WhiteMesh: Leveraging White Spaces in Multihop Wireless Topologies

TBA
Dinesh Rajan, and Joseph Camp

***Abstract*—Many efforts has been devoted to resolve the channel assignment problem for multi-channel multi-radio mesh network these years. The solutions of these works are approaching the optimization by local search algorithms and graph theory. In this paper, we propose a multiband multiradio wireless mesh networking architecture, where each mesh node has multiple radios working in a set of frequency bands with different propagation characteristics. A mixed integer linear model is presented for multiband multiradio network. To resolve this NP-Hard problem, we first present a novel parameter network efficience to describe the network performance and present two algorithms to approach the optimization. Our simulation results shows that these two algorithms can resolve the problem in polynomial time with good results. We also compare our solutions to multi-channel solutions FIXME. The results shows that our algorithms is more fitted for multiband channel assignment problem.**

I. Introduction

Wireless Mesh Network(WMN) is typically mentioned as a multihop wireless network onsisting of a large number of wireless nodes, some of which have wired connection as gateway nodes. Many researchers paid attention to the potential applications of WMN, including last-mile broadband Internet access, last-mile smart grid terminals, neighborhood gaming, and so on [1]. The bottleneck of the applications is that today's WMN still cannot offer enough capacity for customers. The maximum link-layer data rate falls quickly with increasing distance between the transmitter and receiver. The bandwidth problem is further aggravated for multi-hop scenarios because of interference from its neighbor links. Researchers have proposed several *Multi-Radio* solutions for the bandwidth problem with the permission of using non-overlapping frequency channels simultaneously [2]–[4]. However, these works only focus on increasing the bandwidth by reducing the interference in WMN. *White Space Bands* provide opportunities to improve the performance through both reducing interference and building long distance links.

White Space Bands is popularly referred to unused portions of the UHF and VHF spectrum includes, but not limited to 54M-72MHz,76M-88MHz,174M-216MHz,470M-608MHz,and 614M-806MHz [5]. *White Space Bands* have superior propagation and building penetration compared to licensed ISM bands Wifi are working in such as 2.4GHz and 5.8GHz. These characters make *White Space bands* holding rich potential benefits for expanding wireless capacity and improving access ranges for wireless clients. And since 2010, FCC adopted rules to allow unlicensed radio transmitters to operate in the white space bands freed from analog TV broadcast bands providing permission for operating wireless communication in *White Space Bands* [6].

The advantages of white space equipment could be seen straightly in *Wireless mesh network*. *White Space Bands* is able to link further nodes due to the lower frequency propagation characteristics. These links in white space bands bring data rate for the nodes far from the gateway nodes in less hops reducing the relay nodes. Obviously, these white space band long distance link is an economic way to provide back-haul Internet service in rare populated area. Also, as a kind of multi-radio architecture, *Multi-band Multi-radio Mesh Network* has the advantages of *Multi-Channel Mesh Network* who has more bandwidth to increase the network capacity. Benefits and challenges of *White Space Bands* are from these two characteristics in channel assignment.

Channel assignment is to build virtual links among different nodes according to their radios. A channel assignment has to keep several constraints, such as connection, radio amount limition, and so on. The problem is has been proved as a NP-Hard problem. [7]. Previous work in *Multi-Channel Multi-Radios* scenarios could be seen as partial solution of *Multi-band Multi-Radio* problem without considering the propagation difference of links in multiple bands. These works target on different objective with multiple methodology. Ashish [2] use *Load Aware Channel Assignment* to approach the channel assignment optimization in network capacity; Jian [3] employ a channel partition methodology to improve the interference of channel assignment; In [7], Kamal describe the up-bound and lower-band based on *Conflict Graph*.

In this paper, the focus is on the problem of channel assignment in static centralized multiband wireless mesh network scenario. In these networks, static nodes with multiple radio slots form a multihop backhual wireless access network that provides connectivity to end-users. The network nodes cooperate with each other to relay data traffic to gateway nodes who have wired connection. Our hypothesis includes we have the node locations, available bands, path loss exponent, and virtual carrier sensing, etc. Pearlman et. show that path load balancing provides negligible performance improvement, we limit each mesh node connect only one gateway nodes [8]. This work focus on the backhual layer, with the assumption the access layer is using different ISM channels from backhual layer. To get an approaching channel assignment, we propose a *Path Efficiency over Network* (PEN) to evaluate each link and path in the network. Based on this parameter, we develop 2 novel channel assignment heuristic algorithms for the *Multiband Multi-radio Wireless Mesh Network.* The first algorithm is a tree generated process to reduce hop count avoiding interference. The second algorithm starts from the furthest node then iteration improve the *Path Efficiency over Network* (PEN) to improve the channel assignment. To better understand channel assignment problem, we propose a linear optimization model to describe constraints of such a network with more detailed constraints. Though, this model is NP-Hard which could not be resolved in a polynomial time, it helps to understandstand the performance of a multi-band multi-radio wireless network.

The main contributions of our work are as follows:

- We formulate the heterogeneous *Multiband Multi-radio* architecture with channel assignment problem and propose a *Integer Linear Program* model for analyzing.
- We propose a parameter *Path Efficiency over Network* (PEN) to evaluate mixed *Multiband Multi-hop Path.*
- We develop 2 heuristic algorithms,1,2, to approach the channel assignment solution.
- We perform extensive simulation with maxinum throughput calculation to evaluate our algorithms.

The remainder of this paper is organized as follows. In Section II, we formulate the *Multiband Wireless Mesh Network* architecture, describe the *Channel Assignment* problem. We analyze multi-band multi-radio wireless mesh networks performance with variaty factors. In III we represent the *ILP* model and discuss its complexity. In Section IV discusses the mixed *Multiband Multi-hop Path*, based on the analysis, we propose two heuristic algorithms approaching the optimal channel assignment of a multiband network.

II. Problem Formulation

In this section, we describe the multi-band multi-radio wireless mesh network architecture, and formulate the key research issue channel assignment. We propose a linear program to understand the architecture and illustrate the challenges of the problem. Then we leverage the factors of the performance for multi-band wireless network.

A. Multiband Wireless Mesh Network Architecture

Wireless Mesh Network could be chopped as two-tiers: Access layer, consists of static traffic aggregation mesh nodes for clients, and backhual layer for interconnection from mesh nodes to gateway nodes with wired Internet connection [9]. *Multiband Wireless Mesh Network* is for backhual layer, since access layer always need ISM band channels providing access to client's Wifi devices, such as iPhone, laptops. To simply the analysis, we assume the backhual layer uses different channels in ISM band from access layer.

A lot of efforts have been put on the similar architecture *Multichannel Multi-radio Mesh Network* focusing on *Channel Assignment, Multihop Routing, Gateway Placement* problems [4]. In these works, *Multichannel* is a word mention multiple frequency channels have the same propagation performance with small frequency gap, for instance the orthogonal WLAN channels in 2.4GHz from 2.412GHz to 2.484GHz with 22MHz gap. We refer *Multiband* as a combination of different frequency of large gap whose propagation characteristics are different, such as a combination one channel in 2.4GHz and one channel in 900MHz.

Wireless propagation is the behavior of the signal loss characteristics when they are transmitting from one point to another. The factors rule radio propagation are complex and diverse, such as the daily changes of environment, weather, and

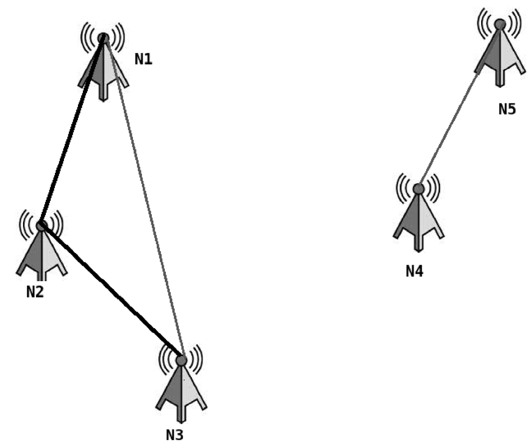

Fig. 1. Multiband Communication and Interference Range

atmosphere changes due to cosmos activities. In most propagation models there are three basic propagation mechanisms: reflection, diffraction, and scattering [10]. For multiband mesh backhual network, the nodes are usually installed on the top of buildings or towers. That makes a line of sight propagation model is a reasonable hypotheses for multiband mesh. In *Friis* propogation model, the received signal power of a node is represented as:

$$P_r = P_t + G_t + G_r + 20log_{10}(\frac{\lambda}{4\pi R}) \quad (1)$$

Path-loss exponent α is used to describe the environment factors, typically in outdoor environments range from 2 to 5. [11]. In 1, the received signal could vary only due to the wavelength λ represents band. This variation makes the performance of radios in multiple bands different even under the same configuration in the same location. Since the radios have the same received signal threshold, lower frequency band could have a larger communication range R, and also a larger interference range I_r.

The broadcast nature of the wireless medium makes it generate multiple access interference in wireless network. Employing *White Space Band* in lower frequency brings advantages for mesh network, 1) more orthogonal bandwidth reduce the contention and conflict in the network, 2) the propagation variation brings flexible topology by reducing connection hop counts in the network. However, at the same time, links in *White Space Band* also increase the interference range in the network making space reuse of the white space band channel difficult. In 1, node *N1* could connect to node *N3* through relay of node *N2* in higher frequency band, or directly connect by lower frequency band channel with larger communication range. If under higher frequency band, link between node *N4* and node *N5* could reuse the higher frequency since they are out of the interference range of this high frequency band; however, if *N1* and *N3* connected with lower frequency band in less hop counts, then *N4* and *N5* could not reuse these lower frequency channels due to the larger interference range. To balance the larger communication range and larger interference range of white space band is a key issue in *Multiband Mesh Network Channel Assignment* different from *Multichannel* scenario.

B. Model and Problem Formulation

Channel Assignment is to assign radios between nodes in mesh network creating virtual links for network communication with minimum interference. Our objective is to get a channel assignment for a wireless mesh network formed by a set of static mesh nodes and wired gateway nodes. Each node in the network is equipped with one or more radios could work in one of the permitted bands. We also assume all the nodes have the same configuration, each radio works under the same transmitting power, antenna with the same gains. To model the connectivity, we adopt classical *Protocol Model* from Gupta [12]. If the received signal is above the threshold, the link would have a communication capacity, otherwise, the link could not exist. In *Protocol Model*, the interference exist as conflict contention when the received signal strength of other links are above the threshold; otherwise, the link will not be interfered by other links.

The *Gateway Nodes* and *Mesh Nodes* locations are given. Other input information includes, transmitting power, antenna gains, communication and interference threshold. From *Friis Model*, we could get *Communication Range* and *Interference Range* of each link in different band. Multiband multi-radio wireless network could be modelled as an undirected graph $G = (V, E)$ according to the communication range and interference range. V is noted as the nodes, and E marked as the links in the network.

The channel assignment is represented as *Connectivity Graph*, $C = (V, L, B)$, L denotes the set of links, B denotes the set of frequency bands. The capacity between two nodes in common channel is noted as $C_{lb}, l \in L, b \in B$. If they are physically located within each others communication range of a band, the value of C_{lb} would be a constant value, otherwise, it is zero.

The associated interference range is larger than the communication range for each node. We extend the *Conflict Matrix* from Jain's work with a flexible approach for interference, $CG = (L_{i,j}, I_{Set}, B)$. $L_{i,j}$ represents the active link, I_{Set} includes all the links are physically inside the interference range,

Our model is similar to *Multichannel Model* in previous works [3], [4], [13]. However, in *Multichannel Model*, the *Communication Range* and *Interference Range* in different channels are the same. The *Multichannel Model* is unnecessary to consider the variation of range due to band propagation. *Multiband Channel Assignment* work toward the same target as *Multichannel Channel Assignment* to provide richer connectivity with minimum interference.

The difficulty of the problem is that we can not know the interference before we assign channel to each node. Previous works have proposed *Coloring, Cluster, Independent Set, Mixed Linear Integer* methodology to approach the solution of *Multichannel Channel Assignment* [3], [14], [15]. However, these work fails to distinguish the trading off between minimize hops and more frequency space reuse among multiple bands. Our work focus on the *traffic-independent* without explicitly considering network traffic/load [16]. To approach the optimization channel assignment, we develop a mixed linear integer model to understand the multiband scenario. We also analyze the intra-relation between the *Hop Counts* and *Space Reuse*, then propose two heuristic approaching for this problem.

C. Evaluation Metric

Mesh Network is designed to provide service for clients. The goal of a backhual network is to maximize its overall goodput within a unit time. This enables the network to support more end-user flows, and in turn more number of users. To evaluate the assignment, we use the idea of *Gateway Goodput* of the network. The gateway goodput X of a network is defined as

$$X = \sum_{g \in G, v \in V} C(g, v) \tag{2}$$

In [17], Robinson proves the bottle neck of mesh network capacity is the gateway wireless connection. The gateway goodput is the traffic arrive at the gateway node and relay to the wired Internet. The goodput performance is correlated with gateway placement, channel assignment and routing. The calculation of *Gateway Goodput* is described in **??** .Jointly optimization of channel assignment, gateway placement, and routing is out of the scope of this paper.

III. Mixed integer Linear Solution

First we present a *Mixed integer linear Program* formulation. A linear program combine both channel assignment and routing solution together. Previous work has shown even in a simplified *MultiChannel Model* a mixed integer linear program is NP-hard [16]. In this subsection we would like to formulate our channel assignment problem as an integer linear program and derive a upbound via its relaxation in running time, iteration improvement, or even omit the integrality requirement.

To keep the fairness constraint, we treat each mesh node with the same demand even generally the demand of the mesh node is random. So the goodput of a integer linear program is the summation of all the demand served by the gateway nodes. We assign a uplink demand variable λu and downlink demand λd to each node. The goodput of the network could be represented as $\sum_{n \in V}(\lambda u_n + \lambda d_n)$, the linear program is givin to $Maximize\ Goodput$.

We define a *Time Share* variable to represent the time division of a single link as $\alpha_{i,j}^{k}$ which is the time share for link $i- > j$ in band k. Two flow variables are defined as uplink and downlink flow on a link $i- > j$ for node k in band l, $uy_{i,j,k}^{l}, dy_{i,j,k}^{l}$.

The ILP is given as:

Sets:

N	set of nodes
B	set of bands

Parameters:

capacity of link (i,j) on band k

$r^k_{i,j}$ $\quad (i,j) \in N, k \in B$

Interference of link (i,j) on band k

$I^k_{ij,lm}$ $\quad (i,j,l,m) \in N, k \in B$

Gateway placement

g_i $\quad i \in N$ *binary*

Variables:

Time share of a link (i,j) on band k

α^k_{ij} $\quad k \in B, (i,j) \in N$

Uplink traffic of node i on (j,k) at band l

$uy^l_{i,j,k}$ $\quad (i,j,k) \in N, l \in B$

Dwonlink traffic of node i on (j,k) at band l

$dy^l_{i,j,k}$ $\quad (i,j,k) \in N, l \in B$

Objective:

$$\max \quad \sum_{i \in N} (\lambda u_i + \lambda d_i) \tag{3}$$

Constraints:

Variable-Type Constraints:

$$\alpha^k_{i,j} \leq 1 \tag{4}$$

$$uy^l_{i,j,k} \geq 0 \tag{5}$$

$$dy^l_{i,j,k} \geq 0 \tag{6}$$

Connectivity Constraints:

$$\sum_i \alpha^k_{i,j} + \sum_i \alpha^k_{j,i} + \sum_l \sum_m (\alpha^k_{l,m} \cdot I^k_{ij,lm}) \leq 1, i \neq j \tag{7}$$

$$\sum_i uy^l_{i,j,k} + \sum_i dyi,j,k^l \leq r^l_{j,k} \cdot \alpha^l_{j,k} \tag{8}$$

Uplink Constraints:

$$\sum_k \sum_l uy^l_{i,i,k} \geq \lambda u_i - J \cdot g_i \tag{9}$$

$$uy^l_{i,j,k} \leq J(1 - g_i) \tag{10}$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \leq g_i \cdot J, i \neq k \tag{11}$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \geq 0, i \neq k \tag{12}$$

$$uy^l_{i,j,i} = 0 \tag{13}$$

Downlink Constraints:

$$\sum_j \sum_l dy^l_{i,j,i} \geq \lambda d_i - J \cdot g_i \tag{14}$$

$$dy^l_{i,j,k} \leq J(1 - g_k) \tag{15}$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \geq -g_i \cdot J, i \neq k \tag{16}$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \leq 0, i \neq k \tag{17}$$

$$dy^l_{i,i,j} = 0 \tag{18}$$

J is a large value to distinguish different behavior of mesh node and gateway node, it could be any large value, such as 10^6 or even more. In implementation we will use the total link capacity of *Gateway* as J to reduce the computaion complexity.J is used to keep the constraints linear. We use two variables uy, dy represents uplink and downlink traffic flow in the model. In the ILP, 7 is to restrict all the links interference each other share time in a unit; 8 deal with the link capacity distributed by time share α; In 9,10, J is a large value helping distinguish different behavior of mesh node and gateway node, if the node is a mesh node, the sumation out-coming flows should be greater or equal the demand of node i, otherwise as a gateway node, it transfer data to wired Internet directly without out-going traffic flow for up-link traffic; 11 12 is to describe relay behavior of mesh nodes. If i is a mesh node, $g_i = 0$, the total in-coming traffic should equal to the total out-coming traffic, otherwise, when $g_i = 1$, traffic get into gateway node, in-coming traffic should be greater than out-coming traffic; 13 make sure no loop in the assignment, there is no traffic generated by node i will go back to node i; Constraints 14, 15, 16, 17, 18 restrict the downlink behavior of the network nodes similar to the uplink constraints, for mesh nodes, the in-coming flows should be greated or equal the demand of node i, a gateway node has no out-coming traffic for itself; As relay nodes, out-coming traffic for others equals in-comming traffic from others, gateway node will provide all the downlink traffic from it self, we use the same trick J to represent such constarints.

The model resolve *Channel Assignment* and *Routing* problem simultaneously. However the model itself is NP-hard could not get an optimization resuslt in polynomial time. But most of the solver has configuration to set the running time or iteration difference. It provides us a methodology to approach a reasonable results for channel assignment.

IV. Mixed Multiband Multihop Path and Solutions

In this section, we discuss the influence of *Multiband* on *Multihop Path* in mesh network. Accodirng to these analysis, we develop two algorithms for *Multiband Channel Assignment*.

A. Path Efficiency over Network

In *Multiband Multiradio Network*, a multihop path could have higher frequency band combination with less interference range or a set of lower frequency band with less hop count. A key issue of multihop path in such network is to answer which combination is better. We focus our work on *Channel Assignment* dealing with more interference factors rather than routing protocol which would be more concern on delay. Other architecture also has such problem such as wireless sensor network.

To discuss this problem, we pick up a multihop path from mesh network and analyze its performance with worst case hypothesis. In mesh network, such a path would have a bottle neck in the link closet to gateway. When a mesh network was built with gateway placement, constructor should considered load-aware demand of mesh nodes and mesh node population. Generally the nodes close to gateway should have more traffic demand and gateway itself should have the most connectivity population. We treat each node equally binding with fairness, otherwise mesh nodes close to gateway could be served more traffic and show a high goodput of the network. For analyze, we assume all the node in the path equally share the time of

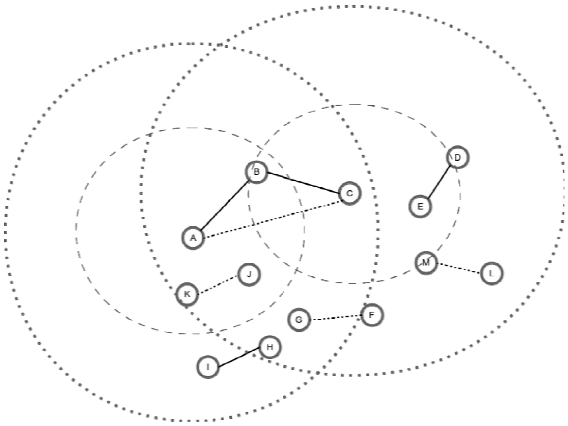

Fig. 2. Path Network Efficiency Introduction, Solid Wire notes 2.4GHz link, Dashed line notes 900MHz

a

the link next to a gateway. It is also the worst case for getting a larger goodput.

First, we introduce the *Intra-Path* traffic. When we have a multihop path, in worst case all the nodes on the path have only one h hop path arrived at a gateway node. The path is made of links from one node to another. Each node has traffic T, nomatter uplink or downlink since both of them occupy link capacity in the same way. And the total traffic on the path $\sum T$ is less than the bottle neck link capacity C.

We define the minimum transmission rate on a path as *Network Efficiency*. With the fairness restriction, the last node in the path has the minimum transmission rate. Then the acitve time in a time unit of each link can be represented as $1, \frac{h-1}{h}, \frac{h-2}{h} \cdots \frac{1}{h}$. The unit time of each link in the path is counted as total cost time of network.

Without considering *Inter-Path* interference which represent interference with links out of the path, an intuition of using lower band is to reduce the hop count to increase the minimum time utility rate which is the active time of the last link over the total active time of the path. However, at the same time, the interference range increase too. An example shown in 2, the picture shows links in different bands, let's say 2.4GHz and 900MHz, as a sketch map, does not represent the real distance. Node A, C could be connected through two 2.4GHz links or a single 900MHz link; with 2.4GHz links, only link D, E will be interferenced; however, with 900MHz A, C link, link $F, G; M, L; K, J$ will be interferenced.

To quantization this *Inter-Path Interference*, the unit time of these links are counted as *Network Time*. When a h hop path transmitting traffic T for the destination node, it stops activity on a number of links in the same band. In a multihop path, when the traffic arrived at the last destination node, all the previous links are serving for these traffic. The active time on a single link can be noted as $\frac{T}{c_h}$. We keep in the worst case when the last node in the path got traffic T, the other node also be served traffic T. With interference counts I_h from the conflict matrix: the *Network Time* counted as $\frac{hT}{c_1} \cdot I_1 + \frac{(h-1)T}{c_2} \cdot I_2 \cdots \frac{T}{c_h} \cdot I_h$, the *Path Efficiency over Network* is defined the traffic over the *Network Time* and could be represented as:

$$E_{PEN} = \frac{T}{\sum_{i \in h} \frac{(h-i+1) \cdot T}{c_i} \cdot I_i} \tag{19}$$

With protocol model, if link exist, then they have the same capacity $c_1 = c_2 \cdots = c_h = c$. To avoid 0 value in the denominator, we add a 1 to adjust the denominator which does not change the parameter characteristics. The *Path Efficiency over Network*could be represented as:

$$E_{PEN} = \frac{c}{1 + \sum_{i \in h} (h-i+1) \cdot I_i} \tag{20}$$

The meaning of the *Network Efficiency* is that in a unit time, the traffic could be loaded by this path. In multichannel scenario, all the channel will have the same communication range, this parameter equals to the conflic graph in many multichannel works which try to minimize the interference [7]. Since we count only one channel not all possible links, it also could be seen as an extention of a single link *Link Load* defined in [2].

The *Path Efficiency over Network* connect hop counts and interference. Then we discuss when a lower *White Space Band* is better to be used in a path. In a path, we use an average interference count $\bar{I}$ replace each interference count with assumption the links in the path all in one higher freq band. Then a *White Space Band* is used to replace two links in the path as a single link with interference count X represent one of the factor $i \cdot I_i$. The problem could be formulated as:

$$\frac{c}{1 + \frac{h(h-1)}{2} \cdot \bar{I} + X} \geq \frac{c}{1 + \frac{h(h+1)}{2} \cdot \bar{I}} \tag{21}$$

From the inequation, when $X \leq 2 \cdot h\bar{I}$ a lower band could be better. X is also a function of hop order in the path, generally the path order lower, the threshold would be more strict; otherwise it could be loose. It matches the intuition the hop order is small, it close to the gateway, it may interference more links so it needs a stricted constraint. It helps to tell the ranking of a set of links and a path where we can start to resolve channel assignment problem.

The previous discussion provide a way to evaluate different path. But the difficulty of channel assignment is that before the channel assignment has been done, we could not get a final conflict matrix, and we can not evaluate each path accurate. Since could not describe how the traffic flow will be assigned, we try to improve the $Minimum\ PathEfficiencyoverNetwork$ with at least one connection to the gateway for each mesh node. To approach the solution, we propose two local search based algorithms to adapt the multiband scenario.

B. Hop by Hop Tree Grow Algorithm

To improve efficiency of a path, one way is to reduce the hop count, another way is to reduce the conflict link counts. In a mesh network, gateway nodes always building in the most busy location [17], [18]. As the service tree rooted at a gateway grows, the links closer to the gateway, the more interference will happen. So a rule to reduce interference is to distribute the links to different channels. Typically a mesh network will be less populated near its edge, in these cases, reduce hop count through lower frequency may bring more benefit. Then a second rule will be use higher freq first at the beginning of the service tree growing. The degree in [18] is taken to evaluate the potential connectivity of a mesh node. The mesh node with less degree will be served first since they may not have other options for connection. [19] has similar process, but their work focus on multichannel scenario without considering topology difference among bands.

We develop the *Hop by Hop Tree Grow* algorithm as shown in 1.

Algorithm 1 Multiband Hop by Hop Tree Grow Algorithm

Input:
M: The set of all mesh nodes
G: The set of gateway nodes
C: Communication graph of potential links among all nodes
I: Interference matrix of all potential links
B: Bands amount
Output:
CA: Channel Assignment from Gateway nodes to Mesh nodes
Initial $S_{current} = G, N_{served} = \emptyset, N_{unserved} = M, I_{active} = \emptyset$
Generate 2 hop Adjacency Matrix A from C
for all $s \in S_{current}$ **do**
  Find one-hop nodes S_{Next}
  Sort S_Next with connection degree, small degree first
  for all $l \in S_{Next}$ **do**
    Calculate one-hop path efficiency from $s \rightarrow l$
    Sort each channel, high frequency first if have same PEN
    Assign(s,l) with the best channel to OC
    Update $N_{served}, N_{unserved}$
    Update I_{active} from I
  end for
  $S_{current} = S_{Next}$
end for
Initial $S_{current} = G, N_{served} = \emptyset, N_{unserved} = M, I_{active} = \emptyset$
Depth tranverse all gateway rooted tree, calculated child node amount as load weight $W_{i,l}$ for each node
for all $s \in S_{current}$ **do**
  Find one-hop nodes S_{Next}
  Sort S_Next with $W_i i, l$
  Calculate load degree $\sum_i W_{i,l}$ of S_{Next}, and the percent of each node in S_{Next}
  Let $N_{current}$ be the node with highest load weight
  Find all links from high load tree to low weight load tree as $TL_{potential}$, denote the nodes of the links in the high load tree as $N_{high\ load}$
  Find the shortest path to all the node of the substree from $N_{high\ load}$, calculate the average hop count $H_{average}$, calculate their average interference as $\bar{I}$
  Mark each link in $TL_{potential}$ with $H_{average}$, plus the hop from the node on the link in low load tree to current subtree root
  Calculate their PEN with the average $\bar{I}$
  Compare the PEN with the PEN adding a channel assignment, then choose the maximum PEN to connect the high load tree and the low load tree
  Iterate to the subtree and connect them.
end for
Find valid close(s,T)
Output $ChannelAssignment$ as Solution

The algorithm use the average $\bar{I}$ and average hop count to approach the channel assignment In [17], Robinson talked about the bottle neck of a network is the links neighbor to the gateway nodes.

C. Sink To End Path Algorithm

Based on the previous path efficiency analyze, the network efficiency is related to each link's interference and the distance to gateway nodes. To find a path for each mesh node, which could be converge to a shortest weight path detect We define weight for each link and improve Dijikstra's algorithm with *PEN* weight to find the best path for each mesh node [20]. To run Dijikstra's algorithm, we define two parameter of each link between two nodes. First is the existing interference of the link I_w, we mark the interference of bands as multiple links. The second is the *Load Weight* of a link l_w, which is the number of path chosen this link. In Dijikstra's algorithm, the weight is calculated as denominator of *PEN*, since the numerator is the same among different bands. This parameter used to adjust the *PEN* with bottle neck links. The weight of Dijikstra's algorithm is related to hop order h_i according to the definition of *PEN*, the weight is calculated as $I_w \times h_i \times l_w$. We iterately find the best path of each node and update the parameters in the graph.

Algorithm 2 Sink To End Path Algorithm

Input:
M: The set of all mesh nodes
G: The set of gateway nodes
C: Communication graph of potential links among all nodes
I: Interference matrix of all potential links
B: Bands amount
Output:
CA: Channel Assignment from Gateway nodes to Mesh nodes
while $notAllnodesVisited(M)$ **do**
  Intialize CA, I_w, l_w
  Run Dijistra's Algorithm with C, I, B to all the Gateways
  Compare the PEN to all Gateway node
  Choose the best one adding to CA
  Update I_w, l_w
  Calculate $\triangle cost$ for all valid operations
  Apply $swap$ with largest positive $\triangle cost$
end while
Output CA as locally optimal solution

V. Experimental Analysis

In this section we examing the performance of the multiband channel assignment algorithms with simulation in Matlab [21] and NS-3 simulator [22].

Network interference weight

$$F_c = \frac{1}{E_C} \sum I_c(e) \tag{22}$$

VI. Conclusion

In this paper, we investigated the multiband placement to leverage the propagation and FCC regulation for mesh network applications.

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