Context-aware Multi-band Adaptation

Pengfei Cui, Jonathan Landon, Joseph Camp, Dinesh Rajan, Onur Altintas, Rama Vuyyuru
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***Abstract*—Unused spectrum white spaces in the currently underutilized analog TV bands are able to exploit for future wireless networks. In this work, we present a in-situ measurement based and a data-driven model to study the impact of multi-band adaptation on network performance. A model is created to predict the throughput of vehicles based on contextual information. We involve an activity level of networks based on the packet received during a time slot in the model to compute the expected throughput. Another on-line information is the signal strength got from the hardware driver sense. We also collect the relation of throughput and signal strength in an channel emulator as the off-line information to look up the throughput in ideal channel. We switch to the frequency band that has the highest expected throughput for transmission. We implement the model on GW2358 and collect data from in-field measurement. We compare the performance of our multi-band protocol and single band protocol.**

I. Introduction

Digital TV is in line to replace analog TV to free more wireless bandwidth for other communication systems. These free bands make it possible to extend wireless networks service across additional bands to achieve better performance. To exploit the TV white space frequency with common wireless communication bands, a number of challenges need to be resolved, including spectrum sensing of both TV signals and wireless devices signals, frequency agile operation, Geo-location, stringent spectral mask requirements, and the ability to provide reliable service in unlicensed and dynamically changing spectrum [**?**] need to be resolved. The first step to resolve these problem is to obtain the information of channel quality. Over the last few years there has been a rapid increase work done for spectrum sensing in traditional communication bands and white spaces [**?**], [**?**], [**?**]. Based on such information, protocols are built for multi-channel, multi-band wireless application [**?**], [**?**], [**?**]. In particular, recent work has researched on optimal bands to transmit [**?**], learn channel information with limited measurements [?], [?], and estimate channel quality through limit information [?]. However, each work has not explicitly considered the wireless channel switching across different bands and the resulting performance due to the channel switching.

In this paper, we present a wireless multi-band adaptation framework that leverages context-aware information of multi bands. A look-up table for ideal channel and a statistic based activity level are included to improve wireless performance. We evaluate our methods by in field experiments across 4 bands (700MHz, 900MHz, 2.4GHz, 5.8GHz), and show that in certain scenarios our approach can improve the throughput by Fix me compared to single wireless band. The specific wireless channel states we involve in this paper are the measured Signal strength, received packages and channel type. Wireless channels map to different types based on the speed, propagation, noise and so on. A simplistic characterization of channel type could be a vehicular A in this paper. The basic problem of interest is as follows: *given the channel type and Signal Strength, find the wireless band that achieves the highest throughput.* To solve the problem, we first build a *Ideal Channel Look-Up Table* through the measured data from channel emulator across a wide range of different scenarios. Based on this LUT, an ideal throughput for particular signal strength without noise and interference can be connected. The protocol also holds a tunable threshold parameter that determines when the *Signal Strength* is different enough from others.

We then analyze the effect of *activity level* and find the available transmission time to be a dominant factor. As a result, we formulate a *Multi-band* adaptation problem to the throughput computed from known Signal Strength and received packages. We verified the protocol on in field experiments to experimentally evaluate our approach.

The main contributions of our work are as follows:

- We define an *Activity Level* and enroll the concept to dynamic throughput prediction framework. The *Activity Level* can describe the channel interference in time domain.
- We propose a simple framework that provides a way to compare the throughput across 4 different bands. Prediction the throughput across multi-band is the precondition to select a band for transmission.
- We build the Look-up Table across different bands, channel models. The LUT refer to the ideal status of the channels across multi bands. It bring benefit for the work in the future.

We experimentally analyze our framework with simulation and in-field experiments on off-the-shelf hardware platform. The off-the shelf hardware platform we use is a Gateworks 2358 board with for 802.11-based Ubiquiti radios(XR2,XR5,XR7 AND XR9) with separate frequency bands. All the radios have a physical layer based on the IEEE 802.11 a/g standard, and the board offers a built-in GPS. The GPS provide information of time slot to compute the *Activity Level* .

The remainder of this paper is organized as follows: In Section II, we discuss related work. Section III presents the background and motivation of the project. Section IV discusses framework under consideration and provides a brief introduction on the functionality of the framework. Section V introduces the implementation on the WARP platform.

Section VI contains experiments used for band switching and evaluation. A list of future work will be discussed for the project in Section VII.

II. Multi-band Adaptation model

In this section, we exploit channel dynamic and accumulate information in contextual data and develop band adaptation frame for dynamic environments.Through the proposed framework, we improve the throughput of a pair of multi-radio nodes according the given context. While in this paper we focus on the application to band adaptation to show gains, the framwork has other possible applications to transmission parameter adaptation based on context information.

A. Problem Formulation

The objective of this work is to demonstrate the improvements in performance by leveraging information of ideal channels to make band adapatation decisions. As noted before, the context information we consider is the channel type, measured received signal strength, received bytes, background noise and channel interference. The channel type indicates the propagation and fading characteristics between the transmitter and receiver. Many factors(e.g., multi-path, path loss, and shadowing) have a substantial influence on the characteristics of the channel type.FIXMEcitation of Hui paper However, in this paper, we assume the channel type to be a static channel type across all the wireless bands. We use the defination of ITU channels, which are widely accepted as representative channel types for urban dan suburban settings [**?**]. Moreover, noise and interference gradually changes in the field. The gradually changing process makes it possible to seperate the noise, and even the interference from time varying experiments.

So far, there is no work has done for such multi-band adaptation. Some multi-channel adaptation and rate adaptation scenarios are focus on *Dynamic Channel State* as represented by [**?**], [?]:.

$$f(SNR, Context-Aware\,Info) \rightarrow Channel \qquad (1)$$

which assumes that the performance is only related to the channel dynamic information. However, in our approach, we consider the intereference of channel state as a factor of statistics of time. The intereference factor gradually changing process makes the statistics have an embedded temporal correlation. We adapt the transmission band for each scenario based on the contextual information and the temporal correlation.

In this paper, we involve a factor *Activity Level* to the framework. For our case, the multi-band adaptation can be simply represented as:

$$f(SNR, Activity\,Level, Context-Aware\,Info) \rightarrow Band \qquad (2)$$

The new factor *Activity Level* is defined as a statistics of band occupacied time ratio. Through the temporal correlation parameter, the prediction of the performance could match in-field system better than only consider the dynamic channel state.

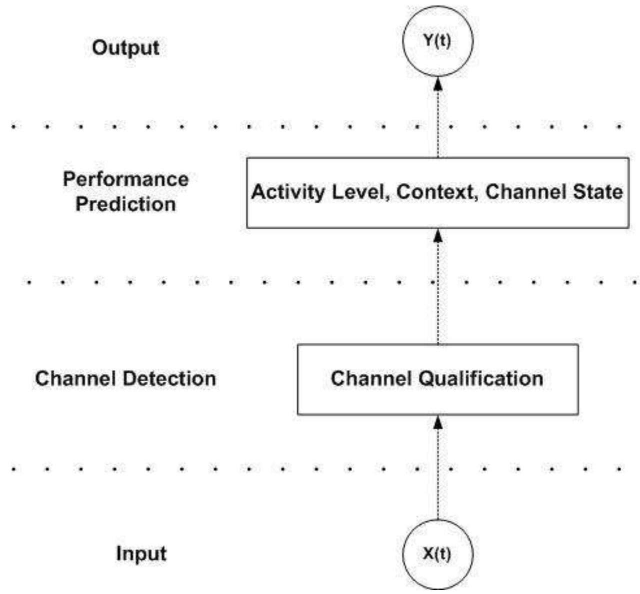

Fig. 1. Multiband framework.

B. Context-Aware Information

Contexts, which defines various operating situations. Depending on a context, the wireless device changes its operational behavior in accordance with a defined profile, when a context parameter changes [**?**]. Context is a database include the knowledge the system stored or learned from the experiments or activities. Based on tons of measurement under different parameters, a relationship between performance and system parameters can be created. In our band adaptation framework, the collected contextual information is the input to the multi-band adaptaion model. In the ideal channel context information, for each given set of bands, SNR, the context table can represent ideal throughput for each bands.

Context-aware information is the experience of a transmitor receiver pair. The performance of a system in the past can help transmiter to find the optimal rate/band based on the parameter collected by the receiver. Such as in FARA algroithm, the receiver uses an SNR characterization table that lists the minimum SNR required for a particular combination of modulation and coding rate [**?**]. Context-Aware information show a way to map the channel states to the performance.

In our band adaptation framework, the collected contextual information is the input to the multi-band adaptaion model. In the ideal channel context information, for each given set of bands, SNR, the context table can represent ideal throughput for each bands. The ideal throughput is part of the input information for our model to get the final decision of band adaptaion. It is the middle state of our model to get the prediction of the performance.

C. Dyanmic and Correlation Info

SNR is the most widely used parameter to qualify channel state [?]. SNR is a parameter can represent the channel state dynamicly. Many hardware manufactures already perform the SNR/Received signal strength detection character as part of the hardware specification [**?**]. Mapping the SNR value to the context information is widely used in cognitive radio for estimation [**?**], [**?**]. In this paper, we employ SNR as one of the factors to estimate the performance.

Moreover, there are also other factors are involved to qualify the channel. FARA tracks the the number of active clients, then update the nexthop table for transmission [?]. The statistics of collisions and link errors also could be considered as channel qualification factors [**?**]. We also define the activity level as a fctor of the channel accumulate in time domain to estimate the wireless performance. In our work, the definition of activity can be represented by:

$$Activity\,Level = \frac{(Total\,Packets) - (Connection\,Packets)}{Average\,Rate * Duration} \tag{3}$$

The activity level is a ratio that occupied by the interefer-ence transmiter during a period. Total packets is the amount of packets received in one band during the period. The connection packets is the amount of packets accepted by particular transmitter and receiver pair. We assume all the nodes have a common rate or could be averaged to a transmission rate. The activity level represent the free time ratio can be used by the focused transmitter and receiver transmission. The interference nodes transmission has correlation between continuous periods, so the previous channel state can be used to estimate the current channel states.

D. Channel State and Performance Prediction

The multi-band adaptation is receiver driven: the receiver node estimate the channel state, coputes the optimal choice of band across all the band, and feeds it back to the sender. The process of estimation is described as follows.

Let set S denote the n-tuple of the number of bands can be selected. In the numerical results, we consider the set S for white space and current common wifi wireless bands. $S = m$, where $m \in \{\mathit{700MHz}, \mathit{900MHz}, \mathit{2.4GHz}, \mathit{5.8GHz}\}$ represents the band that is selected. Let C represent the possible context information from previous measurements for a particular band with given parameters.

In this paper, the optimization metric of interest is the measured throughpt G. The optimization problem is stated as follows: Givern a particular context $c \in C$, select the optimal $s^* \in S$ that maximizes the throughput, G_{th} , wehere the T_{ideal} is the throughput from the ideal channel conditions in emulator. Formally, the problem is posed as follows:

$$\begin{aligned} \max_{s \in S} \quad G_{th} \quad &= (1 - \textit{Activity Level}) * R_{th} \\ \textit{given} \quad &\textit{Signal Strength}, \textit{velocity}, \textit{channel type} \end{aligned} \tag{4}$$

where Activity Level is a ratio as notified represent the time during one period occupied by other nodes. The optimization problem is solved using a look-up table has the relationship of SNR and throughput mapping generated from experiments in ideal channel states, in our case collecting the data on channel emulator.

Different variations of 4 we consider include: (*i*) We map the context-aware information to find the maximize throughput across the bands in vehicular channel model.(*ii*) We verify our protocol through in-field experiments data collecting on campus, so we have an assumption that the velocity of the nodes is limited for a low speed. The corresponding maximal throughput,G^*, serves as an upper bound to the performance that can be achieved by multi-band adaptation. This upper bound is computed off-line from the experiments data on emulator as the performance in ideal channel and all transmission time is free to use for the focused transmission pair.

To be clear, we list the steps to estimate the throughput for multi-band as follow:

- *Step 1* Collect context data on emulator for different scenarios (Bands, Channel type, SNR, Velocity) to find the ideal state or the upper bound of the performance for one band.
- *Step 2* Detect the SNR to qualify the wireless channel dynamicly, map the SNR to the context-aware information in *Step 1* finding the upper bound of for the current wireless channel state.
- *Step 3* Compute the *Activity Level* according to the statistic information, then re-calculate the estimate throughput including the *Activity Level*.
- *Step 4* Compare the estimate throughput across all the bands and make the best choice among the available bands.

Through these steps, the transmitter and receiver pair updates the channel state and put the best band in working.

III. Experiment Design

In this section, we use the emulated channel for repeatability and control to directly compare and evaluate different bands' performance and design in-field experiments to have the data for verification on campus. The experimental results indicate that the application of multi-band adaptation can enhance the performance of a transmitter and receiver pair. Fixme

A. Emulated Channels Experiments

In order to collect data for the creation of the context information database, we use an experimental setup where two wireless nodes communicate across emulated channels. A channel emulator, the Azimuth ACE-MX, is used for channel emulation, allowing controllable propagation, fading characteristics, velocity and other parameters with a broad range of industry-standard models for our experiments [**?**]. The Azimuth ACE MX can simulate a wireless channel band across wide frequency, in 450MHz-2.7GHz, 3.3GHz-3.8GHz, 4.9GHz-5.9GHz [?]. The channel emulator can create repeatable channels for testing each wireless band to measure the performance for a given wireless context. Each mode represents a band with fixed packet size and other parameters. For a given band, we can repeat the experiment many times to observe the performance across different bands in the ideal channel environment.

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To ensure that our results are broadly applicable across wireless device, we employ a widely accepted 802.11 testbed. Gateworks 2358 boards equipped with Ubiquiti XR serial radios, XR2(2.4GHz),XR5(5.8GHz),XR7(700MHz),XR9(900MHz) make up our testbed hardware [**?**], [**?**]. OpenWRT is installed on the testbed hardware as an open source and widely used Linux-based operating system for wireless devices [**?**]. Through this multi-radio testbed, we have the capacity to measure the performance in the same traffic generating system and the same channel state for different bands comparison.

FixmeFigure of emulator measurement

The experimental setup and data flow shows in Fixme The testbed receiver side captures the variation of the SNR and reports the throughput values from Iperf [**?**]. Based on the data, the band adaptation algorithm extracts the relationship between the contextual information and the target band.

B. In-field Experiments

To get the *Activity Level*,*SNR* as the input of our algorithm, we need to map the total received packets, our focused transmitter-receiver pair received packet count, the received signal power, background noise, and interference. We use two Gateworks devices with Ubiquiti radios combining an Agilent Spectrum Analyzer to collect data for our off-line analysis. We map this data synchronous through time-stamp from GPS information on our testbed and the system time on the Spectrum Analyzer.

1) Activity Level Measure: To calculate the *Activity Level*, the raw data we need is the total received packets and the focused transmitter-receiver pair received packets during a small time slot. Madwifi is a driver widely embedded in Linux based wireless operating system, such as the open source operating system OpenWRT [**?**], [?]. Madwifi is used to report the total received packet(RX packet) of one radio in the driver statistics. To measure the throughput and calculate the focused transmitter-receiver pair received packet(Focused RX packet) in a less than 1 second time slot, a custom socket program is used for the experiments. The transmitter side sends packets in a 500ms duration, then turns off the transmission for another 500ms to measure the interference. This raw data is then put into 3 calculate the activity level for the future prediction.

2) Signal Measure: We need the pure signal power from the transmitter to extract the ideal throughput from the context information we got from emulated channel experiments. It is impossible to get the interference during the transmitter sending period. So the transmitter is configured to turn on for a 500ms transmission to measure the throughput and the signal power(noise, interference and transmit power), and then turn off for another 500ms to measure the interference strength.

Fixme figure of the experiment flow

The testbed is capable of reporting the received strength, however, it cannot update the value without transmission. The method we use to collect the signal strength is to record the spectrum activity through an Agilent Spectrum Analyzer. The Agilent MXA N9020 Signal Analyzer monitors a wide band spectrum and records the spectrum activity in a CSV file for a time point [**?**]. To get the continuous record during the experiments, a MFC(Microsoft Foundation Class) dialog software is generated to control the spectrum analyzer to save the record file periodically through Agilent I/O Command Expert [**?**], [**?**]. We also record the signal strength on the testbed to match the record from spectrum analyzer.

A node in a car works as the transmitter, and another node with the spectrum analyzer located in a fixed place work as the receiver. The car drives one loop on campus for a measurement of one band. During one loop, the throughput, RX packets, Focused RX packets, signal strength in transmission on and transmission off are collected.

Then based on this data, the off-line data process shows the gain of multi-band adaptation.

IV. Data Process

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Parsing script In our experiments, we are constantly collecting large amounts of data, including the received signal level, current location, velocity, and time of day. Working with the memory-limited Gateworks boards, it became necessary to implement a solution to collect large amounts of data without exhausting the available memory space on the boards. Thus, we compiled a script to parse an undetermined number of data files containing the raw data collected from the ongoing experiments. Utilizing the Perl programming language, which the Gateworks boards are capable of running, the script scans every file in a directory we specify and parses them, looking specifically for signal level, lat/long location, velocity, and time data recorded from the experiments. Upon finding this information, the script reformats the data by placing it into a .csv file. Additionally, using the location data, the script calculates the distance between the transmitting and receiving boards and adds this information to the .csv file. Upon parsing the data, the raw experimental data files can simply be delete from memory, freeing up space for the data of subsequent experiments.

Activity monitor script For in-situ experiments, the need became apparent to track the number of new incoming packets and compare it with the number of previously received packets. Additionally, this needed to be done for each of the four wireless radios on the board. In doing this, we identify the most efficient frequency band to transmit data. To implement this system, a script was needed to run efficiently in the background while experiments were taking place. To achieve this, we wrote a bash shell script to run directly on the board without relying on any higher level programming language that could potentially cause greater performance overhead. As a result, the script only consumes one to two percent of CPU resource. The script begins by examining the received bytes across each radio for a length of 30 seconds and placing the bytes received each second on a new line in a file. Upon the completion of the 30 second buffering time period, the next second of received bytes on each radio is read and compared with the last 30 seconds of received data. This ratio of the most recent received data to old received data is then calculated and written to four files, one for each radio, for its subsequent use in selecting which radio to transmit/receive from.

V. Related Work

Electromagnetic radio spectrum is a natural resource licensed by governments. the Federal Communications Commission(FCC) published a report prepared by the Spectrum-Policy Task Force, discussed improving the way to manage this resource in the United States [**?**]. The underutilization of the electromagnetic spectrum leads to a definition of *Spectrum Hole* as a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilized by that user [**?**]. The concept of *Cognitive Radio* is introduced as a novel approach for improving the utilization of the wireless spectrum and the tasks for cognitive radio is summarized in [**?**]. The three on-line cognitive tasks include: *Radio-scene analysis*, *Channel identification, Transmit-power control and dynamic spectrum management* [?]. Underutilized terrestrial TV bands will be able to be used by wireless communication. Combine different bands to create Multi-bands/Multi-channels system is a new field of *Cognitive Radio* to improve the performance of wireless systems in different environments(e.g., as in [?]).

A bunch of work has been done on *Radio-scene analysis* and *Channel identification* dating back to Simon Haykin [?]. Some work of Multi-bands/Multi-channels in cognitive radios focus on optimize performance, such as avoiding frequency diversity [?]. In [**?**] an opportunistic algorithm is used to balance the cost of *spectrum sensing, Channel switching* and the gain of these activities.

There is a lot of recent research on the design of adaptation algorithms, both rate adaptation and *band/channel* adaptation of cognitive radio systems. Both kinds of these researches consider the *Spectrum sensing and Channel switching strategies*.

Evaluation of Channel Conditions. Channel conditions are important for adaptation algorithms, no matter rate adaptation or channel, band adaptation. There are two classes of rate adaptation mechanisms that have been developed. These mechanisms are focused on rate adaptation. The first generation adaptation algorithms are loss-triggered. The adaptation algorithm based on the statistics of a previous period of transmission. Second generation rate adaptation schemes diagnose the cause of a loss and appropriately adjust the data rate [**?**], [**?**], as a SNR-triggered protocol. For band adaptation, channel quality is also a precondition for making a switching decision. Our work consider both the statistics information of the previous transmission and the dynamic information of the channel to make a adjust decision.

Evaluation of Adaptation. Most of the prior work of rate adaptation protocols has investigated the effectiveness via throughput comparison [?]. That is the most simple and direct way to evaluate the gain of adaptation.

Primary Second User. Some other works focus on Multi-channel which bandwidth range limits in 2.4GHz [?] or in a continuous bandwidth considering frequency diversity [?]. Significant research on the design of channel selection algorithms has been done [**?**], [**?**]. Algorithms are generated for second user to distinguish whether the channel is free or in less utility state as soon as possible [?]. These works indicate the way to employ limit frequency work in high efficiency. In contrast, we improve the wireless performance cost more frequency bands.

Our work is motivated by prospective white band using for TV today and exploit the comparison across all the available bands and the white band. It is a kind of extension of multi-channel adaptation. Our approach classifies the performance based upon combination of in-field measurements and ideal channel conditions on *channel emulator*. Most of the research focus on the stopping rules of spectrum sensing [?], [?]. In contrast, we use the data and framework to classify the performance across different bands based on the Received signal strength, ideal channel throughput and activity level.

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VI. Conclusion