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 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 partion 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, even more we deal with the influence of different 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 Multiradio 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* to evaluate each link and path in the network. Based on this parameter, we develop 2 novel channel assignment heuristic algorithms for the *Multiband Multiradio Wireless Mesh Network*. The first algorithm is a tree grnerated process to reduce hop count avoiding interference. The second algorithm starts from the worst case then interated improve the *Path Efficiency over Network.*

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 multiradio channel assignment problem with a linear optimization model.
- We propose a parameter *Path Efficiency over Network* 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 IV, we formulate the multiband wireless mesh network channel assignment model and analyze the factors of this architecture. In Section V discusses the algorithms approaching the optimal placment of a multiband netowrk.

II. Propagation in Multiband Mesh Network

In this section, we introduce the influence of propagation across bands in mesh network.

Wireless propagation is the behavior of the signals loss characteritics when they are transmitted 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 [7]. 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, designing multihop routing, 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. [8]. Based on the model propagation difference 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 transmitting power configuration.

Employing multiband gateway nodes bring 2 advantages for mesh network, 1) more bandwidth make the contention in the network lower, 2) the propagation difference brings flexiable topology by increasing the communication range without more contention.

Specifying each link individually enables us to encode propagation characteristics of different bands k. In other words, idealy without considersing cost, 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 on their neighbors.

The path loss exponent varies from plane to mountains, from populated area to rural area make the question which bands should be chosen and how to assign the bands interesting. 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. Furthermore, FCC has different rule to balance white band utility in different areas and environment, the demand of evaluating the white band mesh network in different scenario for industry design request and FCC regulation is urgent.

To answer the question how to balance white space bandwidth and propagation range in a network. We choose the neighborhood area with different propagation characteristics and evaluate the FIXME algorithms to leverage the propagation influence for network deployment and network capacity.

III. Whte Mesh of Typical Cities

In this section, we introduce the multiband mesh network placement problem from policy regulation and our in-field measurement.

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 [9]. In Dallas, the available spectrum is 2 channels, 12MHz which is much smaller than Tuscon, AZ as 16 channels, 96MHz [9].

The gain of a mesh network deployment varies of these cities due to the FCC ruled bandwidth. Also, these cities have different environment, for instance, Arizona cities may have less influence from the vegetation, but in Dallas area, the plants change the large scale propagation characteristics for wireless. Propagation is another factor for deploying mesh network in these cities as mentioned in II. The transmitting click varies from band to band. With the data collection in VI, we leverge the propagation characteristics in different neighborhoods, and connect them with global measurement. The propagation difference exist among these cities according to the global measurement, this difference make the networks have different communication and contention click in the same frequency as introduced in II.

Combined with the propagation characteristics of different environment in these cities, generally there are four scenarios in large scale we are trying to leverage for multiband mesh network placement fit for FCC regulation.

A. More bandwidth Low propagation

The first kind is cities 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 is cities with 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.

IV. White Space Mesh Deployment

In this section, we first formulate the white mesh deployment problem with propagation, connectivity and QOS constraint of multiband scenarios. Then introduce the *Protocol Model* gateway-limited fair capacity of a white band mesh network modified from Robinson's work [10]. For ease of discussion, all capacity points are refered as "gateways" no matter how they get access to internet.

In this paper, we consider wireless mesh networks as two-tiers: Consisting of an access tier for clients to mesh nodes, and a backhaul tier for interconnection from mesh nodes to gateway nodes. Most of the clients devices work in ISM band, such as iPhone, laptops, we assume all the mesh node has the capacity in ISM band for clients in access tier. And for the backhaul tier mesh nodes have multiband capacity with different click range according to the propagation in each band.

Further, we focus on a multiradio, multiband backhual tier architecture. We let the user-specified cost of installing a physical wire or dedicated wireless connection be different for each location and allow non-uniform capacities at each location.

A. Problem Formulation

The objective of the wireless mesh node placement problem in multiband scenario is refered to minimize the number of deployed gateway nodes to provide internet service according to the requirement for the clients.

The problem could be formulated as follows. The set of node locations, N, are known as mesh nodes due to the construction limitation, such as power supply limitation or policy. Gateway nodes are selected from these mesh nodes. In the target areas, B represents the bands across ISM and white space band according to FCC policy. Given the demand of mesh nodes N for the service area as up link demand UD of and down link demand DD. And also the the link capacity between two mesh nodes R on band B according to the *Protocol Model* and propagation character of each band. The cost of connect internet to mesh node making it a gateway node is given as PT, and the cost of installing radio of a band is given as PC. The target of the problem is to minimize the total cost of the network construction, including the gateway connection cost and new radio installing cost.

Generally, the problem is a NP-hard problem only we traverse all the possible combination. To approach the optimization solution, we have a linear model to resolve the location and routing assignment of band and traffic at the same time.

Let G be a binary $(0, 1)$-vector of size n that indicates whether a given mesh node i is built as a capacity point or not. Discrete locations for mesh nodes follows naturally from practical constraints on deployment, such as the availability of wired connection or other infrastructure for gateway nodes installation. On an operational multiband mesh network, $G[i, k] = 1$, for all $i \in G$, having active radio working in band k. Let the monetary cost of installing a capacity point be $f[i] + r(i) \times \sum_k G[i, k]$, $f(i)$ represent the cost for infrastructure, $r(i)$ is the cost for a single band, and G_0 represent the currently deployed capacity points. We define the total cost, $C(G)$, of installing new capacity points in the mesh network as:

$$C(G) = \sum_{\forall i \notin G_0} (f(i) + r(i) \times \sum_k G[i, k]) \times sgn\{\sum_k G(i, k)\} \tag{1}$$

B. 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. In this work the capacity calculation based on *Protocol Model*, a node can use the channel if the distance between the node and next relay nodes is less than the threshold and other nodes in the click is not transmitting. The model is good for 802.11-style MAC [3].

The capacity calculation in this paper considers access networks where all traffic to and from clients must traverse a gateway, making the gateways bottlenecks in the network. Therefore, the performance of gateway nodes represent the capacity of the network. More complete capacity of formulations in other research take into account on-demands and fairness [11], but we do not get into these scenarios in this paper. The advantages of this model are 1) exact computation in polynomial time and 2) extension to local search algorithms by enabling tractable approximations which optimize over one of two components of capacity definition:route lengths or contention [10].

We carry the capacity calculation idea from [10] to model the wireless interface of gateway as alternating its time between transmitting to one-hop neighbors, receiving from one-hop neighbors, and deferring to other neighbors within contention range. The *gateway limited fair capacity* is a functioon of the airtime utilization share of gateways, which depends on the routes used and amount of time the routes lead to a gateway deferring. From the definition, the capacity represent fairness for all nodes in the network. The calculation impose a fairness constraint of each mesh node to receive their fair share of the wireless airtime at the gateway nodes. For multiband scenario we re-define the expression of the capacity calculation.

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 [10]. 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:

$$v_{gk} = \sum_{j=1}^{m} \sum_{i=1}^{n} R[i,j,k] \times I[g,j,k] \tag{2}$$

We assume the access tier and backhaul tier in the same ISM band choose different channels to avoid interference among the two tiers. For the backhaul tier the contension only comes from other mesh nodes.

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:

$$s_{gk} = \sum_{j \in link(gk)} \sum_{i=1}^{n} R[i,j,k] \times I[g,j,k] \tag{3}$$

The capacity of gateway g as the amount of wireless time v_g required to server s_g units of time for internet service, also a gateway node will provide capacity to the area it located in.

$$u_g = \sum_{k \in B} s_{gk}/v_{gk} + R[g,k] \tag{4}$$

The sum is a the worst case for mesh network due to double-counting of contention with the gateway. 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 potential solutions 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 multiband nodes A_{ws}, $G_a = A_{ISM} - A_{ws}$.

To employ the propagation advantages brings a NP-hard problem to arrive the optimal solution [11]. To approach the optimal solution we have FIXME frameworks to solve part of the problem subject to time fairness of each node.

V. Solving The Placement Problem

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 [10].

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 [10]. 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 [12].

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 [10] 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.

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
Foreach $s \in M$ **do**
  while $\sum_{i=1}^{N} u_{prev}[i] - u_{cur}[i] \geq \phi$ **do**
    while $\triangle cost \geq c(G)/p(n, \epsilon)$ **do**
      Find valid add(s)
      Assign(s,T)
      Find valid open(s,T)
      where T is solution to knapsack problem with knapsack size of u[s]
      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 $\triangle cost$
    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 $\hat{u}[i] < u_{prev}[i]$
  end while
Output G as Solution

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 2. 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 $\frac{1}{\phi}$.

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 [10]. 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 $3 + 2/p$ [13], 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
while $\triangle cost \geq C(G)/p(n, \epsilon)$ **do**
  Find all valid swap(S,T)
  where S is set of p gateways to open
  and T is set of p gateways to close
  Assign(S)
  Assign equal number of one hop mesh node for different band
  Calculate $\triangle cost$ for all valid operations
  Apply $swap$ with largest positive $\triangle cost$
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.

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VI. Experimental Analysis for Prediction Algorithms

In this section we examing the performance of the multiband placement algorithms. We study the algorithms on regular grid topologies and then real topologies in different scenarios distinguished by propagation and legal white bands.

J. Robinson has validated the capacity calculation in [10] through TFA network measurement and calculation. Multiband scenario has the same calculation and physical meanings with single band described in [10]. The actual throughput values are able to be mapped to real network.

A. Performance in Regular Grid

First we study the performance of the two algorithms, *Multiband MinHopCount, Multiband MinContention* presented in Section V. For all experiments, we consider an 802.11b system with the single band link wireless throughput assumed to be 6Mbps. All mesh node locations are fixed and gateways can be installed on any mesh node. We compar the algorithms against a FIXME placement strategy.

The topology for experiment in this sub-section is a placement of 7×7 regular grid. A mesh node communicates directly with at most 4 neighbors and contents with all two hop neighbors in a single band.

B. In-Field Data Collection

Next we will introduce the analysis based on in-field experiment. We collect data on a off-shelf multiband platform and smartphone platform. The potential gateway nodes locations are from existing mesh network TFA and Google Wifi. The two algorithms in 4 different kind of environment with propagation and white bands are analyzed in the following.

We introduce the experimental set up for *Multiband Mesh Network*. There are two set of experiments for characteristic leveraging of multiple scenarios presented II. 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.

1) 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 across different environment could be found through the curve fitting.

2) 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 [14]. 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.

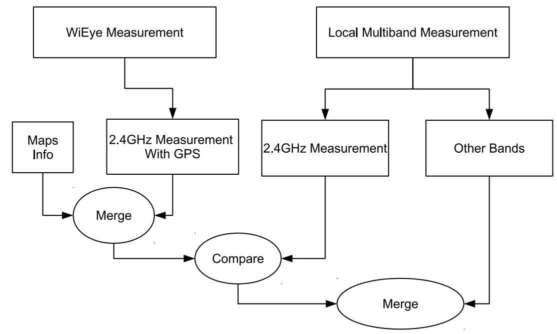

Fig. 1. Data Merge Process

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 [8]. 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

3) Data Processing: First we leverage the propagation exponent from the WiEye data set. Since WiEye WiFi measurement only focus on ISM 2.4GHz with GPS data, from the GPS we can learn the environment of the location from Google map. We map the WiEye single band measurement to our local multiband measurement to estimate the propagation characteristics in other bands.

After the processing step, we can grab the propagation in different environment even in multiple cities. Based on the measured data, we investigate the performance of the algorithms in different scenario.

4) Real-World Topologies: We consider the placement algorithms on the topologies of FIXME currently deployed mesh networks:FIXME For each topology, we fix a number of already installed gateways and focus on upgrading with new gateways. The in-field nodes locations are involved in the experiment.

First, we begin with four known FIXME gateways and place additional capacity points in the network assuming the propagation characteristics are the same in the area.

Then we split the network covered area as different regions according to the geological information and FCC regulation and evaluate the algorithms performance.

C. Performance Analysis of Algorithms

We now investigate the performance of our proposed multi-band network placement algorithms in different scenarios. First we analyze the performance of the two algorithms in a 7x7 regular grid whose mesh nodes could be installed on the cross points. Then we put the algorithms on in-field network placment of TFA and Google network.

VII. Conclusion

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

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