WhiteMesh: Leveraging White Spaces in Multihop Wireless Topologies

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Abstract*—Wireless mesh network deployments are low cost effective way to serve large populations internet connections. As the network usage grows, more mesh nodes may need to improve the performance of existing network. However, this may bring more contention for existing network. Since FCC freed UHF band for wireless communication, to deploy mesh node working in white band could bring additional capacity for existing capacity. In this paper, we study the problem of adding new multiband capacity points to an existing mesh network. We first present a protocol model based multiband capacity calculation for gateway-limited fair capacity as a function of the contention at each gateway. Then, we present FIXME online gateway placement algorithms that use local search operations to maximize the capacity gain on existing network. The difficulty is that the capacity of the existing gateways related to the additional gateway node which would not be determined in advance. And the multiband links make the network topology complex becoming a NP-hard problem. The challenges are addressed with two placement algorithms with different approaches to estimating the unknown gateway capacities. The first placement algorithm, multiband MinHopCount is adapted from a solution to the facility location problem. Multiband MinHopCount minimizes path lengths and iteratively estimates the wireless capacity of each gateway location. The second algorithm, multiband Mini-contention is adapted from a solution to FIXME The performance of different bandwidth and propagation scenarios are investigated with in-field experiments and FCC regulation. The results show that the algorithms outperform the single band network by up to FIXME on realistic topologies.

I. Introduction

FCC adopted rules to allow unlicensed radio transmitters to operate in the white space freed from TV band since 2010 [1]. White space 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 [2]. To use these band, FCC ruling requires white space devices(WSDs) to learn of spectrum availability at their respective locations from a database of incumbents. For example, in Dallas/Fort Worth, TX, 482M-488MHz band should be yielded for TV channels, in Chicago, IL 470M-482MHz band is reserved for TV channels. [3] 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 WSDs due to the propagation characteristic of ISM bands. White space mesh is an economic way to provide back-haul Internet service in rural area or other low density area employing the propagation characteristics. White space could also be used to improve the urban or high density area connectivity through lower interference channels.

Mesh deployment requires selecting the number and locations to place mesh nodes to cover the whole area and the nodes are inter-connected in order to access to Internet gateway points. Unfortunately, prior white space mesh placement research fails to address the compatibility of current existing devices, for instance, iPhone, Mac Laptop do not have white space radios to access white space gateway points. For a realistic mesh network, the end hop to the client need to be able to work in ISM Wifi band. So the practical way to employ white space could be creating Internet access backhual with less nodes or improve existing Wifi network by adding the frequency band, avoiding interference and reduce the hop relay among Wifi network. To appreciate the multiband mesh deployment problem, it is important to understand the differences between white spaces and the popular ISM bands where Wifi devices operate. First, in FCC rules, users in white space band have to yield primary users. Before enter a white space channel, users have to detect the channel occupation. Second, white space band may suffer some unknown interference such as wireless speakers. Such devices may turn on at anytime without warning. Third, white space is cleaner than ISM bands since most of the TV stations have stopped using the bands. And also since in white space is in lower band, the coverage of these band is larger than higher frequency ISM band which could help to reduce the mesh nodes. According to these advantages and disadvantages, the balance between white space bands and ISM bands is possible to provide improvement of mesh network by reducing the construction cost or grabbing more capacity.

This work focus on minimize the mesh nodes when guarantee the coverage and connectivity of the network. We present FIXME mesh node placement algorithms so as to minimize the deployed nodes, guarantee the coverage, and mesh node inter-connectivity.

The main contributions of our work are as follows:

- We formulate the heterogeneous mesh node placement problem as a FIXME problem.
- We propose a methodology to leverage the influence of white space in mesh networks.
- We propose FIXME algorithms to minimize the number of deployed mesh nodes.
- We perform extensive outdoor experiments from multiple environments and simulations to evaluate the proposed algorithms.

II. White Space Mesh Deployment

In this section, we first formulate the white mesh deployment problem with propagation, connectivity and QOS constraint of multiband scenarios. We then propose FIXME white mesh deployment algorithms for multiband multihop networks objectives. For comparison, we also propose FIXME baseline assignment methods based on existing solutions.

A. Problem Formulation

The objective of the mesh node placement problem in multiband scenario could either be to minimize the number of deployed mesh nodes and relay nodes with the constraint of fulfilling coverage of the target area and connectivity to the Internet existing users. or to maximize the capacity of existing mesh network topology with replacing ISM Wifi nodes to white space nodes.

The set of potential gateway node accessing to Internet and relay nodes locations, O, is assumed know. Discrete locations for mesh nodes follows naturally from practical constraints on deployment, such as the availability of wired connection store or other infrastructure for gateway node installation. The coverage area of the mesh network is discredited into small grid of coverage locations N. The center of each grid is the point output the received signal justifying the connection and channel capacity. Mesh nodes R are defined as nodes do not have direct Internet access but can connect to the mesh node and provide Wi-fi coverage of a number of grid. Mesh nodes and gateway nodes could work in white space band and ISM Wifi band represented as bands set B. The vertex set of the input is defined as $O = M \cup N$,the union of coverage grid and the potential gateway nodes location. The solution of the problem could tell which gateway node will be built and where should a mesh node be added. The set of chosen gateway nodes is represented as M_b. The output of the problem is the nodes location and number of wireless nodes $R \cup M_b$, the union of gateway nodes chosen from potential locations and the mesh nodes.

B. Coverage Constraint

The connectivity graph represented as $G = (V, E)$ could indicate the existence of usable links. This formulation encodes the signal quality of each link independently can represent the link quality diversity across bands. The links set, E, from the coverage grids V to either relay nodes or mesh node O, corresponding to the estimated or measured signal strength is above a signal strength threshold. More formally, the connectivity graph where both target coverage locations and potential mesh node locations form a unified connectivity graph. The mesh network have to satisfy the coverage of each grid through an edge E from either a mesh node or a relay node O. Each coverage grid $v_i \in V$ has $E_{B_j}, B_j \in B$ valued $0, 1$, which represents the signal strength is below threshold as 0 or above threshold as 1 in band B_j. The sum of E in band is also valued $(0, 1)$, which means the grid has connection or not. According to the definition of E, mapping to the connectivity constraint, it should satisfy $\sum E \geq V$.

C. Mesh Network Capacity

Wireless bandwidth is shared among all clients and mesh nodes, as a result, it is usually desirable to limit the number of potential shares of the scarce wireless spectrum. The link E II-B could guarantee the minimum bandwidth sharing for the client, however, it could not represent the quality of the service. Our formulation enforces this by imposing a maximum degree $b_v = f(E, P_{rB})$ on the connectivity of a mesh node, represented the down-link/up-link capacity of the mesh node to clients. More complete capacity of formulations in other research take into account on-demands and fairness [4], but we do not get into these scenarios in this paper.

Subject to the *Coverage Constraint* II-B, the capacity of mesh network is the sum of bandwidth assigned for each grid $\sum b_v$. If the metric would be the capacity of mesh network, as the ISM Wifi mesh network has capacity C_{ISM}, white space mesh network has capacity C_{ws}, the capacity gain could be noted as $C_{ws} - CISM$.

We carry the capacity calculation from [5] of access networks where all traffic to and from clients must traverse a gateway. The calculation considers gateway multi-hop deferring to ongoing transmissions in contention range. The *gateway limited fair capacity* [5] is defined as a functioon of the airtime utilization of gateways, which depends on the routes used and amount of time the routes lead to a gateway deferring. From the definition, the capacity is affected by fairness. The calculation impose a fairness constraint of each mesh node to receive their fair share of the wireless airtime at the gateway nodes. We re-define the capacity calculation for single band in [5] to adopt multiband scenario.

Mesh node i has a traffic demand $d[i]$ represents the aggregate demand of all the edn-clients associated with it. We present the routes used by each mesh node to reach one or more gateways as a 3 dimensional matrix R, where $R[i, j, k]$ indicates the amount of node i's demand that traverses physical link j on band k. $src(i)$ is designated as the access tier link for mesh node i and assign $R[i, src(i)] = d[i]$. The calculation ensure fairness by requiring that $\lambda d[i]$ units of mesh nodes i's demand are served by gateways. And R matrix as solution to a transhipment problem optimizing capacity, potentially allowing multipath routing [5]. The contention caused by each physical link j on band k three-dimensional matrix I, where $I[i, j, k]$ indicates if physical link j in contention range of node i of band k.

A link induces contention equal to the number of mesh nodes that cannot be actively transmitting or receiving when the link is active in the band. Contention is used as a simplification of interference only happens in the same band

The total contention on a gateway node $g \in G$ caused by link j in band k is $\sum_{i=1}^{n} R[i, j, k] \times I[g, j, k]$. the total contention on gateway g, v_g is then given by:

$$v_{gk} = \sum_{j=1}^{m} \sum_{i=1}^{n} R[i, j, k] \times I[g, j, k] \tag{1}$$

Gateway g services total demand s_g which is the smu of demands on al links incident to gateway g, denoted as the link subset $link(gk)$ which has connection of the gateway node in band k:

$$s_{gk} = \sum_{j \in link(gk)} \sum_{i=1}^{n} R[i,j,k] \times I[g,j,k] \tag{2}$$

The capacity of gateway g as the amount of wireless time v_g required to server s_g units of time for internet service.

$$u_g = \sum_{k \in B} s_{gk}/v_{gk} \tag{3}$$

The sum is a the worst case for mesh network due to double-counting of contention with the gateway.

The capacity of a wireless is limited by its contention in worst case. Wireless network is able to increase the capacity through decreasing the contention or increase the contention to deploy less nodes for an arbitary network.

Multiband network provide a solution of decreasing the contention and deploy less nodes simultaneously. The question comes out how could a mesh network approaching the objective has the lowest cost for construction subject to the capacity request or achieve the highest capacity under a certain budget.

The gain of minimize deployment mesh node could be noted as the nodes amount of ISM Wifi mesh network A_{ISM} minus the nodes amount of mesh network with white space nodes A_{ws}, $G_a = A_{ISM} - A_{ws}$.

To employ the propagation advantages brings a NP-hard problem to arrive the optimal solution [4]. To approach the optimal solution we have FIXME frameworks to solve part of the problem subject to time fairness of each node.

III. Propagation in Multiband Mesh Network

In this section, we introduce the concept of propagation and the parameter of propagation.

Wireless propagation is the behavior of the signals loss characteritics when they are transmitted, or propagated from one point to another. The factors rule radio propagation are complex and diverse, and in most propagation models three basic propagation mechanisms: reflection, diffraction, and scattering [6]. Wireless propagation could be affected by the daily changes of environment, weather, and atmosphere changes due to cosmos activities. Understanding the effects of varying conditions on wireless propagation has many practical applications for wireless network, from choosing frequencies, to designing multihop routing, to avoiding interference, to frequency reusing.

Usually in wireless networks, the received signal power of a node is represented as $P_{dBm}(d) = P_{dBm} - 10\alpha log_{10}(\frac{d}{d_0}) + \epsilon$. Pathloss exponent α in outdoor environments range from 2 to 5, higher frequency has a heavier pathloss. [7]. The propagation of frequency becomes an important characteristic in multiband network since the pathloss exponent varies with channel frequency. The propagation difference makes the performance of radios vary from band to band in the same location with the same configuration.

Specifying each link individually enables us to encode propagation characteristics of different bands B. In other words, each grid can be covered by an arbitrary node through specific band. The propagation alternation brings the advantages of providing more possible path for multihop network without increase interference of their neighbors.

The path loss exponent varies from urban area to rural area and from plane to mountains make the question which band is fit for the environment interesting for wireless network deployment. A lower band node may have more coverage with a small path loss to decrease the cost of wireless network deployment. However a higher band may have more network capacity through frequency reuse. These characteristics make the white spcae mesh node have a role to get the gain either in reduce the cost for network deployment or increase the network capacity.

To answer the question when white space network should be chosen we choose the area with different propagation characteristics and evaluate the FIXME algorithms to leverage the propagation influence for network deployment and network capacity.

IV. White Mesh of Typical Cities

To access to the white space usability, FCC rules have to be obeyed. FCC has assigned white space with different bandwidth according to the population density and geographical condition across US. There are cities which have strict rule for white space usability, such as in New York, there is no white space band available [8]. In Dallas, the available spectrum is 2 channels, 12MHz which is much smaller than Tuscon, AZ as 16 channels, 96MHz [8].

The gain of a mesh network deployment varies of these cities due to the FCC ruled bandwidth. Propagation is another factor for deploying mesh network in these cities as mentioned in III. Combined with the propagation characteristics of different environment in these cities, there are four scenarios in large scale we are trying to leverage the influence of the white space mesh deployment.

A. More bandwidth Low propagation

The first kind of cities are with lower path loss exponent and wide FCC approved white space band, such as Tuscon, AZ. We measured the propogation as FIXME through WiEye will discuss in VI. In such cities, the advantage white space band has larger coverage and less interference bringing substantial gain of white space.

B. More bandwidth High propagation

The second kind of cities we are considering are high path loss exponent due to geographical conditions or buildings, but have wide FCC approved white space band, such as Austin with 15 channels, 90MHz white bandwidth. FIXMECheck the WiEye database

More bandwidth inject to a networks would bring gains for capacity, but the reduction of the cost for deployment does not benifet a lot from the white band.

C. Less bandwidth Low propagation

A third kind of cities which may benefit for the larger coverage of white space mesh nodes but the capacity is sitll limited by the bandwidth such as Houston FIXME

D. Less bandwidth High propagation

Cities like Dallas who has few available channels, 2 channels, 12MHz, but high propagation in its downtown area are the fourth scenario we are trying to deal with.

In such cities, the advantages of white space band is the least across all these cities, but we still could see some gain from white mesh node deployment.

V. White Mesh Algorithms

A. Multiband Gateway Placement Problem

Multiband gateway placement problme could be defined as follows. Let G be a (0,1)-vector of size n that indicates whether a given mesh node i is a capacity point or not. $f[i]$ is the monetary cost of installing a gateway capacity point i. The total cost $C(G)$ of multiband mesh network installation can be represented as:

$$C(G) = \sum f[i] \times G[i] \tag{4}$$

The placement problem is difficult since it has multiple dynamic subproblems, such as gateway selection, client assignment to gateways.

B. Local Search Approaching

Previous work has found that the problem could be expressed as an integer program. J, Robinson proposed two *Local search algorithms* to optimize the capacity for single band mesh network deployment [5]. We therefore develop the *Local Search Algorithms* to adpot multiband scenario.

The available gateway locations are W, which is a specific subset of all mesh node locations. G represent the set of installed gateway locations throughout the execution of the algorithm, meaning if there is a gateway node in the location, $G[i] = 1$. We start from an designed deployment single mesh placement, since there are tons of methods for a single band mesh deployment [9].

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 [5] 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 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.

C. MinHop Count Cost

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 1. The advantage of hop count as the cost function is that it preserves the triangle inequality, which provable the upbound of network capacity.

VI. Experimental Analysis for Prediction Algorithms

In this section, we introduce the experimental set up for *Multiband Mesh Network*. There are two set of experiments for characteristic leveraging of multiple scenarios presented **??**. One is the *local Multiband Measurement* grab propogation information across bands; the other is *WiEye* helps to find the propogation relationship of multiple cities. The methodology to process the data is also introduced.

A. Local Multiband Measurement

To discover the propagation diversity, we measure 4 different bands, 450MHz, 900MHz, 2.4GHz, and 5.8GHz on our off-shelf multiband platform. The measurement platform is made of Gateworks 2358 with GPS, Smartbridge 450MHz radio, Ubiquite XR2, XR5, and XR9 radios. The software on the platform is Linux based Openwrt with several third party applications such as Iperf, TCPdump. We bring 2 of this platform on cars and run Iperf at the transmitter with GPS records to generate traffic on the four bands simultaneously sending through the radios on the platform. The TCPdump running on the receiver side sniffs the packets and report the SNR with GPS information.

Comparing the GPS records on both side help to grab the distance between the transmitter and receiver with time stamps. The SNR and distance could be synchronized according to the time stamps. The propagation relationship of four different bands could be found through the curve fitting.

B. WiEye Measurement

WiEye is an Android application help users to measure the *Access Point* signal strength provided by SMU *Wireless Networks Group* for free. It also help *Wireless Networks Group* collecting measurement data of signal strength to leverage the propogation characteristics on large scale [10]. Due to the hardware limitation, most of the cellphones can only work on 2.4GHz, most of the measurement data is on 2.4GHz. The data from WiEye helps to get the propogation of a city in 2.4GHz and according our 2.4GHz multiband measurements, we map the propogation in other bands of the cities.

An issue of the WiEye measurement is that the *Wifi Access Points* are unknown of the users. To overcome the issue, we propose a methodology to estimate the *Access Point* through multiple measurement. The *Path Loss Exponent* varies from 2 to 5 in different environment [7]. First we grab measurements in the same area, pull out their location information and signal strength information. Then, we assume the area have a small *Path Loss Exponent*. If there are *Access Points* at the location of the users, their connectivity circle click will cover the actual *Access Point*. The area covered by the most virtual click is believed to be the plane contain the *Access Point*. Third, we increase the *Pass Loss Exponent* to decrease the click of the virtual click getting close to the *Access Point* in the plane of the last step. We iteratively repeat the process to narrow the possible location of the *Access Point* till there are only two virtual click cover the same location in the previous step plane. Then the location is believed as the *Access Point*.

Base upon the estimation, the distance from the *Access Point* to the users could be calculated and mapping to the SNR for propagation estimation.

FIXMEAdd diagram to describe the process

VII. Related Work

Since FCC ruling obviated mandatory spectrum sensing in whtie spaces networks, prior research in UHF white spaces has focused on accurate detecting the primary user [11]; assigning white spaces channels [12]. In [13], database is applied to detect white space channel. Employing the energy advantage of UHF bands is proposed to improve the performance for indoor networks [14].

In [15], a placement algorithm for wireless mesh networks is proposed for white space bands.

However, these works only focus on white space bands fails to connect the ISM bands and tons fo existing wireless devices for pratical application.

Tons of works have been done for multichannel multiradio.

Cognitive Radios

Previous works has shown that multiradios in the same band do not use the second radio efficiently [16].

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