V-Scope: An Opportunistic Wardriving Approach to Augmenting TV Whitespace Databases

Tan Zhang and Suman Banerjee
Department of Computer Sciences
University of Wisconsin-Madison, USA
{tzhang, suman}@cs.wisc.edu

ABSTRACT

The recently released TV whitespaces offer a promising land for wireless communications. The secondary users of TV whitespaces today rely on spectrum occupancy databases to determine vacant TV channels for unlicensed communications. However, the accuracy of these databases (that depend solely on propagation models as per guidelines of the FCC) may be low. In this paper, we propose V-Scope - a vehicular sensing framework aimed to collect wide-area spectrum measurements for evaluating the accuracy of these databases. A key design feature of *V-Scope* is to leverage spectrum sensors mounted on public vehicles for collecting and reporting measurements from the road (opportunistic wardriving). We have currently deployed a version of our system on a single public transit bus traveling across a mid-sized city in the US. Based on measurements collected at over 1 million locations across a 100 square-km area, we find that databases tend to over-predict the coverage of certain TV broadcasts, unnecessarily blocking the usage of whitespace spectrum in a large area (up to 42% measured locations). We further propose ways of leveraging these measurements to enhance existing propagation models in databases.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

Keywords

TV Whitespaces; Spectrum Sensing; Opportunistic Wardriving

1. INTRODUCTION

Wireless providers are facing spectrum crisis when trying to meet the growing demand of mobile users. The recently released TV whitespaces (512MHz-698MHz) have become an effective solution to the spectrum crunch. However, there exists a fundamental challenge to correctly identify vacant and good channels for unlicensed usage. The state-of-art approach is to rely on a spectrum occupancy database that solely uses propagation models to predict the strength of primary signals. However, such approach can sometimes have low accuracy in urban environment. In this work, we propose *V-Scope* - a vehicle sensing (wardriving) framework aimed to collect wide-area measurements for evaluating and augmenting commercial databases. An unique feature of *V-Scope* is to leverage whitespace spectrum sensors mounted on public buses for this purpose, thus avoiding costly and laborious measurement campaigns while collecting measurements at an unprecedented scale.

In a whitespace network, a spectrum occupancy database plays a central role in assigning operating channels to secondary devices (TVBDs). On one hand, it distributes unused TV channels to TVBDs based on their locations, thereby fulfilling the FCC's requirement of protecting licensed signals. As per FCC's ruling [2], there exist three types of primary incumbents to be protected, i.e., digital TV, analog TV and wireless microphones. To detect TV signals, the database leverages well-known propagation models (e.g., R6602 [2]) to estimate the signal strength at the locations of TVBDs. It concludes a channel as being occupied if the estimated power is above a reception threshold (-84dBm). To protect microphones, the database reserves two dedicated channels for their exclusive usage, and allows more to be reserved upon request. On the other hand, the database (e.g., SpectrumBridge [4]) might inform TVBDs with channel quality in whitespaces predicted by the model. Hence, the accuracy of a spectrum database largely affects the protection of primary incumbents and channel selection by TVBDs.

Unfortunately, the database has inevitable inaccuracy in achieving above functions. First, it is inaccurate in predicting the coverage of a TV broadcast, which leads to either waste of whitespace spectrum or harmful interference to primary incumbents. The underlying reason is that its propagation model is tuned to average propagation conditions, and unable to capture the environment-induced variation, e.g., shadowing and multipath fading of specific objects and topologies. Our measurement shows this variation can be as high as 25dBm for two locations separated by merely 10 meters. Second, a database is incapable of estimating the power of unlicensed mobile transmitters operating in whitespace channels, some of which can cause high-power interference to other unlicensed communications. The incapability of predicting the coverage of a mobile transmitter is because the propagation model usually requires accurate information about the mobile transmitter, e.g., location and transmission power, which is rarely available to the database and might change frequently. Both these factors motivate the need of spectrum sensing, which provides spectrum measurements for better tracking local propagation characteristics.

In this paper, we propose an opportunistic whitespace sensing infrastructure-*V-Scope*, which uses spectrum sensors mounted on public vehicles to collect large-scale measurements. Since the public vehicles usually travel at a low speed, across wide area and for long time, *V-Scope* can leverage a few spectrum sensors to collect

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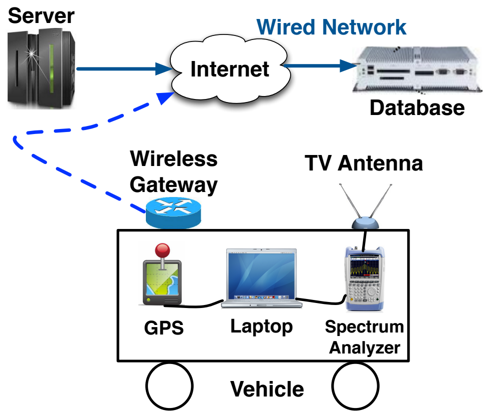


Figure 1: System architecture of *V-Scope*.

wide-area measurements for augmenting databases. Further, it obviates the need for expensive spectrum sensing hardware and their overheads in the end TVBD devices, while organically bringing some of the advantages of spectrum sensing. As a key component in *V-Scope*, we propose a zoom-in pilot detection algorithm that can reliably detect TV signals at -120dBm and operate in real-time.

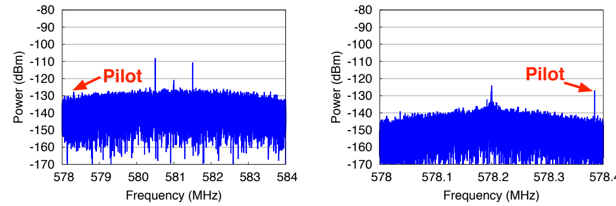
We have deployed *V-Scope* on a single public transit bus in Madison, WI. Since our bus operator tends to rotate their buses through multiple routes in the course of each day, we have been able to collect spectrum measurements at more than one million locations over a 100 sq. km. area for a two week period. Our measurements show that commercial databases that are based solely on propagation models have significant inaccuracies (up to 42% of measurement locations). Furthermore, we find the quality difference among whitespace channels tends to be high due to interference from mobile transmitters, which can hardly be predicted by the existing propagation models. Finally, we propose how to use measurements collected by *V-Scope* to refine existing propagation models.

2. V-SCOPE DESIGN

In this section, we first describe the architecture of *V-Scope* and then present our primary detection algorithms.

System architecture: *V-Scope* consists of a central server and multiple clients. Each client is envisioned to run on a different vehicle. Figure 1 shows the overall architecture of *V-Scope*. We use a laptop at the client to control all the measurement procedures running in parallel. Specifically, the laptop instructs the spectrum analyzer to sweep across all the TV channels in the UHF band. The spectrum analyzer transfers spectrum samples (FFTs) to the laptop over Ethernet. Upon receiving all the samples for each channel, the laptop performs a set of real-time analysis, e.g., primary detection and power calculation. In the meanwhile, the laptop obtains the vehicle's location from a GPS module. It includes this GPS reading into the analysis results, and upload them to the central server using some wide-area networks, e.g., cellular networks.

The server is equipped with an Ethernet connection to receive measurement results. It uses the GPS reading to query the database for vacant channels. It stores the database's response with the measurements for later comparison. One design caveat is to use the central controller instead of each client to query the database. This is due to the intention of reducing burden on the wireless link. Moreover, the client is robust to connection outage by storing the measurements in the local disk and uploading them asynchronously. Since the TV signal remains stable for long period of time (order of days), the extra round-trip delay over Ethernet and the brief outage period (usually <2s) introduce negligible inaccuracy to the measurements.



(a) (b)

Figure 2: Spectrum of a digital TV signal at -114dBm. (a) Full-channel capture; (b) Zoom-in capture at first 488KHz band.

Zoom-in pilot detection: Central to our measurement is a set of algorithms to detect primary incumbents. We adopt the same detection criteria as the sensing-based TVBDs [2], i.e., to detect primary signals as low as -114dBm. The reason for being able to detect such weak signal is to *account for the transmission range of TVBDs*.

Detecting a weak TV signal is very challenging because most of spectrum analyzers generate thermal noise at a much higher power. For example, our high-end device (WSA4000 [5]) produces -91dBm noise over a 6MHz TV channel. This requires a detection algorithm to identify primary signals at very harsh SNR (-23dB). We note alternative approaches of using amplification hardware (e.g., directional antennas or low noise amplifiers). However, it causes significant distortion that reduces detection accuracy.

Our algorithm leverages two interrelated techniques, i.e., zoom–in and pilot tracking. For pilot tracking, both analog and digital TV signals have pilots to assist decoding. These pilots are at a specified frequency and more robust to noise than other spectral components. Moreover, TV standards [1] specify a fixed difference in power between a TV signal and its pilot. For example, the pilot in digital TV should be 11.3dB below the total power. Thus, we simplify the detection task by tracking pilots at an equivalent strength.

Unfortunately, even the pilot of a weak TV signal can be overwhelmed by noise. Figure 2(a) shows such a weak TV signal. We leverage a zoom-in technique to reduce noise. It configures the spectrum analyzer (through decimation) to capture at very narrow bands (488KHz). This reduces the amount of noise passing through the radio front-end, thus effectively improving SNR by 12dB. Figure 2(b) shows the beginning fraction of the TV channel where the same pilot signal is present. We observe a clear peak at 578.38KHz in front of reduced noise. Now, we can reliably detect a weak TV signal by tracking its pilot.

Combining the two ideas, our final algorithm takes two narrowband captures at fixed frequencies of a TV channel. We extract the pilots by searching for the maximum FFT bin (f_{max}, p_{max}) within a predetermined frequency range (f_{start}, f_{end}). Upon detecting this maximum bin, we include all the continuous FFT bins around it as part of the pilot, if they have a power p_i higher than a threshold $(p_{max} - \delta)$. Formally, $Pilot = \{(f_i, p_i) : (f_i, p_i) \in FFT, p_i \geq p_{max} - \delta \wedge f_i \geq f_{start} \wedge f_i \leq f_{end}\}$. We extract several features (e.g., power, center frequency and bandwidth) from the pilot bins, and feed them into a decision tree based classifier for TV detection.

3. EVALUATION

In this section, we present our results about the performance of a commercial database. We highlight our findings that the database tends to over-predict the coverage of TV broadcasts, causing up to 42% lost in whitespaces. We start by benchmarking the accuracy of our primary detection algorithms.

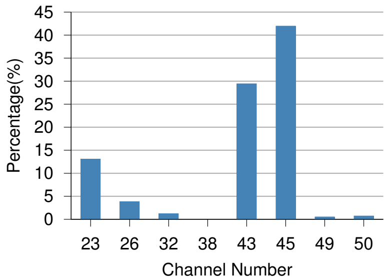


Figure 3: Fraction of whitespace loss in a model-driven database.

Figure 4: Prediction errors of a model-driven database in channel 45.

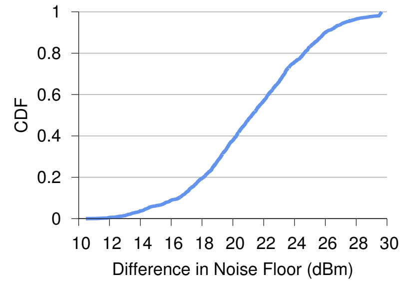


Figure 5: Quality difference in whitespace channels at same locations.

Accuracy of detection algorithms: We collect spectrum traces from 31 TV channels in the UHF band at different indoor locations. Using a high-end TV tuner, we identify that five channels have digital TV broadcasts, one has analog broadcast, and the rest has noise or microphone signals. We further attenuate the TV signals to obtain traces at a wide range of power (-40dB to -114dB at 10dB step). We apply a standard cross-validation procedure by randomly choosing 90% of the traces as the training data to detect the remaining 10%. Table 1 shows our algorithm has very low error rates (<5%). We also measure the detection latency and find it to be less than 1s. This short delay enables *V-Scope* to conduct very dense measurements, e.g., 10m separation in our deployment.

Accuracy of spectrum databases: We now evaluate the accuracy of a commercial database from SpectrumBridge [4] in predicting whitespace spectrum. The dataset is collected on a metro bus during a two-week period, containing measurements at more than 1 million distinct locations over a 100 sq. km. area around Madison, WI. All 31 channels in the UHF band were measured, among which 8 channels had active TV broadcasts in part of the measured area. We define two types of prediction errors, i.e., false positive and false negative. A false positive is the case where the database mis-predicts an occupied channel as whitespaces. The opposite is a false negative. We find very low (<0.4%) false positive rates in all these TV channels, which is similar to the prior report [3]. This demonstrates that current databases can faithfully protect TV broadcasts. However, Figure 3 shows high false negative rates in channels that have TV broadcasts. The worse channel (45) has 42% area unnecessarily blocked for unlicensed usage.

To reveal the underlying reason, Figure 4 shows the locations of false negatives in channel 45 from traces collected in one day. We note most prediction errors are densely located at the east side of the city. This is because at the east side stands several tall buildings blocking TV signals. The database failed to capture this shadowing effect, thus over-predicting the coverage of a TV broadcast.

Difference in channel quality: We compare the noise floor of different whitespace channels at each measured location. Figure 5 shows the CDF of maximum difference between the best channel and the worst channel. We note that the median quality difference can be 21dBm at same locations. This indicates that randomly selecting a whitespace channel can lead to poor communication performance. After examining spectrum waveforms, we identify large variation is mainly due to microphone transmissions and small variation is caused by both microphones and adjacent channel leakage from TV broadcasts. Since the database can hardly predict the signal strength from these mobile transmitters, spectrum measurements are necessary in facilitating channel selection by whitespace devices, and can be opportunistically performed by *V-Scope*.

Detected / Groundtruth	Digital	Analog	MIC
Digital	94.9	0.7	4.4
Analog	0.5	97.4	2.1
MIC	1.2	0.7	98.1

Table 1: Accuracy of primary detection algorithms.

4. FUTURE WORK AND CONCLUSION

Developing measurement-driven models: The measurements collected in *V-Scope* can be used to construct local propagation models that can better capture a propagation environment. A set of geostatistical interpolation methods (e.g., regression, Kriging) can be used to construct these local models, which we intend to explore.

Augmenting spectrum occupancy databases: *V-Scope* can be leveraged to build a hybrid database, which uses measurements or predictions from local models when available. There are a variety of open challenges for building this database, e.g., the scalability issue in storing local measurements, when to switch between local and global models, and how frequent should measurements be repeated.

In conclusion, we present the design and deployment of a vehicular sensing infrastructure called *V-Scope*. *V-Scope* is able to collect large-scale measurements in TV whitespaces by using spectrum sensors mounted on public vehicles. We are currently developing approaches to augmenting the database with these measurements.

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