WhiteMesh: Leveraging White Spaces in Multihop Wireless Topologies

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***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 focusing on the optimization for multi-radios network have channels working in close frequency. In this paper, we propose a multiband multiradio wireless mesh networking architecture has multiple channels with large gaps in frequency. In such a mesh network, each mesh node is equipped multiple radios work in a set of frequency with different propagation characteristics. Though multi-band multi-radio bring benefit for mesh network, the channel assignment problem is an NP-hard problem.**

To resolve this problem, we first analyze the factors of the network and bring a novel parameter path efficiency over network to describe the network performance and present two algorithms according to the analysis to approach the optimized solution. Finally a performance study is carried out to access the effectiveness of our proposed algorithm. The results shows that these two algorithms can resolve the problem in polynomial time with better performance over Common Channel Assignment and Breath First Search Channel Assignment.

I. Introduction

Wireless Mesh Network(WMN) is typically mentioned as a multihop wireless network consisting 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 limitation, 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 Interference over Network* (PIN) 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 Interference over Network* (PIN) 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 understand 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 Interference over Network* (PIN) 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 maximum 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 variety factors. In **??** we represent the *ILP* model and discuss its complexity. In Section III 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 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* propagation model, the received signal power of a node is represented as:

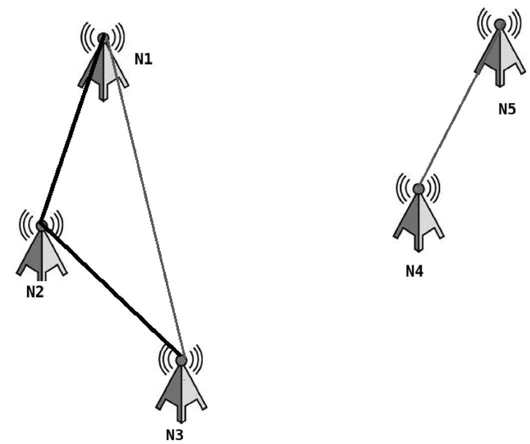

Fig. 1. Multiband Communication and Interference Range

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

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 formulated 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 many 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 good put 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 Good put* of the network. The gateway good put 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 good put is the traffic arrive at the gateway node and relay to the wired Internet. The good put performance is correlated with gateway placement, channel assignment and routing. The calculation of *Gateway Good put* is described in **??** .Jointly optimization of channel assignment, gateway placement, and routing is out of the scope of this paper.

D. Mixed Integer Linear Formulation

We now present a *Mixed Integer Linear Program* formulation for the *Multiband Multi-Radio* fixed wireless mesh network described in II.

Assume that we are given the nodes and available bands as the variable set. The communication links and conflict graph are given as parameters.

N set of nodes
B set of bands
Parameters:

$r^k_{i,j}$	$(i,j) \in N, k \in B$	capacity of link i, j on band k
$I^k_{ij,lm}$	$(i,j,l,m) \in N, k \in B$	Interference of link (i,j) on band
g_i	$i \in N$ *binary*	Gateway placement
$uy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	UL of node i on (j,k) at band l
$dy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	DL of node i on (j,k) at band l

In order to the link constraints, we define a *Time Share* variable to represent the time division of a single link as $\alpha^k_{i,j}$ which is the time share for link $i->j$ in band k. Two flow variables are defined as up-link and down-link flow on a link $i->j$ for node k in band l, $uy^l_{i,j,k}, dy^l_{i,j,k}$.

Variables:	α^k_{ij}	$k \in B, (i,j) \in N$	Time share of (i,j) on band k
	λ_i	$i \in N$	Satisfied demand of node i

The constraints is given as:

Constraints:

Variable-Type Constraints:

$$\alpha^k_{i,j} \leq 1 \tag{3}$$

$$uy^l_{i,j,k} \geq 0 \tag{4}$$

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

Connectivity Constraints:

$$\sum_i \alpha^k_{i,j} + \sum_i \alpha^k_{j,i} + \sum_l \sum_m (\alpha^k_{l,m} \cdot I^k_{ij,lm}) \leq 1, i \neq j \tag{6}$$

$$\sum_i uy^l_{i,j,k} + \sum_i dyi,j,k^l \leq r^l_{j,k} \cdot \alpha^l_{j,k} \tag{7}$$

Uplink Constraints:

$$\sum_k \sum_l uy^l_{i,i,k} \geq \lambda u_i - J \cdot g_i \tag{8}$$

$$uy^l_{i,j,k} \leq J(1 - g_i) \tag{9}$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \leq g_i \cdot J, i \neq k \tag{10}$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \geq 0, i \neq k \tag{11}$$

$$uy^l_{i,j,i} = 0 \tag{12}$$

Downlink Constraints:

$$\sum_j \sum_l dy^l_{i,j,i} \geq \lambda d_i - J \cdot g_i \tag{13}$$

$$dy^l_{i,j,k} \leq J(1 - g_k) \tag{14}$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \geq -g_i \cdot J, i \neq k \tag{15}$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \leq 0, i \neq k \tag{16}$$

$$dy^l_{i,i,j} = 0 \tag{17}$$

In these constraints, J is a large value to represent different behavior of mesh node and gateway node in linear. In implementation we will use the total link capacity of *Gateway* as J to reduce the computation complexity. In the ILP, 6 is to restrict the link conflict constraint; 7 represent the link capacity distributed by time share α; 10 11 is to describe relay behavior of the network. If node i is a mesh, then $g_i = 0$, the total in-coming traffic should equal to the total out-coming traffic; otherwise node i is a gateway, when $g_i = 1$, traffic get into gateway node, in-coming traffic should be greater than out-coming traffic; 12 make sure no loop in the assignment, there is no traffic generated by node i will go back to node i; 15, 16, 17 make gateway node provide all the down-link traffic from itself.The in-coming traffic equals to the out-coming traffic for relay traffic on mesh nodes. The constraints above are need to be satisfied, otherwise the channel assignment could not be scheduled.

Other constraints could be modified according to different objectives. When the objective is to find the maximum throughput with fairness, $Max \sum(\lambda u_i + \lambda d_i), \lambda u_i = \lambda u_j, \lambda d_i = \lambda d_j, i \neq j$, constraints 8,9 could be represented as above. If the node is a mesh, the summation out-coming flows should be greater or equal to the demand of node i, otherwise as a gateway, it transfers data to wired Internet directly without out-going traffic flow for up-link traffic; Constraints 13, 14, restrict the down-link behavior of the network nodes similar to the up-link constraints. For mesh nodes, the in-coming flows should be greater or equal than the demand of node i, a gateway node has no out-coming traffic for itself.

Similar linear program has been proved as NP-hard problem [3], [13]. The model itself provide a way to understand the factors need to be considered in channel assignment and provide methodology to achieve the throughput upper bound of a channel assignment. When we have the channel assignment $A^k_{i,j}$, we could modify the objective function, the parameters and the constraints to find the maximum satisfied demand in the network. More details will be discussed in IV

III. Mixed Multiband Path Analysis

In this section, we discuss the influence of *Multiband* on *Multihop Path* in mesh network. According to these analysis, we develop two algorithms for *Channel Assignment* in multi-band multi-radio scenario.

A. Path Interference over Network

A link is a wireless channel from one node to another. A path is a combination of links to connect two nodes far away from each other. In *Multiband Multiradio Network*, a multihop path could be mixed with higher frequency links have less interference range and lower frequency links have less hop count. That's the significant difference from *Multi-Channel Multi-Radio* since the multi-channel in the same band will have the same communication range and interference range. A key issue of multihop path in multi-band network is to answer which combination is better.

To discuss this problem, we pick up a multihop path from wireless mesh network and analyze its performance with worst case satisfied throughput hypothesis. In wireless mesh network, such a path would have a bottleneck in the link closest to gateway. Generally the nodes close to gateway should have more traffic demand in gateway placement process and a gateway itself should have the most connectivity population. We assume each node equally binding with the same demand. Under this assumption, all the node in the path equally share the time of the common links. First, we introduce the *Intra-Path* traffic. In a spanning tree, the mesh nodes on the path have only one h hop path arrived at a gateway node. The links in a path are in different bands could work simultaneous or normalized links in the same band but share the time equally. Each node has traffic T, no matter uplink or downlink since both of them occupy link capacity with no difference. 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 benefit from using lower band is to reduce the hop count to

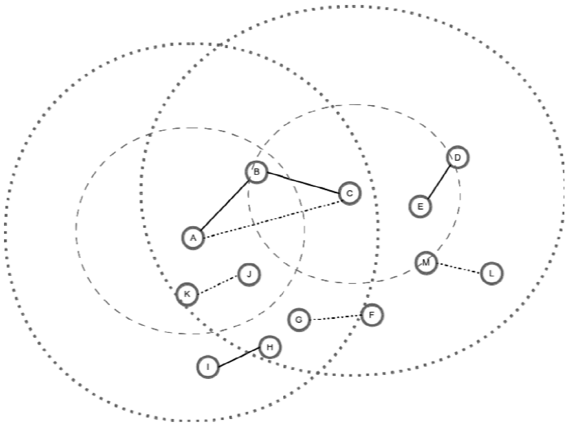

Fig. 2. Path Efficiency Introduction, Solid Wire notes 2.4GHz link, Dashed line notes 900MHz

a

increase the minimum time utility rate which is the active time of the last link over the total active time of the path. Furthermore, as hop count goes up, the interference range increase too. An example shown in Fig. 2, the picture shows links in different bands. The links are in 2.4GHz and 900MHz. As a sketch map, the link in the figure 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 each link is counted as a unit time of *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 $\frac{T}{c_h}$. With interference counts I_h from the conflict matrix: the *Network Time* counted as $\frac{hT}{c_1} \cdot I_1 + \frac{(h-1)T}{c_2} \cdot I_2 \cdots \frac{T}{c_h} \cdot I_h$, then the *Path Efficiency over Network* is defined the traffic of the node over the *Network Time* and could be represented as:

$$E_{PEN} = \frac{T}{\sum_{i \in h} \frac{(h-i+1) \cdot T}{c_i} \cdot I_i} \tag{18}$$

With protocol model, if link exist, then they have the same capacity $c_1 = c_2 \cdots = c_h = c$. The *Path Efficiency over Network*could be represented as:

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

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 links 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. The denominator is defined as the *Path Interference* (PIN) which is the summation of interference links amount in the network. Then we are going to answer 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:

$$\frac{c}{\frac{h(h-1)}{2} \cdot \bar{I} + X} \geq \frac{c}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{20}$$

From the inequation 20, when $X \leq 2 \cdot h\bar{I}$ a lower band link could be better than 2 high frequency links. X is also a function of hop order in 19, generally the path order lower, the threshold would be more stricter. 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.

According to these analysis, to improve the performance of a channel assignment in multi-band multi-radio scenario has two ways. First is to reduce the hop count, second is to reduce the interference among links. And at the same time, we have to trade off between the hop count reduction and single link interference which does not happen in multi-channel multi-radio scenario.

The discussion in r̃efsubsec:PEN provide the methodology to improve channel assignment. But the difficulty of channel assignment is that before the process has been done, it could no be evaluated to tell which is better. To approach the solution, we propose two local search based heuristic algorithms to adapt the multiband scenario.

B. Growing Spanning Tree Algorithm

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. And in the edge of the network, it is less populated in which cases reduce hop count through lower frequency may bring more benefit. The main idea behind the *Growing Spanning Tree* Algorithm is to find the link has least interference on the network for each node in a greedy manner each step. The hop count for gateway nodes themselves are 0. We first initialize the mesh nodes ranking with the distance to all the gateway nodes. In the ranking order of the mesh nodes, the 1 hop links from gateway nodes ranking with the *Path Interference*. Then select the lowest interfered link for this node and update the assignment information for next steps. Iterate these steps to assign channels for all mesh nodes. This process is phase 1 of our algorithm which is similar to but not exactly the same as the breath first search channel assignment.

In phase 2 of the algorithm, we sort the mesh nodes with their hop count to gateway nodes. The algorithm traverses all the nodes whose hop count are less than the current node. If there are radio slots for the less hop nodes, it is possible to re-connect the mesh node to reduce the hop count. We rank all possible option with their path interference, then choose the lowest one re-connect the mesh node. If there exist new link has the same path interference, we count the number of nodes has connected to the gateway nodes, select the gateway has less node connected. Phase 2 process will be iterated till no changes in the network.

The *Growing Spanning Tree* Algorithm is described in 1.

Algorithm 1 Multiband Growing Spanning Tree 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: Available frequency bands
Output:
CA: Channel Assignment of the Network
Initial $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
Rank mesh nodes according to their distance to gateway nodes
while $N_{served} = !M$ **do**
  for all $s \in S_{current}$ **do**
    Find one-hop nodes in S_{Next}
    Sort S_Next according to distance from gateway nodes, shorter distance first
    for all $l \in S_{Next}$ **do**
      Calculate one-hop path interference of link $s \rightarrow l$
      Sort the links, choose the one has the least path interference
      Assign(s,l) with the least interference link
      Update $N_{served}, N_{unserved}$
      Update I_{active} from I
    end for
    $S_{current} = S_{Next}$
  end for
end while
Sort mesh nodes with their hop counts to gateway nodes N_{sorted}
while Change of Channel Assignment Exist **do**
  for all $s \in N_{sorted}$ **do**
    Traverse all the 1 hop arrived nodes have less hop count than node s
    Check if these nodes have radio slots for node s
    Sort path through possible nodes with the path interference
    Choose a new path if it has less interference than the previous one
    If more than one path has the same interference, choose the gateway node has least leaves nodes
  end for
end while
Output $ChannelAssignment$ as Solution

The *Growing Spanning Tree* Algorithm greedy assign a single link to the network and balance the gateway load in the adjust process. The BFS complexity is $O(n^2)$, sorting of nodes is $O(nlogn)$. Hence assigning a node takes $O(n^2)$ time. Thus the complexity of the assignment is $O(n^3)$.

C. Best Path Selection Algorithm

The *Growing Spanning Tree* Algorithm starts from the gateway nodes to generate the channel assignment, in contrast, *Best Path Selection* Algorithm starts from the mesh node who has the largest distance from the gateway nodes. When a path is select for such a node, the relay node on the path is served. The main idea behind the *Best Path Selection* Algorithm is to improve the worst path in the network.

The algorithm first sort the mesh nodes in order of their distance to any gateway nodes. Then we select the mesh node has the furthest distance to gateway nodes. In the network, it is impossible traverse all the path with different combination of bands from a mesh node to any gateway nodes. Based on the analysis in III-A, if paths has the same bands combinations, a shortest path most of the time could have the best performance. In the same path under a bands combination, we will choose the link in a channel has the least interference. In case two path has the same path interference, we choose the path who has more high frequency links for spacing re-use. Thus, the next step of the algorithm is to find the shortest path in different bands combinations. Comparing to the number of mesh nodes, the amount of channels b in different bands is small. The time complexity of calculation the combination is $O(2^b)$. The second path of finding the shortest path in Dijkstra algorithm will cost $O(E^2)$ [19], E is the links in the network. So the total would be $O(E^2 \cdot 2^b)$. Then the algorithm calculate the *Path Interference* of the candidate path and select the path will bring the least interference to the network for the starting mesh node.

After a path is assigned, the algorithm update the network assignment with served nodes, activated links, and nodes' radio information. Then we assign the next node till all the mesh nodes are connected in the network.

The *Best Path Selection* Algorithm is described in 2.

Algorithm 2 Best Path Selection 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: Available frequency bands
Output:
CA: Channel Assignment of the Network
Rank mesh nodes according to their distance to gateway nodes
Initial $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
while $N_{served} = !M$ **do**
  Select the node has the largest distance to gateway nodes
  Find the Adjacency Matrix in different bands combinations A_c
  for all $A_i \in A_c$ **do**
    Find the shortest path SP_i in the mixed adjacency matrix A
    for all Link $l \in SP_i$ in order from Gateway node to mesh node **do**
      Find the link has less interference
      If there are links have the same interference, choose high frequency
      Calculate the path interference of path SP_i
    end for
    Store the shortest path SP_i in as SP
  end for
  Assign the path in the Network
  Update $N_{served}, N_{unserved}$
  Update I_{active} from I
end while
Output CA as locally optimal solution

The complexity of the assign a node would be $O(E^2 \cdot 2^b)$, which could be marked as $O(n^2 \cdot 2^b)$, n is the mesh node number. To assign all the node in the network, the complexity would be $O(n^3 \cdot 2^b)$.

IV. Experimental Analysis

We performed a set of simulations to evaluate the performance of the heuristic algorithms. The results are illustrated in the next subsections with different metrics.

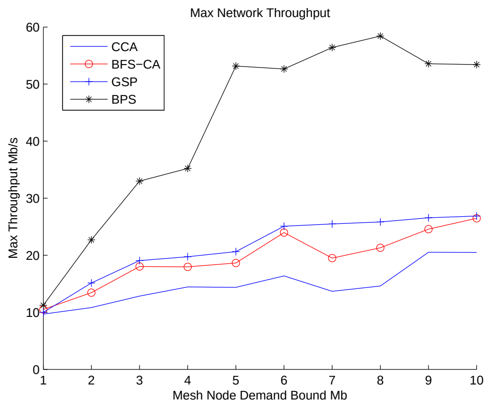

Fig. 3. Max Tpt under Demand Bound

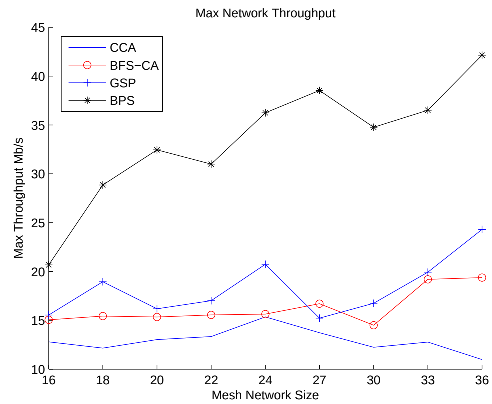

Fig. 4. Max Tpt of Network Size

A. Max Network Throughput

The capacity of a network binds with multiple factors, such as gateway placement, routing and also channel assignment. Stefano bring the good put in the network without considering the interference as maximum throughput to evaluate the channel assignment [20]. However, without considering the interference, the traffic flow in the network is not scheduled. And to find the best routing associate with channel assignment is out of our scope. We would like to calculate the max network capacity as follow.

In a mesh network, the bottleneck of the network are the links around the gateway nodes [21]. And any packet transmitted to the wired gateway node is the same. So the best way to get a scheduler maximum throughput is to serve the nodes close to the gateway nodes. Thus to employ more capacity of the gateway neighbor links, we would like to serve the nodes close to the gateway nodes. We first serve the node has 1 hop path to the gateway nodes, then choose the path has the least interference on the network and serve the demand as more as possible. Then we satisfy the demand of 2 hop layer nodes and so on, till there is no demand could be satisfied. This calculation process is kind of routing protocol which help us to reach a scrollable maximum throughput of the network.

We randomly assign demand of mesh nodes with an upper bound, calculate the scalable maximum throughput, and repeat the process 20 times, then output the average maximum throughput for this demand upper bound. The performance of the two heuristic algorithms and *CCA* [22], *BFSCA* [23] in a 30-node regular grid topology with 6MB link capacity are shown in figure 3.

To evaluate the performance in different size of network, we assign the demand of each node $5MB/s$ as demand upper bound, and vary the number of nodes in the regular grid network. The performance of the algorithms are shown in 4.

B. Min Conflict Weight

Conflict Weight is the amount of links interfered by a single link [24].

V. Related Work

A number of papers have been published on the problem of channel assignment for a multi-hop mesh network. [2], [7], [9]. However, none of them is adaptive to the propagation difference in the wireless mesh network. Prior research could be classified as *Static Channel Assignment* and *Dynamic Channel Assignment*. The *Static Channel Assignment* focus on assigning a network once with everything known of the network [25]. The *Dynamic Channel Assignment* is to resolve the channel assignment according to dynamic parameters, such as demand, dynamic interference [23], [26].

A simple approach *Common Channel Assignment* (CCA) for utilizing multi-radios network is presented in [22], though the main purpose of the author is to have multi-raidos working for routing to benefit from multi-channel structure. Further investigations include [16] and i [2] show that it is possible to improve the performance of multi-channel network by applying smart channel assignment algorithms.

Assuming the knowledge of the set of connection request to be routed, both an optimal algorithm based on solving a Linear Programming an a simple heuristic are proposed to route such requests given the link bandwidth availability determined by the computed channel assignment in [3]. These formulation are NP-hard problems, the authors solve the LP relaxation of the problem. The output is a network flow along with a possibly unfeasible channel assignment.

Distributed channel assignment and routing algorithms are developed based on game theory [27], [28].Nodes advertise their cost to reach the gateway they are currently associated with. Cost dynamically changes as it depends on residual bandwidth to achieve load balancing. If a node is notified of a less cost path towards another gateway, it starts a procedure to associate with that gateway. If the cost of a path is less than current occupacied path, the node starts evaluate wheather to associate the new path. Since cost is dynamic, the strategy may leadd to route flaps and to a non convergent network behavior. Thus the equilibrium need to be carefully designed.

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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