Toward Dynamic Real-Time Geo-Location Databases for TV White Spaces

Ahmed Saeed, Mohamed Ibrahim, Khaled A. Harras, and Moustafa Youssef

Abstract

Recent FCC regulations on TV white spaces allow geo-location databases to be the sole source of spectrum information for white space devices. Geo-location databases protect TV band incumbents by keeping track of TV transmitters and their protected service areas, based on each transmitter location and transmission parameters using sophisticated propagation models. In this article, we show that keeping track of both TV transmitters and TV receivers (i.e., TV sets) can achieve significant improvement in the availability of white spaces. We first identify temporal and spatial wasted spectrum opportunities due to the current approach to white space detection. We then propose our DynaWhite architecture, which is responsible for orchestrating the detection and dissemination of highly dynamic, real-time, and fine-grained TV white space information, based on both TV transmitter and receiver information. DynaWhite proposes the development of a new generation of geo-location databases that combine conventional geo-location databases with novel unconventional sensing approaches based on the detection of passive TV receivers using standard cell phones. We present a quantitative evaluation of the potential gains, reaching 24 extra 6 MHz channels in some cases, in white space availability for potential deployments of DynaWhite. We finally identify research challenges associated with the adoption of our DynaWhite architecture.

The unlicensed usage of TV white spaces, which refers to the unused portions of the UHF spectrum and parts of the VHF spectrum in the United States, has been regulated by the FCC as a means to support mobile users' ever increasing demand for high-quality communication and multimedia streaming [1]. Utilizing these white spaces is only allowed while strictly forbidding interference with primary spectrum incumbents such as TV receivers and wireless microphones. The ruling ensures the mitigation of interference between spectrum incumbents and white space devices (WSDs) by enforcing WSDs to use either spectrum sensing or geo-location databases. Following the former method, WSDs use white spaces after sensing the spectrum for TV transmissions with a very low threshold of –114 dbm. Spectrum sensing capabilities add complexity and cost complications to WSDs, especially with this low threshold. The latter method relies on consulting geo-location databases that keep track of available white spaces in certain areas [1] by maintaining a record of TV transmitter information including location, antenna height, transmission power, and channels used. Geo-location databases utilize this information with sophisticated propagation models in order to determine the protection area of a TV transmitter, where no WSD can be active [2]. This approach is currently the preferred approach for detecting white spaces by several regulators (e.g., FCC, Ofcom, and ECC [3]). Recently, mixing both approaches was also proposed to increase the detection accuracy [4]. However, the proposed approaches protect TV band incumbents by detecting the protected area of TV transmitters and preventing use of portions of the spectrum used by those transmitters.[1] These approaches focus on *spectrum white spaces*, which are defined as portions of the spectrum that lack the presence of any decodable transmission within the TV band spectrum.

The focus on TV transmitters ignores the main spectrum incumbents, which are *TV receivers*. This focus is attributed to the *passive* nature of the TV receivers, that is, they do not transmit signals and thus are difficult to detect. Hence, while current geo-location databases regulations guarantee high protection of spectrum incumbents, they waste significant spectrum opportunities by protecting the entire coverage area of TV *transmitters*. In particular, it is not necessary for the entire coverage area to contain only active (i.e., turned on) TV *receivers*; there must also be inactive TV receivers that create wasted spectrum holes. These holes within the coverage area of a TV station introduce *geographic white spaces*, which we define as areas that lack the presence of any TV receivers. The magnitude of these geographic white spaces can be esti-

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[1] Protection of wireless microphones is guaranteed in the FCC regulation by providing two channels specifically for wireless microphones and allowing events with large numbers of wireless microphones to register in the geo-location databases.

mated based on recent studies showing that while average Americans watch 5.2 hours of TV a day, less than 10 percent of these TV viewers watch broadcast channels [5]. Our goal, therefore, is to present a characterization for these geographic white spaces.

In this article, we propose the *DynaWhite* architecture for future dynamic real-time TV white space spectrum awareness. DynaWhite's approach leverages both TV transmitter and receiver information to provide fine-grained real-time information on spectrum availability. For TV transmitter information, DynaWhite follows the conventional geo-location databases approach [2]. On the other hand, DynaWhite handles the problem of sensing passive TV receivers by using an unconventional sensing approach that leverages ubiquitous standard cell phones and other mobile devices. In particular, we argue for a crowd sourcing approach, where today's sensor-rich cell phones can be used to detect a TV receiver's location and state (i.e., ON/OFF and TV channel viewed) based on their acoustic, visual, and other fingerprints [6]. By combining the information of TV transmitters and receivers, DynaWhite has the potential for increasing the number of white space channels by up to 24 channels in some urban areas (e.g., Miami City) according to our results presented in this article. This potential gain in spectrum availability is a great incentive for leveraging dynamic real-time TV white space awareness, especially in spectrum-hungry urban areas that will experience exponential demand on wireless bandwidth.

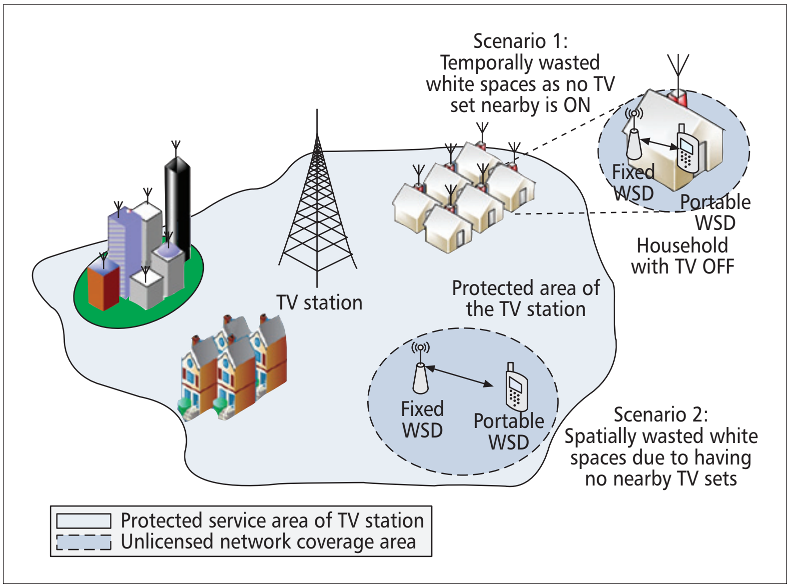

Figure 1. Two scenarios that illustrate different geographic white spaces.

TV White Spaces: Wasted Opportunities

Spectrum opportunity waste occurs when the state of the TV set (e.g., whether it is ON/OFF, or to which channel it is currently tuned) is ignored. Moreover, another form of white space opportunities is wasted when areas that have no TV sets are protected. Figure 1 illustrates different scenarios in which white space opportunities are missed. In scenario 1, labeled as the temporally wasted opportunity, although the white space network lies within the TV station's protected service area, the TV set in the vicinity of the network is turned OFF (or currently tuned to a particular channel, leaving other channels available for unlicensed usage). Conventional geo-location databases, which are not aware of the location of TV sets or their state, will declare the entire set of allocated channels in the area unavailable. However, in residential areas or work places, where TVs are switched off, ample mobile devices are being used or left idle in pockets or desks. These devices can use their sensors to automatically and periodically detect the acoustic or visual fingerprints on TV sets. On the other hand, in scenario 2, the white space network lies within the protected service area, but has no TV sets in the vicinity of the network (e.g., public parks). These areas can be registered as TV-set-free areas where various sensing approaches, as in scenario 1, can be used to detect operating TV sets. More importantly, less than 10 percent of TV viewers watch broadcast channels [5], which makes systems that can detect TV shows and songs based on the acoustic fingerprint (e.g., Shazam) a very useful tool to differentiate between broadcast TV viewers and cable TV viewers.

The common thing about these two scenarios is that both of them represent a geographically TV-set-free area that was defined earlier as geographic white spaces. DynaWhite's novel unconventional TV receivers sensing approach using mobile devices aims to detect these geographic white spaces. Avoiding waste of these white spaces is particularly important in urban areas, where large numbers of wireless devices and congested RF spectrum are the norm. Table 1 shows the available white spaces for both fixed and portable WSDs in four urban and four rural cities using the ShowMyWhiteSpace application developed by the FCC approved geo-location database company Spectrum Bridge Inc. [7].

The DynaWhite Architecture

The identified wasted spectrum opportunities require geo-location databases to evolve from storing and processing the relatively static TV tower information (e.g., location, transmission power, antenna height, and channel) to collecting, processing, and storing dynamic real-time TV set information. In order to address this evolution, we propose the DynaWhite architecture that can generate real-time geo-location databases after processing and aggregating sensory information. This architecture aims to address the expected bandwidth demand on white space networks by tracking every available spectrum opportunity in real time.

Geographic White Space Information Handling

Figure 2 provides a DynaWhite operational scenario. Contributing devices, equipped with localization mechanisms, submit location-tagged ambiance sensing data (from standard cell phones) to the DynaWhite servers, which are possibly present at a cloud infrastructure. DynaWhite divides the area of interest into fine-grained cells and calculates white space availability for each cell separately based on the collected sensory information. A cell is considered a "free cell" with respect to a certain channel in two cases: when there is no TV signal on the channel within the cell, or when the cell has no TV sets that are tuned to the channel. It should be noted that DynaWhite defaults to traditional geo-location databases when there is no sensory information available for a particular cell or when the confidence of the spectrum information is not high.

Figure 3 shows how a typical spectrum availability query is handled by DynaWhite. The multi-layered flow is divided based on the different types of available white space opportunities. These opportunities vary in terms of persistence and reliability. We define white space information *persistence* as the duration of time the spectrum information will be valid.

Urban areas: available channels			
City	Fixed WSD (4 W)	Portable 100 mW WSD	Portable 40 mW WSD
New York, NY	0	0	0
Los Angeles, CA	1	0	0
Miami, FL	1	0	3
Philadelphia, PA	1	0	2
Rural areas: available channels			
Hudson, NY	11	8	9
Palatka, FL	15	11	9
Amador City, CA	18	10	10
Conconully, WA	23	16	8

Table 1. Urban and rural areas channel availability using the ShowMyWhiteSpace application by Spectrum Bridge Inc (as of July 23th, 2013). [7]

Moreover, we define white spaces' information *reliability* as a function of DynaWhite's confidence in the contributors and conclusion made based on the collected sensory information. For each location-annotated *White Spaces Information Query*, DynaWhite aims to obtain the most persistent and reliable available information. The following is a description of the different operations in DynaWhite.

Spectrum white space information processing: The first layer consults conventional geo-location databases producing information with the highest reliability and persistence because it relies on accurate information of TV transmitters and propagation models.

Geographic white space information processing: The second layer uses standard cell phones to detect the presence and state of TV sets within the white space network's coverage area. This is particularly useful when the TV transmitter is operational while no TV sets are tuned to its channel. This type of white space information is highly volatile because TV viewers may randomly change channels.

White space information aggregation: Each piece of white space information obtained from geographic white spaces might have different persistence and reliability levels. Thus, it is DynaWhite's responsibility to determine which sources of information to use.

Confidence and validity period: Each mobile sensor is required to associate its TV set detection decision with a confidence level (Conf) based on an estimated accuracy of the classification algorithm used for detecting the TV set. Detection decisions made with confidence less than or equal to a certain threshold are ignored (the effect of the Conf parameter is investigated below). Readings from the same location are accumulated over a period, such as a week, to have an initial estimate of the TV viewing behavior in that location (e.g., program viewed and its viewing time). We rely on the TV viewers' loyalty to their TV programs [8] to predict the period of time in which they will be watching a certain channel. Although TV programs last for at least several minutes, we limit the maximum value of a validity period to 60 s, after which the white space opportunity expires, and the WSD is required to send a new query to DynaWhite.

Fusing reports from several mobile devices: As several people can watch the same TV at the same time, different mobile devices could be used to report on the same TV set. This can enhance the accuracy of detection by allowing for the fusion of detection information from different mobile devices. The results of the fusion could be further enhanced by basing prior probabilities on the history of viewing a certain channel in that location, the population density in that area, and the popularity of the viewed channel.

Geographic White Space Detection

Sensory information collected by standard mobile devices (cell phones, laptops, tablets, etc.) can be used as unconventional spectrum sensors to deduce whether a TV set is available in a certain cell or not. The use of these devices is motivated by recent statistics that show that in 2013, 77 and 68 percent of consumers use their laptops and mobile phones, respectively, while watching TV, which has grown from 61 and 42 percent, respectively, in 2012 [9]. Furthermore, statistics show that a smartphone user holds the smartphone 12.5 in from her eyes while surfing and 14.1 in away from her eyes while texting [10]; thus, chances of the phone being directed toward the TV set increases. Moreover, if the detection algorithm is triggered by spatial events (e.g., the user being at home), temporal events (e.g., the time of the mobile phone user's favorite show), and other sensory information (e.g., accelerometer readings showing the user is sitting on the couch), less energy consumption will be required by the detection algorithm, and higher detection accuracy can be attained.

Using these smart devices, if a TV set is detected, regular checks are performed to determine whether the TV is turned ON or not and to detect the channel to which the TV is currently tuned. Moreover, smart infrastructures (e.g., smart TVs or smart home sensors) can also be used for inferring such information since they are equipped with sensors designated for different functionalities required to improve the

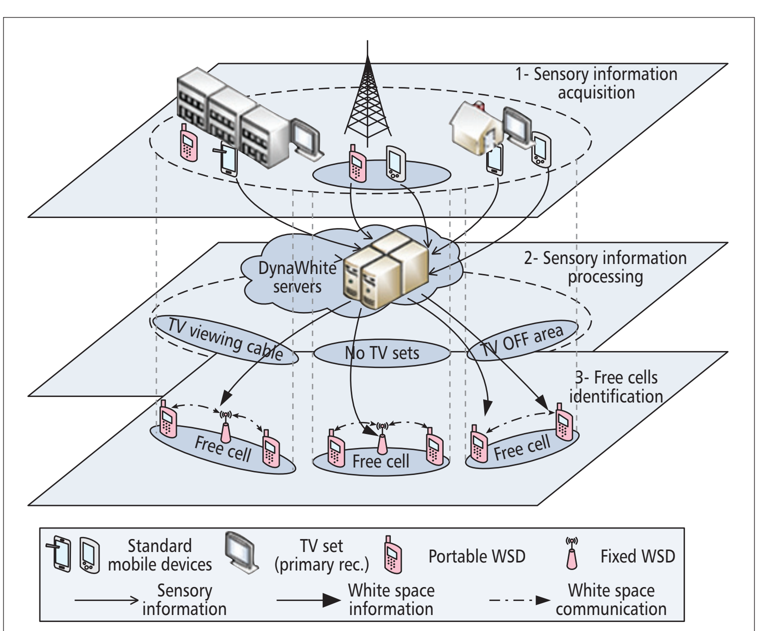

Figure 2. DynaWhite operation scenario.

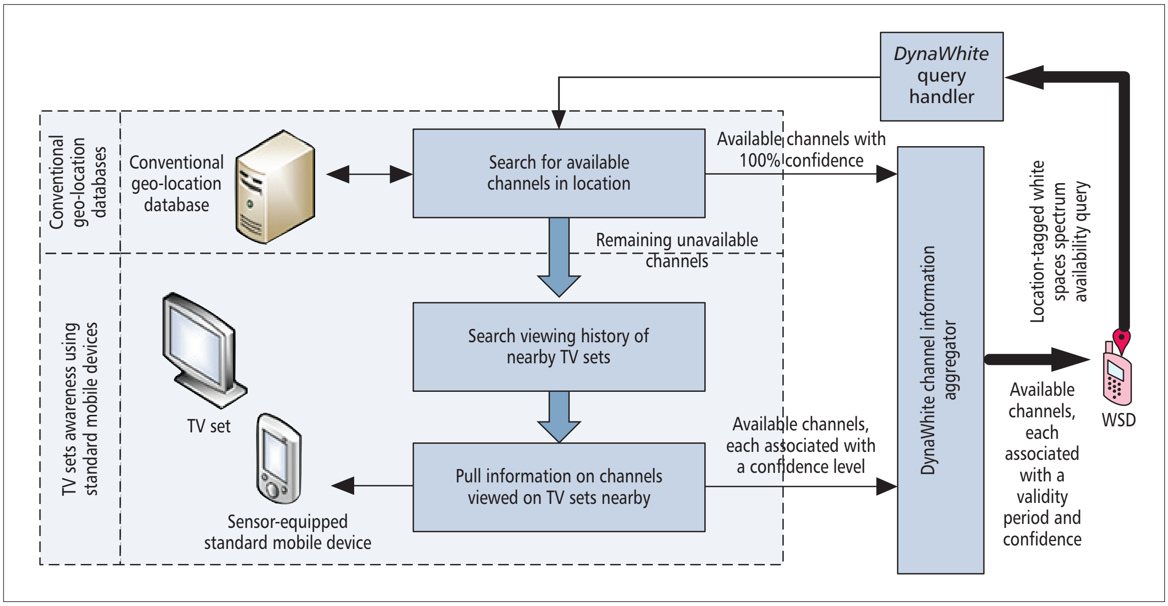

Figure 3. DynaWhite query processing flow.

quality of people's life. These sources of information can reliably tell whether there is a TV that is ON in a given area of interest and the channel to which that TV is tuned, which are reported to DynaWhite.

We develop a passive TV set detection system using mobile phones as an infrastructure that can be used to detect geographic white spaces. We briefly recount the system features and a subset of its accuracy results to demonstrate the feasibility of DynaWhite deployment. The detection system uses the camera and microphone to passively detect TV sets' behavior (i.e., visual and acoustic fingerprints) without any input from devices' owners. Video and audio snapshots are automatically recorded and matched to known TV fingerprints to detect the presence of TV sets and whether they are ON or OFF. Moreover, using online streaming sites and channel guides, the channel currently playing can also be detected using only the acoustic fingerprint of the TV set.

The accuracy of the acoustic TV detection algorithm is measured by the ability of the algorithm to differentiate between sounds coming from TV sets, laptops, and people talking. On the other hand, the accuracy of the visual TV detection algorithm is measured by the ability of the algorithm to differentiate between TV sets and other similar objects (e.g., windows and framed pictures). For more details on the algorithms used, the reader is advised to consult the work in [6].

Figure 4 shows the results of our TV detection system using only the microphone and camera of a single mobile phone using algorithms presented in [6]. These results, while not showing the feasibility of large-scale deployments, support and motivate the feasibility of DynaWhite deployed on a small scale. By accumulating and aggregating detected channel information for each TV set, collected from different sources with different reliability levels, and correlating them with time, high confidence TV set detection decisions can be reached. DynaWhite then becomes capable of estimating a viewer's watching profile.

Potential Gain in White Spaces

Simulation Setup

We conduct simulations for Miami City, Florida, and New York County (Manhattan), New York, in order to illustrate the potential gain in spectrum availability in urban areas that can be achieved using DynaWhite. According to the United States Census Bureau, Manhattan has 732,204 households over 22.83 sq mi, and Miami has 149,077 households over 35 mi^2 [11]. In our simulation, we distribute these households uniformly over the two areas, assigning one TV set per household. We randomly pick 21 percent of TV sets to be ON, reflecting statistics showing that the average American watches TV about 5.2 h a day, and only 52 percent of TV viewers watch TV while using their mobile devices. Then we select 10 percent of the TV sets to show a broadcast channel [5]. It should be noted that this setup accounts for the worst case scenario for DynaWhite since we do not account for the time of day of the TV sets' operation, the density of TV sets, or the verticality of their distribution in terms of number of floors, which is deemed to decrease the density of operating TV sets especially in Manhattan.

For each TV set, a broadcast TV channel is selected based on the TV's designated area (27 channels in Manhattan and 26 channels in Miami City) [7]. For each channel, we assign a random uniform popularity level that we use to determine the probability of the channel being selected by TV viewers. This uniform channel popularity presents an extreme case as well. We assume that all TV sets have a mobile device nearby reporting the TV status to DynaWhite [9]. Each mobile device assigns a confidence level to its TV channel detection accuracy. In our simulation, the confidence level is randomly picked between three different levels (i.e., 0.8, 0.9 and 1) that were chosen based on the lowest detection accuracy obtained in our experiments [6].

We distribute 1000 WSDs over the two areas to measure the potential increase in the number of available channels. Then we measure the amount of free white spaces on which each WSD can operate without violating the FCC's protection criteria for the TV sets, that is, the allowed signal-to-noise ratio (SNR) at the TV set caused by the WSDs. The protection criteria for co-channel transmission is set to 23 db SNR and –33 db SNR for adjacent channel transmissions [1]. We apply the Okumura-Hata model for urban areas to identify the separation needed between the WSD and the TV set in order to maintain the minimum field strength of 41 dbu for TV service at the TV set as specified by the FCC [1]. The simulation is conducted with 1, 5, 10, 40, and 100 mW transmission powers to cover all possible operational scenarios.

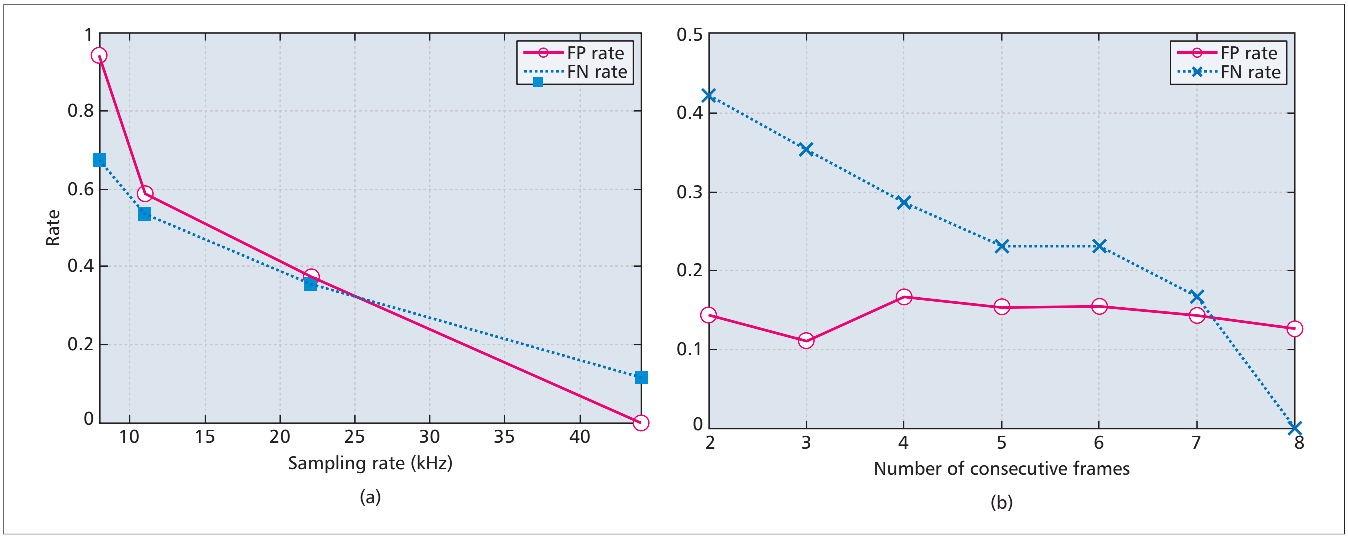

Figure 4. Summary of individual sensor detection accuracy results: a) the effect of the sampling rate of audio taken by the microphone on false positive and false negative rates of detection of a TV set; b) the effect of number of frames taken by the camera on false positive and false negative rates of detection of a TV set.

Sample Results

The results of the Miami and New York simulations are summarized in Figs. 5a and 5b, respectively. A WSD's transmission power is the parameter that a WSD can control to increase its chances in getting more channels. WSDs working at low power levels (e.g., 1 to 5 mW) are suitable for enterprise local area networks. The figures show that low-power WSDs can gain significantly more white space due to their limited range, which reduces the probability of having TV sets within their range. As the transmission power increases, the probability of having TV sets within the WSD's interference range increases; thus, the probability of getting extra channels decreases. However, devices working at 100 mW can still gain up to three channels as a worst case in Miami, and 100 mW can gain one to two extra channels in New York. These results highlight the importance of a WSD's power control that corresponds with the channel availability information supplied by DynaWhite.

From a different perspective, the parameter that is a DynaWhite design choice is the minimum allowed sensor confidence in deducing white space availability. TV sets near mobile devices that do not meet Conf are considered ON and viewing all channels; thus, no WSDs can operate near them. As Conf increases, more TV sets are not allowed to fall in the coverage area of any WSDs, which consequently decreases the probability of the number of extra channels gained.

Outstanding Challenges

The DynaWhite architecture can significantly alter the perception of white spaces, especially within urban cities. This section discusses a number of research challenges that need to be tackled by the research community to realize DynaWhite's potential.

TV Sets Detection Accuracy

In the previous section, we established the importance of the confidence level assigned by each sensor to its decision. Hence, accurate TV set detection algorithms in large deployments need to be established. These advancements will allow for the development of better confidence limit determination models for DynaWhite, thus enabling more accurate detection of geographic white space opportunities.

Given current regulations, if a mobile white space device is not connected to the database, it has to stop operating after 60 s, which conforms with our proposed approach for DynaWhite. On the other hand, fixed WSDs need to re-consult the database every 24 h. For fixed WSDs that use DynaWhite, the WSD will stop using the white spaces as soon as their validity period expires (i.e., 24 h for spectrum white spaces and the assigned validity period for geographic white spaces). However, validity periods for geographic white spaces are different in the sense that they rely on consumers' TV viewing habits. Thus, work hours and late night hours could allow for larger validity periods given known TV viewing patterns. This will require further studies to determine valid ranges for DynaWhite's validity periods.

Incentives and Privacy

Convincing mobile holders to sense and share their sensory data with others to allow for better spectrum utilization is a challenging problem. This is particularly important as users will have to use their scarce battery and network connection to share their information with DynaWhite servers. While batched uploads can be used to send data when free WiFi is available or the device is connected to power, this will be at the expense of the real-time aspect of the sensed information.

Another aspect is the privacy of the user who shares her phone sensor information. One solution is to submit only final detection results, that is, TV ON with current channel or OFF, instead of sharing the raw data (e.g., acoustic and visual data). This significantly lowers privacy concerns as it could be perceived as logging user activity on any online media streaming service (e.g., Youtube). However, this approach may consume the battery faster as audio and video processing algorithms will be performed locally on the mobile device. Another potential solution is to leverage the user's other more capable, less restricted devices (e.g., laptops, gaming consoles, or media centers) onto which such computations can be offloaded.

Regulations

DynaWhite cannot be deployed until regulatory authorities issue rulings allowing for ambiance sensing as a source of spectrum information. We propose following the same regulations of unlicensed operation of low-power devices operating in AM and FM bands [12]. These regulations allow unlicensed operation of low-power devices in those bands as long as their coverage range does not exceed 200 ft (61 m). Following the

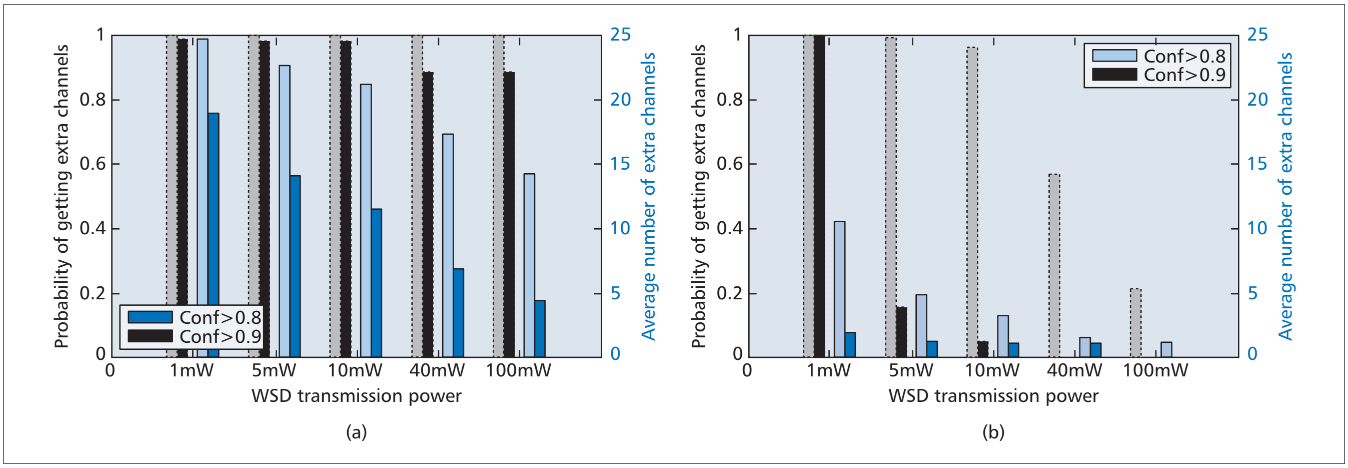

Figure 5. The impact of changing the confidence level and transmission power on the probability of gaining access new channels (in black) and the average number of extra channels (in blue) if access was gained: a) simulation results for Miami; b) simulation results for New York.

same regulations, small-scale deployments of white space networks could be made while the network administrator/owner will be responsible for making sure that the TV sets within the coverage of the white space network are detected. Even this limited scale can allow for several applications including wireless streaming of HD videos between different devices (e.g., TV set and gaming console).

On the other hand, passing regulations for wide, unlimited adaptation of DynaWhite will require controlled field tests to be carried out to show the feasibility, gains, and any conflicts the proposed fine-grained geo-location databases can cause.

Related Work

There are currently two approaches to ensuring the protection of TV white space incumbents, both based on TV transmitter information. The first approach, adopted by the FCC, relies on geo-location databases that keep track of TV transmitter parameters and propagation models in order to estimate the areas that need to be protected [2]. The second approach, adopted by the IEEE 802.22 standard, relies on collaborative spectrum sensing between the WSDs. In this approach, WSDs submit their spectrum view to a central entity responsible for performing spectrum sharing functionalities [13]. DynaWhite incorporates the first approach and extends it by its unconventional sensing for TV receivers.

On the other hand, detecting TV receivers has been addressed before, using either special hardware that senses the power leakage of a receiver's local oscillator [14], or using central trusted *manually* updated databases [15]. The former technique requires the use of special hardware that needs to be set up in the vicinity of the TV set. Such techniques do not scale and are hard to deploy. The latter technique studies the effect of knowing TV receiver information on the available white spaces in terms of the amount of additional available frequencies. They assume that in some countries (e.g., Norway) everyone who has a TV receiver must register the TV receiver information in order to pay the broadcasting license fees.

Conclusion

We present DynaWhite, an architecture for creating and maintaining the next generation geo-location databases characterized by being highly dynamic, real-time, and fine-grained. The proposed architecture detects *geographic white space*, in addition to the conventional spectrum white spaces, by incorporating an unconventional technique for TV sets localization and state detection using ambiance sensors. We develop two city-scale deployments simulations in Miami and New York to study the potential gain of using *DynaWhite*. Results show that DynaWhite has the potential of providing up to 24 extra channels to operating white space devices. Finally, we lay out possible future directions of research for improving the performance of this new generation of geo-location databases.

Acknowledgments

This work is supported in part by a grant from the Egyptian National Telecommunication Regulatory Authority (NTRA), as well as by the Qatar Foundation through Carnegie Mellon University's Seed Research program.

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