EXPLOITING SPECTRUM AGILITY IN WIRELESS LINKS AND NETWORKS

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Exploiting Spectrum Agility in Wireless Links and Networks

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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, offering 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, wireless mesh networks were previously thought to be an ideal solution for large-scale Internet connectivity in metropolitan areas. However, in-field trials revealed that the node spacing required for WiFi propagation induced a

prohibitive cost model for network carriers to deploy. The digitization of TV channels and new FCC regulations have reapportioned spectrum for data networks with far greater range than WiFi due to lower carrier frequencies. Also, channel occupancy of change the performance of wireless network across both ISM bands and white space bands. In this work, we consider how these white space bands can be leveraged in large-scale wireless mesh network deployments with in-field measured channel capacity. In particular, we present an integer linear programming model to leverage diverse propagation characteristics and the channel occupancy of white space and WiFi bands to deploy optimal WhiteMesh networks. Since such problem is known to be NP-hard, we design a measurement driven 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 up to 160% traffic achieved gateways gain 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. Further, through the result, we leverage the channel occupancy and spacing impacts on white mesh network and study the general rules of band selection.

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 [16], 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 [10]. 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 [3]. 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 [21] and Philadelphia [6]). Thus, while a few mesh networks have been deployed in certain communities [5, 2], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [13]. Around the same time, the digital TV transition created more spectrum for use with data networks [1]. These white space bands operate in available channels from 54-806 MHz, having increased propagation characteristics as compared to WiFi [3]. 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 [18, 25, 24], which could be the fundamental issue for the success of mesh networks going forward.

Beamforming is recognized as an prospective technology to further improve the performance of wireless networks, through increasing both time reuse and spatial reuse. However, people still have the question: in what degree beamforming could add capacity and reduce the cost for the network. This is the fundamental issue which could inspire new technology utilization in the wireless networks.

1.1. Challenges

For wireless networks, both the clients and the vendors require better service and low cost. However, due to the nature and policy, wireless channels suffer a lot in providing efficient and stable service for either link communication or network deployments. Spectrum adaptation offers new solution for these issues. However, the

diversity of spectrum and network complexity present great challenges in designing multiband communication systems, for both link and network layers.

First, accurate knowledge of channel status is hard to be detected at the receiver. In recently, cognitive radio mechanisms which interleave channel accesses motivate the frequency band selection problem of finding the optimal spectrum on which to transmit [7]. 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 [23]. In particular, there has recently been an acceleration in spectrum sensing work [19, 14, 4]. Based on these works, protocols have been built for multi-channel and/or multiband wireless operation [12, 20, 22]. Other works have presented methods for searching for the most efficient transmission channel [17], discovering channel information [19, 22], and estimating channel quality [12]. Moreover, the emergence of a number of diverse sensors on a vehicle motivates work on heterogeneous wireless networks, which have different frequency bands and technologies [9]. 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. 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.

Second, in access layer network deployment, 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 [24]. Specifically, previous work has investigated wireless network deployment in terms of gateway placement, channel assignment, and routing [8, 15]. 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.

Third, in backhual layer, researchers have done both centralized and distributed work for channel assignment and routing [18, 26]. However, FCC's new policy import new diversity to this issue, propagatation difference becomes a new parameter for the optimization. Since the origin problem is already a NP-hard problem, the problem developing from the new white space policy make it more complex. Thus, new channel assignment methods for the multiband scenario is a new question people have to answer.

Lastly, beamforming makes the wireless network similar to the wired network in some degree. However, lacking of protocols and assignment methods make it hard to apply the technology in field. The issues of beamforming in application, such as deafth, new hidden problem need to be leveraged and resolved by new protocols and algorithms. This new technology inspire the optimization more challenging and

meaningful.

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.

In this link spectrum adaptation, 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 the access layer network deployment, 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. 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

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available channels from multiple bands. Furthermore, we discuss to centralized using frequencies or distributed using them in single access point. Through our numerical simulation, we show that in dense area centralized using spectrum gain more than sparse area.

In the backhual layer network deployment, 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 [11], 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. 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 chan-

nel 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.

In the beamforming application, we are going to design protocols to optimize the network deployment cost under the limitation of QoS. Through the beamforming, we are going to increase the time reuse in the traditional RTS/CTS link communication and the reduce the cost for network deployment.

1.3. Proposal Overview

In Chapter 2, we discuss the background of this work, including the basic knowledge related to this work and the hardware platform and software tools that we use. Chapter **??** provides an analysis and solution of vehicular link spectrum adaptation for multiband scenario. We also proposed an access layer network deployment framework in Chapter **??** and discuss the optimization of a single access point with spectrum limitation. In Chapter **??**, we propose an algorithm to assign channels in multiband scenario for optimizing the throughput performance in backhual networks. In Chapter **??**, we discuss the potential beamforming technology application in link communication and networks. Finally, we conclude our work in Chapter **??**.

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.

2.1. White Space Bands

The white space band term is mentioned the frequencies channels previously used by analog TV broadcasts. In United States, full power analog television broadcasts, which operated between the 54 MHz and 806 MHz television frequencies (Channels 2-69), ceased operating on June 12, 2009 per a United States digital switchover mandate. At that time, full power TV stations were required to switch to digital transmission and operate only between 54 MHz and 698 MHz. [1]

Industry and academia have recognized the value of white space bands in wireless communication. Various proposals, including IEEE 802.11af, IEEE 802.22 and those from the White Spaces Coalition, have advocated using white spaces left by the termination of analog TV to provide wireless broadband Internet access. Some company from industry has designed device intended to use these available channels as a "white-spaces device" (WSD), such as Ubiquiti SR serials products. These devices are designed to detect the presence of existing but unused areas of airwaves, such as those reserved for analog television, and utilize these unused airwaves to transmit signals for data traffic. Such technology is predicted to improve the availability of broadband Internet service, especially in rural areas.

White space band not only provide more bandwidth for wireless communication, but also bring the diversity in transmission range. Our algorithms and frameworks try to combine white space bands and WiFi bands in link communication and network deployment improvement.

2.2. Gateworks Platform

The off the shelf platform we use for our measurments is the GW2358. GW2358 is a member of the Gateworks Cambria Single Board Computer family. The GW2358 meets the requirements for enterprise and residential network applications. This single board computer consists of an Intel IXP435 XScale operating at 667MHz, 128Mbytes of DDRII-400 DRAM, and 32Mbytes of Flash. Peripherals include four Type III Mini-PCI sockets, two 10/100 Base-TX Ethernet ports with IEC-6100-4 ESD and EFT protection, two USB Host ports, and Compact Flash socket. Additional features include digital I/O, serial EEPROM, real time clock with battery backup, system monitor to track operating temperature and input voltage, RS232 serial port for management and debug, and watchdog timer. The GW2358 also supports GPS and RS485 serial port as ordering options. Power is applied through a dedicated connector or through either Ethernet connector with the unused signal pairs in a passive power over Ethernet architecture. An opensource software OpenWrt board support package is included for Linux operating systems.

We use Gateworks platform with Ubnt radios to perform 802.11 multiband measurements for both indoor and in-field. It helps to collect the SNR, throughput and packet information for the post process.

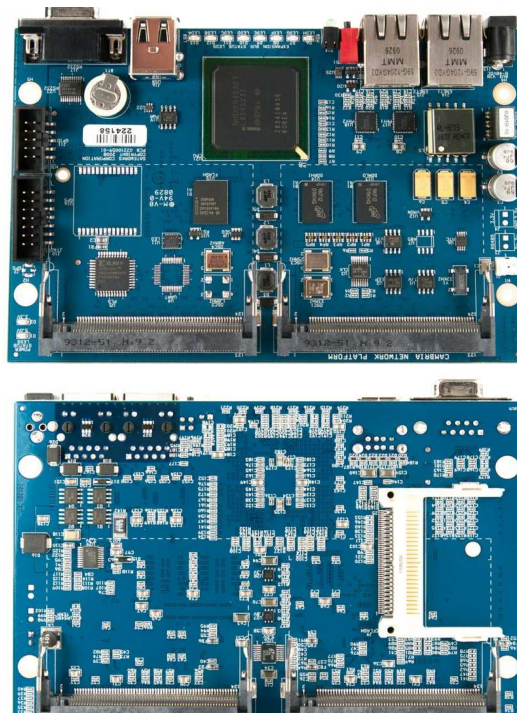## 2.3. Rohde & Schwarz FSH8 Spectrum Analyzer

Figure 2.1. The Gateworks GW2358 off-shelf Platform.

Figure 2.2. Rohde & Schwarz FSH 8 Spectrum Analyzer.

The R&S FSH 8 spectrum analyzer is portable and designed for use in the field. Its low weight, its simple, well-conceived operation concept and the large number of measurement functions make it an indispensable tool for anyone who needs an efficient measuring instrument for outdoor work.

FSH 8 could sense the signal in the air from 9 KHz to 8 GHz. The spectrum analyzer could sense both 802.11 signals and non-802.11 signal in the air. Through the time stamp, we could merge data from Gateworks platform and FSH8 platform to perform our algorithms and frameworks.

2.4. Mesh Network Deployment

Wireless Mesh Network is the infrastructure to provide wireless access for clients. Wireless mesh network is made up of radio nodes organized in a mesh topology. Each

node forwards messages on behalf of the other nodes. The nodes connected to clients are counted as the access tier, the nodes to relay data traffic to wired networks are backhual tier. For access tier, the nodes need to cover the service area and provide enough capacity for the clients in the service area. The backhual tier need to have high efficient connection to the wired network. We analyze the mesh network deployment in multiband scenario, and propose our solution for access and backhual network deployment.

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