* has one member-the root. Afterwards, Figure 5 demonstrates the final placement obtained by ILSearch. It chooses five Relay MRs to connect

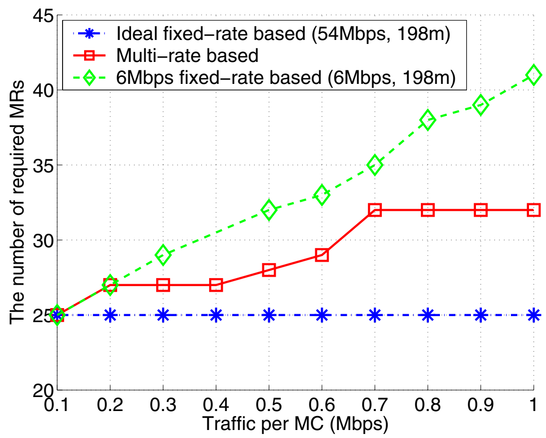

Figure 6: The number of required MRs when increasing MCs' traffic

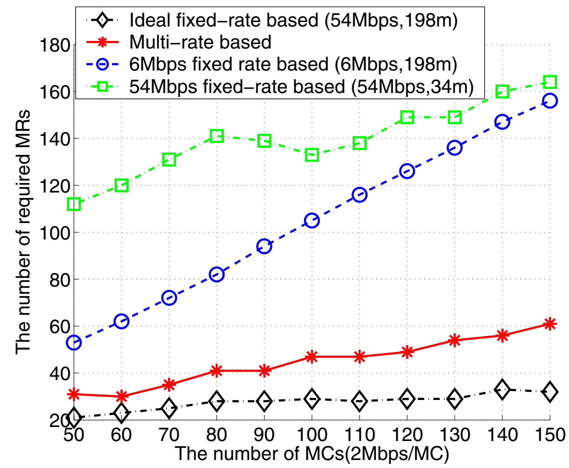

Figure 7: The number of required MRs when increasing the number of MCs

all these trees to the IGWs. The dotted lines shows the validated links that connect Relay MRs with trees.

When the unit traffic per MC increases, we expect to observe that ILSearch leads to more number of MRs. Figure 6 demonstrates this increment and compares it with another two placements: 6Mbps fixed-rate based placement where the common transmission range is $198m$ as specified in [5]; and ideal fixed-rate based placement where the common transmission range is $198m$ and link capacity is set as $54Mbps$, as assumed by many previous works. As the traffic from each MC increases from $0.1Mbps$ to $1Mbps$, the required MR number in the multi-rate based placement increases from 25 to 32. The MR number grows as well in 6Mbps fixed-rate based placement, but the incremental MRs in each round are more than that in the multi-rate one. In contrast, the ideal placement requires the least number of MRs and this number does not change as traffic load varies. This is because each link is assumed to have unrealistic $54Mbps$ capacity, which is enough to support variable traffic load when it grows from $0.1Mbps$ to $1Mbps$ per MC.

Furthermore, Figure 7 shows how the number of required MRs changes as the number of MCs varies. The results for the multi-rate based placement are compared with those for three fixed rate based placements, i.e., ideal, 6Mbps based, 54Mbps based (The corresponding transmission range is $34m$) respectively. In this part, each MC generates $2Mbps$ unit traffic. The newly added MCs in each round are randomly distributed in the network area. We can see the number of MRs in the multi-rate placement increases from 31 to 61 when the MCs grows from 50 to 150. In the 6Mbps fixed rate based placement, the number of the required MRs increases rapidly from 53 to 156. This is because few tree combinations could happen in this circumstance due to the small ratio between link capacity ($6Mbps$) and $2Mbps$ traffic per MC. Thereby, many Coverage MRs need some dedicated Relay MRs to transfer the traffic and these Relay MRs could not share the load from other coverage MRs. This causes the rapid MR increment as the number of MCs increases. Nonetheless, 6Mbps rate based solution needs less MRs than the 54Mbps fixed-rate based one, which needs far more MRs as compared to the multi-rate solution. In the 54Mbps fixed-rate based placement, the transmission range becomes the dominative factor when determining MRs. For example, two MRs that could be connected directly given long transmission range, e.g, $198m$, now need the help of six additional Relay MRs. Thus, it is not surprise that this kind of placement needs more MRs even when the traffic load is low. As before, the ideal placement leads to the least number of MRs in each round but the number is not static any more. This MR growth in the ideal placement is mainly because the newly added MCs in each round may appear in the areas that could not be covered by the Coverage MRs in the previous round and so more Coverage MRs are needed. If the MC distribution doesn't change, the number of final MRs in ideal fixed-rate based placement will not change even if the traffic load increases as shown in Figure 6.

The ideal placement needs less number of MRs than multi-rate based one, but at the expense of network capacity as shown in Figure 8. The method we use to estimate the network capacity is introduced in Section 4.3. The normalized capacity of a network c_{NW} is one if the traffic in the bottleneck interference set does not exceed the channel capacity. Otherwise, the network capacity is less than one and can be calculated by Equ.(5), i.e., $C_{NW} = 1 - \frac{MAX(f_{I_{ij}} - c_{ij})^{\alpha}}{\sum_{t \in V_{MC}} f_t}$. Here we set $\alpha = 1$ to get the upper-bound remaining traffic in the network, which means only overflowed traffic would be dropped. The actual dropped traffic could be far more than that when the overflow happens in a interference set and the network capacity could degrade more than what

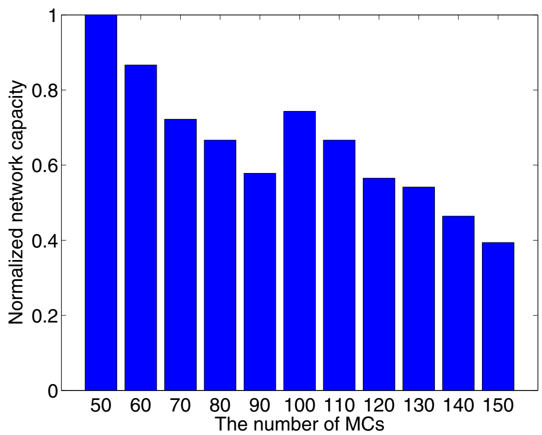

Figure 8: Capacity degradation for ideal fixed-rate based MR placement

is showed in Figure 8. Given the ideal placement obtained in the previous simulation, Figure 8 demonstrates that its network capacity declines as the number of MCs increases from 50 to 150. In the worst case, the network will drop 50 percent traffic due to unrecoverable confliction in the interfere set.

6. Conclusion

This paper investigates a NP-hard multi-rate based MR placement problem. We first model it after a mixed integer programming problem. We then propose a heuristic placement algorithm called ILSearch that takes into account both multi-rate feature and co-channel interference when placing MRs in the network. ILSearch consists of two main components: Coverage MR determination and Relay MR determination. The first is to determine a set of Coverage MRs by greedily exploiting the capability of each selected MR to cover all the MCs. The second is to find a set of Relay MRs to connect all Coverage MRs to the IGWs. Our simulation results have demonstrated that ILSearch is capable of finding a MR deployment solution, in which the MRs are placed only at permitted locations and provide enough bandwidth to meet the traffic demand in the network. We also show that our multi-rate based MR placement outperforms those fixed-rate counterparts in terms of smaller number of MRs and better network capacity.

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