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

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 [1]. FCC adopted rules to allow unlicensed radio transmitters to operate in the white space freed from TV band since 2010 [2]. These bands provides superior propagation and building penetration compared to licensed ISM Wifi bands like the 2.4 and 5GHz bands, holding rich potential for expanding broadband capacity and improving access for wireless users. The advantages of white space equipment could be seen straight forward from using in *Wireless mesh network*. Wireless mesh network is able to provide broadband Internet access to large contiguous areas through less mesh nodes equipped with white space devices(WSDs) for the last-one-mile due to the propagation characteristic of ISM bands. White space mesh is an economic way to provide back-haul Internet service in neighborhood area employing the propagation characteristics. The propagation advantages White space could also be used to improve the urban or high density area connectivity through lower interference channels.

As a kind of multi-radio architecture, *Multi-band Multi-radio Mesh Network* also has the same advantages of *Multi-Channel Mesh Network* as increasing the network capacity. And also the challenges of reducing interference among active links is a main issue. The problem of assign channels in mesh network has been proved as a NP-Hard problem. [3]. The performance challenges of *Multi-channel Multi-radio Mesh Network* have long been recognized and have led to a lot of research on the traffic profiling, channel assignment, routing, and topology control. A vast array of channel assignment for *Multichannel Mesh Network* have been proposed and reviewed in several articles. Ashish [4] use *Load Aware Channel Assignment* to approach the channel assignment optimization; Jian [5] employ a channel partition methodology to improve the channel assignment; In [3], Kamal describe the up-bound and lower-band based on *Conflict Graph*.

This paper also deals with the problem of computing the optimal channel assignment of a mesh network, plus dealing with the influence of different range size due to propagation across multi-band. We give wireless network configuration specified as inputs. The inputs have the node locations, available bands, ranges etc. We consider the *Communication Range* and *Interference Range* variety of bands as a new factor in our *Multiband Multi-radio Wireless Mesh Network* architecture. With the new multiband factor, a single link could get a better RSSI with better throughput according to propagation models, such as Friis model; However, at the same time, the interference in the whole network increase too. To balance the good and bad things, as Christelle proposed a framework in [6], we propose a linear optimization model to describe constraints of such a network with more detailed constraints. However, this model is still a NP-Hard which could not be resolved in a polynomial time.

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 worst case then iteration improve the *Path Efficiency over Network* (PEN).

This work focus on channel assignment of mesh network given multiband gateways and mesh nodes information. We analysis the problem and algorithm complexity through a regular grid network and evaluate our approaching in two in-field network placement.

The main contributions of our work are as follows:

- We formulate the heterogeneous multiband multi-radio channel assignment problem with a linear optimization model.
- We propose a parameter *Path Efficiency over Network* (PEN) to evaluate multi-hop path.
- We develop 2 heuristic algorithms to approach the optimized channel assignment.
- We perform extensive simulation on regular grid network and in-field mesh network topology to evaluate our algorithms.

The remainder of this paper is organized as follows. In Section II, we formulate the multiband wireless mesh network channel assignment model and analyze the factors relate to the performance of this architecture. In Section **??** discusses the algorithms approaching the optimal channel assignment of a multiband network.

II. Multiband Mesh Architecture and Model

In this section, we first introduce the *Multiband Mesh Network Architecture* with white space band propagation, connectivity and interference characteristics. Then we analysis the architecture and formulate the architecture into a graph model with hypothesis.

A. Multiband Mesh Network Architecture

Generally *Wireless Mesh Network* is been described as two-tiers: Consisting of an access layer for clients to mesh nodes, and a backhual layer for interconnection from mesh nodes to gateway nodes with wired Internet connection [7]. Nodes in backhual layer are static. Our work focus on *Wireless Mesh Network* with *White Space Frequency* in backhual layer. The clients devices in industrial, scientific and medical (ISM) band, such as iPhone, laptops, access to mesh node with independent channel of ISM band from backhual layer.

A lot of efforts have been put on *Multichannel Multi-radio Mesh Network* architecture focusing on *Gateway Placement, Channel Assignment, Multihop Routing* problems [8]. *Multi-channel* is a word mention different frequency channels with small gap, for instance the orthogonal WLAN channels in 2.4GHz from 2.412GHz to 2.484GHz with 22MHz gap. We refer *Multiband* with a combination of different frequency of large gap, such as a set 2.4GHz and 900MHz whose propagation characteristics are different.

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, and in most propagation models there are three basic propagation mechanisms: reflection, diffraction, and scattering [9]. Wireless propagation could be affected by the daily changes of environment, weather, and atmosphere changes due to cosmos activities. In multiband mesh backhual layer, 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 a popular propagation model *Friis Model*, the received signal power of a node is represented as:

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

Path-loss exponent α is used to describe the environment factors, typically in outdoor environments range from 2 to 5. [10]. The received signal could be different only related to the wavelength λ represents band. The propagation difference makes the performance of radios in different bands vary with the same configuration in the same location. With the same received signal threshold, lower frequency band could have a larger propagation range R.

In multiband scenario, both wired *Gateway Nodes* and *Mesh Nodes* are equipped with multiple radios working in different frequency band, including ISM bands and white space bands. The radios could work simultaneously bringing more capacity to the network which is a evolution of *Multi-channel Multi-Radio Mesh Network* with radios working in the same band in different channels.

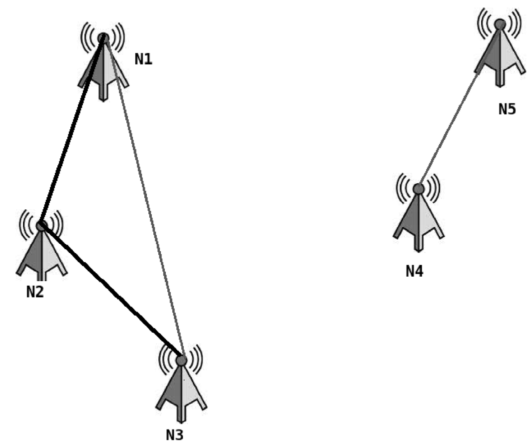

Fig. 1. Multiband Communication and Interference Range

The broadcast nature of the wireless medium makes it generate multiple access interference. Employing *White Space Band* in lower frequency brings advantages for mesh network, 1) more orthogonal bandwidth make the contention in the network lower, 2) the propagation difference brings flexible topology by reduce connection hop counts in the network. However, at the same time, *White Space Band* also increase the interference range in the network making more interference in the same band. Both goods and bad are embedded in *White Space Band* for mesh network. In 1, node *N1* could connect to node *N3* relay on node *N2* in higher frequency band or through lower frequency band directly. If under higher frequency band, link between node *N4* and node *N5* could reuse the higher frequency because they are out of the interference range of this high frequency band; however, if *N1* and *N3* use lower frequency band with less hop count, then *N4* and *N5* could not reuse the lower frequency 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.*

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. We consider a wireless mesh network formed by a set of stationary mesh nodes and wired gateway nodes. Each node is equipped with one or more radios in different bands. To clarify the *White Space Band* influence, we assume radios in a node works in unique non-overlapping channels of multiple band, radios in two nodes share a common channel in the same band. All the radios work under the same transmitting power, antenna with the same gains. To model the connectivity, we adopt classical *Protocol Model* from Gupta [11]. If the received signal is above the threshold, the link would have a communication capacity, otherwise, the link could not exist. For the interference, when the received signal is above the interference threshold, there will be contention exist; otherwise, the signal will not influence other links.

The *Gateway Nodes* and *Mesh Nodes* locations have been known as input. In a network, *Channel Assignment* naturally binds with a routing protocol for application, but have different target. We bind our model with a *Shortest Path Routing* protocol for *Channel Assignment* application and evaluation.

From the input nodes location, transmitting power, antenna gains, communication and interference threshold, and bind with *Friis Model*, we can get *Communication Range* and *Interference Range* of each node in different band. We model the connectivity between mesh nodes by an undirected graph *Connectivity Graph*, $C = (V, L, B)$, V denotes the set of nodes, L denotes the set of links, B denotes the set of frequency bands. A pair of nodes have a link with capacity C_l in L of band b in B, if they are physically located within each others communication range of a band.

This model associates an interference range which is larger than the communication range for each node, defining the range up to which a transmitter can interference with the reception of a link. We extend the *Conflict Graph* from Jain's work with a flexible approach for interference, $CG = (L_{i,j}, I_{Set}, B)$. $L_{i,j}$ is 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 [5], [6], [8]. 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 with the influence on topology from the new multiband factor.

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* [5], [12], [13]. However, they fails to distinguish the *Multi-hop* and *Conflict Graph* variation among multiple bands. Our work focus on the *traffic-independent* channel assignment which works in the worst case with fairness for all the nodes. *Traffic-independent* is done without explicitly considering network traffic/load [14]. To approach the optimization channel assignment, we develop a mixed linear integer model to fit the multiband scenario. We also analyze the intra-relation between the *Hop Counts* and *Conflict Graph* and propose a partition and a 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 [15], 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. Our work focus on the channel assignment after gateway placement done, binding with shortest path routing. Jointly optimize the problem is out of the paper topic.

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 [14]. In this subsection we would like to formulate our channel assignment problem as an integer linear program and derive a upbound via its relaxation to an LP problem, such as 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 $\alpha^k_{i,j}$ 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, $uy^l_{i,j,k}, dy^l_{i,j,k}$.

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:

$$\alpha_{i,j}^{k} \leq 1 \tag{4}$$

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

$$dy_{i,j,k}^{l} \geq 0 \tag{6}$$

Connectivity Constraints:

$$\sum_{i} \alpha_{i,j}^{k} + \sum_{i} \alpha_{j,i}^{k} + \sum_{l} \sum_{m} (\alpha_{l,m}^{k} \cdot I_{ij,lm}^{k}) \leq 1, i \neq j \tag{7}$$

$$\sum_{i} uy_{i,j,k}^{l} + \sum_{i} dyi,j,k^{l} \leq r_{j,k}^{l} \cdot \alpha_{j,k}^{l} \tag{8}$$

Uplink Constraints:

$$\sum_{k} \sum_{l} uy_{i,i,k}^{l} \geq \lambda u_i - J \cdot g_i \tag{9}$$

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

$$\sum_{j} \sum_{l} uy_{i,j,k}^{l} - \sum_{m} \sum_{l} uy_{i,k,m}^{l} \leq g_i \cdot J, i \neq k \tag{11}$$

$$\sum_{j} \sum_{l} uy_{i,j,k}^{l} - \sum_{m} \sum_{l} uy_{i,k,m}^{l} \geq 0, i \neq k \tag{12}$$

$$uy_{i,j,i}^{l} = 0 \tag{13}$$

Downlink Constraints:

$$\sum_{j} \sum_{l} dy_{i,j,i}^{l} \geq \lambda d_i - J \cdot g_i \tag{14}$$

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

$$\sum_{j} \sum_{l} dy_{i,j,k}^{l} - \sum_{m} \sum_{l} dy_{i,k,m}^{l} \geq -g_i \cdot J, i \neq k \tag{16}$$

$$\sum_{j} \sum_{l} dy_{i,j,k}^{l} - \sum_{m} \sum_{l} dy_{i,k,m}^{l} \leq 0, i \neq k \tag{17}$$

$$dy_{i,i,j}^{l} = 0 \tag{18}$$

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, the model itself is NP-hard could not get the optimization resuslt in polynomial time. But it helps to find a compariable result in a limited time window. To obtain a compariable result, we config the computer to run in a time window, such as 2 hours to get a partial optimization result.

IV. Solving The Placement Problem

Then *Tree Generated Algorithm* and *Heuristic Efficiency Improvement Algorithm* are introduced

We propose two local search based algorithms with $BandAssign$ operation to adapt the multiband scenario. The gateway placement problem could be formulated as an integer program (IP), however, the solution based on IP has following disadvantages: (i) can not be solved exactly in polynomial time, (ii) has an unbounded integrality gap (iii) IP is not suitable for online computation [15].

To approach the maximizing capacity, we switch to local search algorithms. *Local Search Algorithms* optimize one of the two major components of our capacity calculation: the size of the routes in R or the the impact of contention in I on mesh nodes.

In the worst case, without proper algorithms to approach the optimal placment, running the brute force algorithm to find the optimal placement is almost an impossible mission. The combination of placement in a n nodes network is 2^n, with the capacity of calculation for each node, the complexity is $O(n2^n)$. It is a nightmare even for a powerful server. That is why we have to approach the optimal placement verse finding the solution by traversing all possible options.

Previous work J, Robinson proposed two *Local search algorithms* to optimize the capacity for single band mesh network deployment [15]. We therefore develop the *Local Search Algorithms* to adpot multiband scenario.

A. Minimizeing Hop Count

The available gateway locations are W, which is a specific subset of all mesh node locations. G represent the set of installed gateway with multiple radios work in different bands locations throughout the execution of the algorithm, meaning if there is a gateway node work in band k in the location, $G[i, k] = 1$. We start to add network capacity from an designed deployment single mesh placement, since there are tons of methods for a single band mesh deployment [7].

We perform *add(), assign(), open() and, close(),* to output a deployment of mesh network. To terminate the process, we require that each step lowers the cost by at least $c(S)/p(n, \varepsilon)$, S is the deployment for this step, $p(n, \varepsilon)$ is a chosen polynomial in n and $1/\varepsilon$.

$add(s)$ installs a multiband mesh node at potential location s, $assign(s, T)$ install a gateway at node s and discover the coverage of different band, assign the band to different mesh nodes according to the demands and fairshare of the nodes. $open(s, T)$ installs a gateway at location s and removes all the gateway nodes in set T, and $close(s, T)$ removes the gateway at location s and installs gateway nodes at all nodes in set T.

As found in [15] all possible combinations for set T can not be evaluated in polynomial time, we inherited the methodology of solving a knapsack problem for the set T discovering. T is found as the set of items to put in the knapsack which has an arbitrary capacity. The details of the operation is described as:

- add(s) for all non-gateway nodes s, evaluate the cost to open a gateway at $s \in W$. This cost evaluation requires solving a transhipment problem to find optimal routing matrix R for the set of all installed gateways in $G \cap \{s\}$
- assign(s,T) Assign the bands to the nodes in coverage according to the demands and contention. Distribute the capacity of a multiband gateway node to mesh nodes. We first assign the lower band for remote mesh nodes and then the higher band for the close nodes. If we have more bandwidth than required for the first step, then we assign the remaining higher bandwidth to close nodes and then the lower bands for all nodes in coverage since the nodes close to the gateway may suffer more contention. The process of assign helps to reduce the hop count/contention of the network. The operation adopt the propagation characteristics of different making the problem scale of transship and knapsack become smaller.
- open(s,T) Install gateway at location $s \in W$ and remove gateways in set $T \subseteq G - \{s\}$, transfer the traffic on T to teh gateway nodes s. Gateway s could be a node with some unused capacity.
- close(s,T) Remove $s \in G$ and install a set of gateways $T \subseteq W - \{s\}$. Then reassign routes destined to s to gateways in T without any effect on mesh nodes served by other gateways. T should be gateway nodes have unused capacity.

Hop count is a first-order approximation of the capacity. The relation between the capacity and the hop count is the decrease of the hop count will reduce the contention and increase the capacity in **??**. The advantage of hop count as the cost function is that it preserves the triangle inequality, which provable the upbound of network capacity. The local search operations are not able to know a priori of the placement, we use lower bound estimates for the gateway capacities $u[i]$ and update the capacity every successful interation. The process will end when the current sum of the lower bound capacity estimate $u_{cur}[i]$ does not decrease by more than user-chosen parameter ϕ from the previouse estimate, $u_{prev}[i]$. In the process, subject to the lower capacity bound, we capture the optimal placement. The run time of the *Multiband MinHopCount Algorithm* is polynomial in $\frac{1}{\epsilon}$ and $\frac{1}{\phi}$.

Algorithm 1 Multiband MinHopCount Algorithm

Input:
M: The set of all mesh nodes
$u_{init}[i]$: Initialize values of capacities
Output:
G: Installed Gateway Locations
Valid Here means satisfies budget
Start with arbitrary, valid solution G
1: **Foreach** $s \in M$ **do**
2: **while** $\sum_{i=1}^{N} u_{prev}[i] - u_{cur}[i] \geq \phi$ **do**
3: **while** $\triangle cost \geq c(G)/p(n, \epsilon)$ **do**
4: Find valid add(s)
5: Assign(s,T)
6: Find valid open(s,T)
where T is solution to knapsack problem with knapsack size of u[s]
7: Find valid close(s,T)
where T is minimal covering kanpsack with knapsack size of u[s]
Calculate $\triangle cost$ for all valid operations
Apply operation to G with best $\triangle cost$
8: **end while**
Output G as locally optimal solution
Calculate capacities $\hat{u}[i]$ of placement G
Update $u_{cur}[i]$ to new lower bound if $\hat{u}[i] < u_{prev}[i]$
9: **end while**
10: Output G as Solution

B. MinContention

The second approaching, Multiband MinContention, finds the gateway placement that minimizes the average contention in the network. The main idea of the Multiband MinContention algorithm is to install k gateways to minimize the average contention on the mesh nodes, related to the links contend with each node and how often these links are used in routes. We can not count the total contention on gateways, since the full gateway placement is not known in advance. The problem could be mapped to a k-median problem [15]. In this work, we introduce the k-median problem and propose a *Multiband MinContention* local search algorithm. We find the placement with the lowest average contention region size.

1) k-median: The k-Median Problme is a variant of the facility location problem where there are only a fixed number k of facilities that can be opened. The objective is to minimize the cost of connecting all clients to a facility. There is a local search algorithm for the uncapacitated k-median problem with a locality gap of $3 + 2/p$ [16], where the locality gap is the maximum difference between the worst local optimum and the global optimum and the parameter p controls the number of gateways the algorithm considers for simultaneous swapping. This locality gap results in an approximation ratio of $3 + \epsilon$. The algorithm repeatedxly swap p open gateways for p unopen gateways iuntil no swaps can improve the solution. Larger p can improve the accuracy but result in exponential increase running time.

For multiband scenario, to employ the local search algorithm, designer need to balance the contention among different bands. It happens that one band may reach the best contention placement but other bands are not in optimization status. The main difference from single band MinContention algorithm is that when we choose an additional gateway node, we try to assign the same number of one hop links for different band. To implement the equal assignment, we prefer to use higher frequency band since there click is smaller than lower frequency band. A similar process is designed to start from assigning higher band first and then lower band with interation.

2) Swap-Function: Swap-based Local Search: The Multiband MinContention algorithm is summarized in 2. THe cost of a placement is the sum of the active link weights, which are each sassigned to be the total number of mesh nodes in contention range of the link.

Algorithm 2 Multiband MinContention Algorithm

Input:
M: The set of all mesh nodes
$u_{init}[i]$: Initialize values of capacities
Output:
G: Installed Gateway Locations
Valid Here means satisfies budget
Start with arbitrary, valid solution G
1: **while** $\triangle cost \geq C(G)/p(n,\epsilon)$ **do**
2: Find all valid swap(S,T)
where S is set of p gateways to open
and T is set of p gateways to close
3: Assign(S)
Assign equal number of one hop mesh node for different band
4: Calculate $\triangle cost$ for all valid operations
5: Apply $swap$ with largest positive $\triangle cost$
6: **end while**
Output G as locally optimal solution

3) triangle: Triangle Inequality for Contention A simple example is a three nodes mesh network. The contention caused by link AB is less than the sum of the contention of links AC and BC. This characteristic is useful to find the minimum contention links.

bitcpf: IV-A 1

V. Conclusion

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

References

[1] Wiki, "White space(radio)," http://en.wikipedia.org/wiki/White_spaces, 2013.
[2] FCC, "White space," http://www.fcc.gov/topic/white-space, 2012.
[3] 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.
[4] 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.
[5] 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.
[6] 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.
[7] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer networks*, vol. 47, no. 4, pp. 445–487, 2005.
[8] 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.
[9] 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.
[10] 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.
[11] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *Information Theory, IEEE Transactions on*, vol. 46, no. 2, pp. 388–404, 2000.
[12] 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.
[13] 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.
[14] 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.
[15] 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.
[16] V. Arya, N. Garg, R. Khandekar, A. Meyerson, K. Munagala, and V. Pandit, "Local search heuristics for k-median and facility location problems," *SIAM Journal on Computing*, vol. 33, no. 3, pp. 544–562, 2004.