SPECTRUM ADAPTATION ACROSS LINK AND NETWORK

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SPECTRUM ADAPTATION ACROSS LINK AND NETWORK

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Spectrum Adaptation across Link and Network

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Due to the convenience of deployment and utility, wireless devices and network has become the dominant tools for telecommunication. However, the spectrum resource is limited in natural and has to be approved for accessibility, there is a huge challenge for individual devices and infrastructure to efficiently exploit the licensed frequency. In 2009, the FCC has approved the use of broadband services in the white space of UHF TV bands, which were formerly exclusively licensed to television broadcasters. These white space bands are now available for unlicensed public use, offerring new opportunities for new design of device and network with better performance in throughput and economy cost. In this work, we investigate multiband adaptation in both link communication and network deployment. Furthermore, we design algorithms with in-field measurement to improve the link and network performance. First, we leverage knowledge of in-situ operation across frequency bands with real-time measurements of the activity level to select the the band with the highest throughput. To do so, we perform a number of experiments in typical vehicular topologies. With two models based on machine learning algorithms and an in-situ training set, we predict the throughput based on: (*i.*) prior performance for similar context information (*e.g.*, SNR, GPS, relative speed, and link distance), and (*ii.*) real-time activity level and relative channel quality per band. In the field, we show that training on a repeatable route with these machine learning techniques can yield vast performance improvements from prior schemes. Second, we measure the spectrum utility in the Dallas-Fort Worth metropolitan and surrounding areas and propose a

measurement-driven band selection framework, Multiband Access Point Estimation (MAPE). In particular, we study the white space and WiFi bands with in-field spectrum utility measurements, revealing the number of access points required for an area with channels in multiple bands. In doing so, we find that networks with white space bands reduce the number of access points by up to 1650% in sparse rural areas over similar WiFi-only solutions. In more populated rural areas and sparse urban areas, we find an access point reduction of 660% and 412%, respectively. However, due to the heavy use of white space bands in dense urban areas, the cost reductions invert (an increase in required access points of 6%). Finally, we numerically analyze band combinations in typical rural and urban areas and show the critical factor that leads to cost reduction: considering the same total number of channels, as more channels are available in the white space bands, less access points are required for a given area. Furthermore, we model the heterogeneous white space and WiFi access tier deployment problem. We propose a relaxed ILP to get the lower bound of the amount of access point under resource limitations and a heuristic approach of the problem. We start from the uniform population distribution wireless network deployment, then discuss the non-uniform population distribution wireless network deployment. Then, we discuss white space band application in multiple spectrum resource degree. In particular, we map the problem as a Bin packing problem and resolve it with Multiband Hetegeneous Access Point deployment method. In doing so, we discuss the benefit of white space bands in reducing the number of acess points and provide heuristic solution for access point selection. Our numerical simulation shows that hetergeneous access point could benefit most of the scenarios in wireless access tier deployment. Forth, we present an integer linear programming model to leverage diverse prop- agation characteristics of white space and WiFi bands to deploy optimal WhiteMesh networks. Since such optimization is known to be NP-hard, we design a heuristic algorithm, Band-based Path Selection (BPS), which we show approaches the performance of the optimal solution with reduced complexity. We additionally compare the performance of BPS against two well-known multi- channel, multi-radio deployment algorithms across a range of scenarios spanning those typical for rural areas to urban areas. In doing so, we achieve between 3 to 6 times the gateway goodput of these existing multi-channel, multi-radio algorithms, which are agnostic to diverse propagation characteristics across bands. Moreover, we show that, with similar channel resources and bandwidth, the joint use of WiFi and white space bands can achieve a served user demand of 170% that of mesh networks with only WiFi bands or white space bands, respectively. Lastly, we propose to discuss the beamforming application in large scale network deployment. Beamforming is a efficient way to increase the spatial reuse. With the application of beaforming, a single access point could communicate with multiple device simultaneously. In large scale network deployment, beamforming could increase the capacity of an access point and lower the cost through reducing the number of access points. In our work, we will investigate in what degree the beamforming could benifet the vendors in wireless network deployment.

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Write something here. I dedicate this thesis to someone important to me.

Chapter 1

Introduction

Wireless network is the most convenient method to get service for users. The demand of wireless device users inspires vendors to provide faster, stable service in their networks. Because of the prevalence of individual devices, vehicular wireless devices and wireless sensors, wireless data traffic is expected to increasde a thousand-fold over the next decade [1], greatly motivating the improvement of link communication and network deployment.

However, unlike wired networks, wireless devices have to share crowd and unstable channels in limited frequencies. Especially in vehicular environment, the situation is even worse due to the moving. Fortunately, drivers and passengers around the world could utilize a wide array of vehicular applications ranging from real-time traffic monitoring and safety applications to various infotainment applications. However, the continuous use of such applications is limited due to the challenge of transmitting over highly-dynamic vehicular wireless channels. In such networks, the increasing availability of different frequency bands with correspondingly diverse propagation characteristics could allow flexibility and robustness of vehicular links. Even with spectral flexibility, links are extremely tenuous, demanding instantaneous decisions to remain connected, motivating an algorithm that can find the appropriate frequency band quickly and according to the current environmental context.

Obviously, more frequencies could improve the performance for both link and network communication. The FCC has approved the use of broadband services in the white spaces of UHF TV bands, which were formerly exclusively licensed to television broadcasters. These white space bands are now available for unlicensed public use, enabling the deployment of wireless access networks across a broad range of scenarios from sparse rural areas (one of the key applications identified by the FCC) to dense urban areas [12]. The white space bands operate in available channels from 54-806 MHz, having a far greater propagation range than WiFi bands for similar transmission power [4]. In WiFi and white space heterogeneous wireless network, the service area degree of an access point depends on the capacity of radios, the propagation range and the demands of the serving area. The scant frequencies of radios, the propagation distinctive and the demands diversity of population distribution bring the variation of an access point service area. These issues are substantial to designing an optimal network deployment and provide potential commercial wireless services to clients in any location. Thus, the new opportunities created by white spaces motivate the following questions for wireless Internet carriers, which have yet to be addressed: (i) To what degree can white space bands reduce the network deployment cost of sparsely populated rural areas as opposed to comparable WiFi-only solutions? and (ii) Where along the continuum of user population densities do the white space bands no longer offer cost savings for wireless network deployments? and To what degree can hetergeneous access points benefit the dense population areas and sparsely populated rural areas?

White space is not only benefit the access tier network, but also benefit the backhual tier networks. About a decade ago, numerous cities solicited proposals from network carriers for exclusive rights to deploy city-wide WiFi, spanning hundreds of square miles. While the vast majority of the resulting awarded contracts used a wireless mesh topology, initial field tests revealed that the actual WiFi propagation could not achieve the proposed mesh node spacing. As a result, many network carriers opted to pay millions of dollars in penalties rather than face the exponentially-increasing deployment costs (e.g., Houston [22] and Philadelphia [7]). Thus, while a few mesh networks have been deployed in certain communities [6, 3], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [15]. Around the same time, the digital TV transition created more spectrum for use with data networks [2]. These white space bands operate in available channels from 54-806 MHz, having increased propagation characteristics as compared to WiFi [4]. Hence, the FCC has identified rural areas as a key application for white space networks since the reduced population from major metropolitan areas allows a greater service area per backhaul device without saturating wireless capacity. Naturally, the question arises for these rural communities as well as more dense urban settings: how can the emerging white space bands improve large-scale mesh network deployments? While much work has been done on deploying multihop wireless networks with multiple channels and radios, the differences in propagation have not be exploited in their models [19, 26, 25], which could be the fundamental issue for the success of mesh networks going forward.

Lastly, to further improve the performance of wireless networks, beamforming which could increase both time reuse and spatial reuse is becoming an prospective and pratical option for industry. To answer the question how could beamforming benefit the network deployment we propose our future focus on beamforming networks.

1.1. Challenges

Cognitive radio mechanisms which interleave channel accesses also motivate the frequency band selection problem of finding the optimal spectrum on which to transmit [9]. Prior work has considered a number of challenges in leveraging white space frequencies including spectrum sensing, frequency-agile operation, geolocation, solving stringent spectral mask requirements, and providing reliable service in unlicensed and dynamically changing spectrum [24]. In particular, there has recently been an acceleration in spectrum sensing work [20, 16, 5]. Based on these works, protocols have been built for multi-channel and/or multiband wireless operation [14, 21, 23]. Other works have presented methods for searching for the most efficient transmission channel [18], discovering channel information [20, 23], and estimating channel quality [14]. Finally, the emergence of a number of diverse sensors on a vehicle motivates work on heterogeneous wireless networks, which have different frequency bands *and* technologies [11]. Thus, the various communication standards have diverse throughput capacity, allowing the choice of technology to possibly usurp frequency band decisions. For example, an 802.11n link at 5.8 GHz with high levels of loss might still be a better choice than a Bluetooth link at 2.4 GHz with little loss due to the discrepancy of hundreds of Mbps in throughput capacity.

1.2. Contributions and Futurework

This work propose spectrum adaptation for both the link communication and network optimization to improve the performance of wireless devices in multiple bands accessiable environment.

However, for the purposes of this work, we assume the underlying technology is the same to evaluate the choice of frequency band. While these works have considered spectral activity and developing protocols and algorithms to find spectral holes, less of a focus has been on coupling such information with historical performance in a given propagation environment. In this paper, we develop multiband adaptation protocols which couple the prior knowledge of in-situ performance of various bands with the instantaneous knowledge of spectral activity, SNR, and current location of each band to arrive at a decision on the optimal band to transmit. To do so, we use an off-the-shelf platform that allows direct comparison and simultaneous experimentation across four different wireless frequency bands from 450 MHz to 5.8 GHz with the same physical and media access layers.

- We first develop a framework for multiband adaptation using both historical information and instantaneous measurements. This framework is broad enough to study adaptation across licensed and unlicensed bands, including white space frequency bands.

- We propose two different machine-learning-based multiband adaptation algorithms. The first machine learning algorithm, referred to as the *Location-based Look-up Algorithm*, is based on the idea of k-nearest-neighbor classification. The second machine-learning-based algorithm uses *decision trees* for classification. For comparison, we also create two baseline adaptation algorithms which attempt to make the optimal band selection based on only: (i.) historical performance data, and (ii.) instantaneous SNR measurements across various bands.

- We perform extensive outdoor V-2-V experiments to evaluate the proposed algorithms. Our results indicate that the proposed machine learning based algorithms improve throughput by up to 49.3% over these baseline methods.

In this paper, we perform a measurement study which considers the propagation characteristics and observed in-field spectrum availability of white space and WiFi channels to find the total number of access points required to serve a given user demand. Across varying population densities in representative rural and metropolitan areas, we compare the cost savings (defined in terms of number of access points reduced) when white space bands are not used. To do so, we first define the metric to quantify the spectrum utility in a given measurement location. With the in-field measured spectrum utility data in metropolitan and surrounding areas of Dallas-Fort Worth (DFW), we calculate the activity level in WiFi and white space bands. Second, we propose a measurement-driven framework to find the number of access points required for areas with differing population densities according to our measurement locations and census data. We then evaluate our measurement-driven framework, showing the band selection across downtown, residential and university settings in urban and rural areas and analyze the impact of white space and WiFi channel combinations on a wireless deployment in these representative scenarios.

1.3. Proposal Overview

Specific to rural areas, the lack of user density and corresponding traffic demand per unit area as compared to dense urban areas allows greater levels of spatial aggregation to reduce the total number of required access points, lowering network deployment costs. In densely populated urban areas, the greater concentration of users and higher levels of traffic demand can be served by maximizing the spatial reuse. While many works have worked to address multihop wireless network deployment in terms of maximizing served user demand and/or minimizing network costs, the unique propagation characteristics and the interference from coexisting activities in white space bands have either not been jointly studied or assumed to have certain characteristics without explicit measurement [25]. Specifically, previous work has investigated wireless network deployment in terms of gateway placement, channel assignment, and routing [10, 17]. However, each of these works focus on the deployment in WiFi bands without considering the white space bands. Moreover, the assumption of idle channels held in these models fails to match the in-field spectrum utility, which could degrade the performance of a wireless network. These two issues are critical for designing an optimal network deployment and providing commercial wireless services to clients in any location.

The main contributions of our work are as follows:

- We perform in-field measurements of spectrum utilization in various representative scenarios across the DFW metroplex, ranging from sparse rural to dense urban areas and consider the environmental setting (e.g., downtown, residential, or university campus).

- We develop a measurement-driven Multi-band Access Point Estimation (MAPE) framework to jointly leverage propagation and spectrum availability of white space and WiFi bands for wireless access networks across settings.

- We analyze our framework under capacity and coverage constraints to show that, with white space bands, the number of access points can be greatly reduced from WiFi-only deployments by up to 1650% in rural areas.

- We quantify the impact of white space and WiFi channel combinations to understand the tradeoffs involved in choosing the optimal channel setting, given a certain number of available channels from multiple bands.

In this paper, we perform a relaxed linear program which considers the variation of hetergeneous access point service area too find the lower bound total number of access points required to serve a given user demand. Further, we represent an FIXME greedy algorithm to approach the lower bound. Across varying hetergeneous white space and WiFi radios combination, population densities in representative rural and metropolitan areas we compare the cost savings (defined in terms of number of access points reduced) when white space bands are not used. We then evaluate our FIXME, showing the hetergenous band selection across downtown, residential and university settings in urban area and rural areas and analyze the impact of white space and WiFi combinations on a wireless deployment in these representative scenarios.

The main contributions of our work are as follows:

- We develop an optimization framework based on linear programming to jointly leverage white space and WiFi bands approaching the lower bound in terms of numer of access points to serve the demands of a given area.

- We design a FIXME algorithm, which model the problem as a bin package problem. We represent a

- We evaluate the performance of the presented algorim, comparing with the lower bound and the hexagon WiFi access point deployment in sparse rural areas given similar channel resources. The numberic results shows that FIXME.

- We further analysis the performance of hetergenous access point performance in variation of population density. The numberic results shows that hetergenous access point could improve the budget saving in FIXME(dense area/sparse area).

In this paper, we leverage the diversity in propagation of white space and WiFi bands in the planning and deployment of large-scale wireless mesh networks. To do so, we first form an integer linear program to jointly exploit white space and WiFi bands for optimal WhiteMesh topologies. Second, since similar problem formulations have been shown to be NP-hard [13], we design a heuristic algorithm, Band-based Path Selection (BPS). We then show the algorithm approaches the performance of the optimal solution but with a reduced complexity. To assess the performance of our scheme, we compare the performance of BPS against two well-known multi-channel, multi-radio deployment algorithms across a wide range of scenarios, including those typical for rural areas as well as urban settings. Finally, we quantify the degree to which the joint use of both band types can improve the performance of wireless mesh networks.

The main contributions of our work are as follows:

- We develop an optimization framework based on integer linear programming to jointly leverage white space and WiFi bands to serve the greatest user demand in terms of gateway throughput in wireless mesh networks.

- We build an algorithm, Band-based Path Selection (BPS), which considers the diverse propagation and overall interference level of WiFi and white space bands using a two-stage approach. In the first stage, we prioritize the bands with the greatest propagation to reduce the overall hop count. In the second stage, we compare the interference level of path choices with similar hop count.

- We perform extensive analysis across offered loads, network sizes, and WiFi/white space band combinations, showing that BPS outperforms existing multi-channel, multi-radio algorithms techniques by 3 and 6 times in terms of the served user demand.

- Given similar channel resources (bandwidth and transmission power), we additionally show that while WiFi-only mesh topologies would largely outperform mesh networks with only white space bands, the joint use of the two types of bands (i.e., WhiteMesh networks) can yield up to 170% of the served user demand compared to mesh networks with only one type of band.

Chapter 2

Background

In this chapter, we describe the background of our research, including the basic technology related to this work and the hardware/software tools that we used to implement and evaluate our proposed algorithms in this work.

Chapter 3

Spectrum Adapatation in Access Tier Network

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3.1. Introduction

The FCC has approved the use of broadband services in the white spaces of UHF TV bands, which were formerly exclusively licensed to television broadcasters. These white space bands are now available for unlicensed public use, enabling the deployment of wireless access networks across a broad range of scenarios from sparse rural areas (one of the key applications identified by the FCC) to dense urban areas [12]. The white space bands operate in available channels from 54-806 MHz, having a far greater propagation range than WiFi bands for similar transmission power [4].

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Chapter 4

Spectrum Adapatation in Backhual Tier Network

Chapter 5

Proposed Work

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