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 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* (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 Interference 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 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* (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 **??** 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* propogation model, the received signal power of a node is represented as:

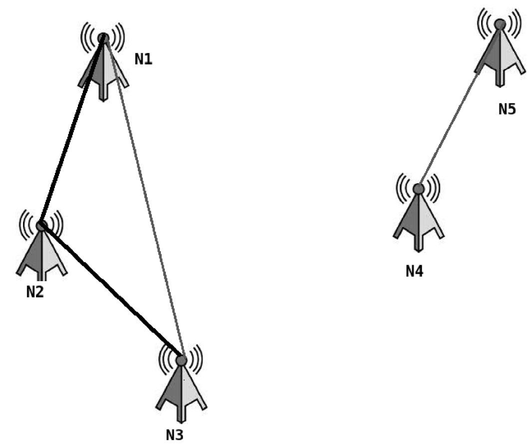

Fig. 1. Multiband Communication and Interference Range

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

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 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 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.

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 asparameters.

N	set of nodes
B	set of bands

Parameters:

$r_{i,j}^k$	$(i,j) \in N, k \in B$	capacity of link i,j on band k
$I_{ij,lm}^k$	$(i,j,l,m) \in N, k \in B$	Interference of link (i,j) on band
g_i	$i \in N$ $binary$	Gateway placement
$uy_{i,j,k}^l$	$(i,j,k) \in N, l \in B$	UL of node i on (j,k) at band l
$dy_{i,j,k}^l$	$(i,j,k) \in N, l \in B$	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 $\alpha_{i,j}^k$ 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, $uy_{i,j,k}^l, dy_{i,j,k}^l$.

Variables:	α_{ij}^k	$k \in B, (i,j) \in N$	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:

$$\alpha_{i,j}^{k} \leq 1 \tag{3}$$

$$uy_{i,j,k}^{l} \geq 0 \tag{4}$$

$$dy_{i,j,k}^{l} \geq 0 \tag{5}$$

Connectivity Constraints:

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

$$\sum_i uy_{i,j,k}^{l} + \sum_i dyi,j,k^{l} \leq r_{j,k}^{l} \cdot \alpha_{j,k}^{l} \tag{7}$$

Uplink Constraints:

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

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

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

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

$$uy_{i,j,i}^{l} = 0 \tag{12}$$

Downlink Constraints:

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

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

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

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

$$dy_{i,i,j}^{l} = 0 \tag{17}$$

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 computaion 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 downlink 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 sumation 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 downlink behavior of the network nodes similar to the uplink constraints. For mesh nodes, the in-coming flows should be greated 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 $A_{i,j}^{k}$, we could modify the objective function, the parameters and the constraints to find the maximum satisfied demand in the network. More details will be disscussed in IV

III. Mixed Multiband Path Analysis

In this section, we discuss the influence of *Multiband* on *Multihop Path* in mesh network. Accodirng 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

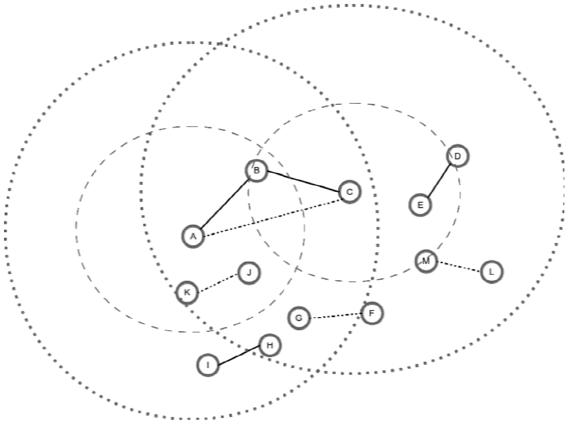

Fig. 2. Path Efficiency Introduction, Solid Wire notes 2.4GHz link, Dashed line notes 900MHz

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. 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 interferred 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 interated till no changes in the network.

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 = ∅, N_unserved = M, I_active = ∅
Rank mesh nodes according to their distance to gateway nodes
while N_served = M do
  for all s ∈ 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 ∈ S_Next do
      Calculate one-hop path interference of link s → 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 ∈ N_sorted do
    Tranverse 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 is described in 1. 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. Best Path Selection 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 [19]. 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 △cost for all valid operations
  Apply swap with largest positive △cost
end while
Output CA as locally optimal solution
```

IV. Experimental Analysis

In this section we examing the performance of the multiband channel assignment algorithms with simulation in Matlab [20] and NS-3 simulator [21].

Network interference weight

$$F_c = \frac{1}{E_C} \sum I_c(e) \tag{21}$$

V. Conclusion

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

References

[1] P. Bahl, "Opportunities and challenges of community mesh networking," in *Keynote Presentation@ MICS Workshop in ETH Zurich*, 2004.

[2] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.

[3] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and qos routing in multi-channel wireless mesh networks," in *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2005, pp. 68–77.

[4] W. Si, S. Selvakennedy, and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 70, no. 5, pp. 505–524, 2010.

[5] Wiki, "White space(radio)," http://en.wikipedia.org/wiki/White_spaces, 2013.

[6] FCC, "White space," http://www.fcc.gov/topic/white-space, 2012.

[7] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Wireless networks*, vol. 11, no. 4, pp. 471–487, 2005.

[8] M. R. Pearlman, Z. J. Haas, P. Sholander, and S. S. Tabrizi, "On the impact of alternate path routing for load balancing in mobile ad hoc networks," in *Mobile and Ad Hoc Networking and Computing, 2000. MobiHOC. 2000 First Annual Workshop on*. IEEE, 2000, pp. 3–10.

[9] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer networks*, vol. 47, no. 4, pp. 445–487, 2005.

[10] J. B. Andersen, T. S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *Communications Magazine, IEEE*, vol. 33, no. 1, pp. 42–49, 1995.

[11] J. Camp, J. Robinson, C. Steger, and E. Knightly, “Measurement driven deployment of a two-tier urban mesh access network,” in *Proceedings of the 4th international conference on Mobile systems, applications and services*. ACM, 2006, pp. 96–109.
[12] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *Information Theory, IEEE Transactions on*, vol. 46, no. 2, pp. 388–404, 2000.
[13] J. Yuan, Z. Li, W. Yu, and B. Li, “A cross-layer optimization framework for multihop multicast in wireless mesh networks,” *Selected Areas in Communications, IEEE Journal on*, vol. 24, no. 11, pp. 2092–2103, 2006.
[14] A. Mishra, S. Banerjee, and W. Arbaugh, “Weighted coloring based channel assignment for wlans,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 3, pp. 19–31, 2005.
[15] Y. Peng, Y. Yu, L. Guo, D. Jiang, and Q. Gai, “An efficient joint channel assignment and qos routing protocol for ieee 802.11 multi-radio multi-channel wireless mesh networks,” *Journal of Network and Computer Applications*, 2012.
[16] M. K. Marina, S. R. Das, and A. P. Subramanian, “A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks,” *Computer Networks*, vol. 54, no. 2, pp. 241–256, 2010.
[17] J. Robinson, M. Uysal, R. Swaminathan, and E. Knightly, “Adding capacity points to a wireless mesh network using local search,” in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*. IEEE, 2008, pp. 1247–1255.
[18] B. He, B. Xie, and D. P. Agrawal, “Optimizing deployment of internet gateway in wireless mesh networks,” *Computer Communications*, vol. 31, no. 7, pp. 1259–1275, 2008.
[19] B. Golden, “Shortest-path algorithms: A comparison,” *Operations Research*, pp. 1164–1168, 1976.
[20] MATLAB, *Matlab R2012b*. Natick, Massachusetts: The MathWorks Inc., 2012.
[21] NS-3, *NS-3 Version:3.18.1*. NS-3 Community, 2012.