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 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.

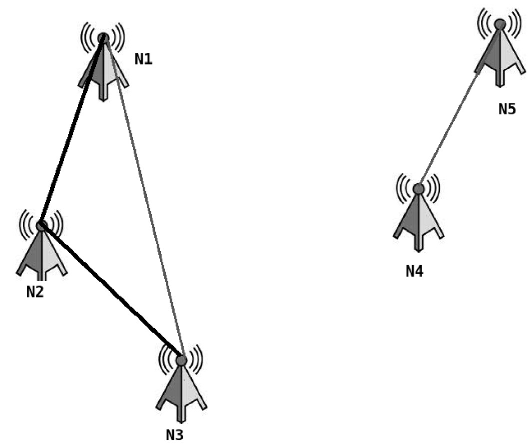

Fig. 1. Multiband Communication and Interference Range

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:

$r^k_{i,j}$	$(i,j) \in N, k \in B$	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 k
g_i	$i \in N\ binary$	Gateway placement

Variables:

α^k_{ij}	$k \in B, (i,j) \in N$	Time share of a link (i,j) on band k
$uy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	i Uplink traffic on (j,k) at band l
$dy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	i Uplink traffic on (j,k) at band l

Objective:

$$\max \quad \sum_{n \in V}(\lambda u_n + \lambda d_n) \tag{3}$$

Constraints:

Variable-Type Constraints:

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

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

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

Connectivity Constraints:

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

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

(9)

To provide affordable solution for *Channel Assignment Problem* in multiband scenario, a novel parameter *Network Efficiency* is defined to represent the performance of multi-hop path in multiband mesh network. The influence of *White Space Band* influence on the network is presented based on this parameter in this section.

IV. Conclusion

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

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