Towards a Characterization of White Spaces Databases Errors: An Empirical Study

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ABSTRACT

Spectrum regulators consider geo-location databases as the most reliable source of spectrum information for White Space Devices (WSDs). Geo-location databases protect TV band incumbents by keeping track of TV transmitters, and their protected service areas based on their location, transmission parameters, and sophisticated propagation models. However, propagation models inaccuracies can cause an overestimation of the protected area of TV transmitters leading to the inefficient usage of white spaces. In this paper, we present a large scale study, spanning an area of around 3000 km^2 over a driving path of around 190 km, showing that one of the most accurate propagation models, the Irregular Terrain Model (IMT), overestimates the signal power by up to 97% of the time. Based on this study, we provide a characterization of spectrum sensory readings that can be used to amend the prediction of propagation models. This characterization allows spectrum sensors to detect the absence of white spaces with a fairly high threshold of -84 dbm, which enables low cost and accurate spectrum sensing. Furthermore, we present the initial design of *SPOC*, a system that combines spectrum sensing and propagation modeling in order to better detect white spaces.

Categories and Subject Descriptors

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

Keywords

Spectrum Sensing; white spaces; empirical study

1. INTRODUCTION

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 US, has been regulated by the FCC as a means to support the mobile users' ever increasing demand for high quality communication and multimedia streaming [11]. 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 [11]. Spectrum sensing capabilities add complexity and cost complications to WSDs, especially with such a low sensing threshold. The latter method relies on consulting geo-location databases that keep track of available white spaces in certain areas [11] by maintaining records of TV transmitter information including location, antenna height, transmission power, and channels used. Geo-location databases utilize this information with propagation models in order to determine the protected area of a TV transmitter, where no WSD can be active [13,17]. This approach is currently the preferred method for detecting white spaces by several regulators (e.g. FCC, Ofcom and ECC [18]).

However, the accuracy of propagation models, used in geo-location databases, is questionable. For instance, the work in [23] shows that the FCC's 66602 propagation model, used in commercial white space geo-location databases [11], wastes a lot of spectrum opportunities by overestimating the protected area of TV stations. Furthermore, the authors of [23] propose *V-Scope*, an opportunistic wardriving-based system that leverages public vehicles to collect spectrum sensing measurements for constructing region-specific propagation models. These models are fused with the FCC's 66602 model to enhance the model's performance. However, *V-Scope* relies on spectrum sensing measurements made at the low sensing threshold of -114 dbm. On the other hand, according to FCC planning factors for evaluating DTV broadcast coverage, the area surrounding a TV station (a.k.a. the station's protected area) must have a signal of at least -84 dbm [2]. This implies that the protected area using spectrum sensing is much larger than the actual area that needs protection.

Our main hypothesis, as depicted in Figure 1, is that the actual protected area of a TV station is much smaller than either the area protected by using the most sophisticated propagation models, or the area protected using spectrum sensing. In fact, the area protected using propagation mod-

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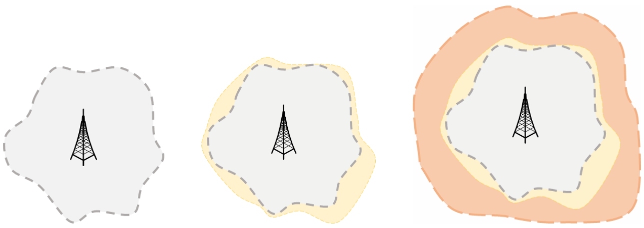


(a) Actual protected area of a TV tower.

(b) Adding the yellow area protected using propagation models.

(c) Adding the orange area protected using spectrum sensing.

Figure 1: A schematic comparison of the different views of the protected area showing the overestimation in resulting from propagation models and spectrum sensing.

els is smaller than the one protected using spectrum sensing due to the low sensing threshold of around -114 dbm used to avoid hidden node cases. This sensing threshold also adds to the complexity and cost of spectrum sensing devices. Hence, we propose an approach to fuse the global view of the protected area obtained from propagation models and the local view of individual signal strength readings obtained from spectrum sensors. This approach would amend the propagation model's view while using a higher spectrum sensing threshold.

Along these lines, we conduct a large scale measurement study to quantify and establish the erroneous nature of one of the most accurate propagation models, Irregular Terrain Model (ITM) [14]), used to estimate the coverage areas of TV stations. This study is conducted in Alexandria, Egypt with a driving path of a total length of 190 km, covering an area of around 3000 km^2. We also present a numerical comparison between the area protected using spectrum sensing and the area protected using the ITM propagation model. Based on our results, we identify geographical areas where spectrum sensing would help the most in improving the performance of spectrum databases. In particular, the goal of the study is to characterize spectrum sensing readings that are most accurate (i.e. do not fall in a hidden node case, and not malfunctioning or malicious) and hence useful to add to the spectrum databases. We derive three conditions, as a basis of this characterization, that spectrum sensory reading must satisfy in order to be used to amend propagation model predictions.

Based on these conditions, we present the design and initial evaluation of our **S**ignal **P**rediction and **O**bservation **C**ombiner (*SPOC*), a system that allows for the fusion of spectrum sensing readings with geo-location databases based on the aforementioned characterization. The main advantage of this approach is that it makes use of spectrum sensory readings that are within the decodable signal strength range (i.e. higher than -84 dbm) to detect spectrum incumbents, instead of the extremely low thresholds currently proposed for spectrum sensing (i.e. lower than -114 dbm). *SPOC* relies on the characterization of spectrum sensing errors which allows for identifying hidden node cases and malicious users without the need for sensing with low thresholds. Thus, this characterization allows for the elimination of the complexity of low threshold spectrum sensing while enabling a crowdsourcing approach of spectrum sensory readings that can be used to amend errors made in propagation model predictions.

The rest of this paper is organized as follows. Section 2 presents an overview of white space detection methods. In Section 3, we present a study comparing ground truth to propagation model predictions, followed by a characterization of spectrum sensory readings that can be used to enhance propagation models. We then present the initial design of a system that combines spectrum sensing and propagation modeling in Section 4. The related work is presented in Section 5 and finally the paper is concluded in Section 6.

2. WHITE SPACE DETECTION OVERVIEW

White spaces are wireless channels that are not used by any TV transmitters within a certain area. The process of detecting them requires satisfying two main conditions: i) safety, meaning that it prevents interference with the spectrum incumbents and ii) efficiency, meaning that it does not waste white space opportunities. In this section, we present the two most popular white space detection approaches and show their focus on safety which in turn results in wasting a lot of white space opportunities by over protecting TV towers (Figure 1).

2.1 Radio Propagation

This approach relies on having a comprehensive database of all TV stations covering the area of interest. Propagation models are then applied using the parameters of each TV transmitter to determine its protected area. A TV station's protected area is determined using a certain protection criteria based on the type of the TV station. Propagation models are used to determine the area that achieves a minimum field strength criteria that must be satisfied within the protected area of the TV station. For example, the FCC sets the minimum field strength value at the border of the protected area of a Class A Digital TV station at $41dB\mu V/m$ [11]. On the other hand, the European Communications Committee (ECC) sets the minimum field strength value to $56.21dB\mu V/m$ at the border of the protected area of a TV station [5].

The work in [17] presents the *Senseless* white spaces database which compares the performance of different propagation models to ground truth measurements. *Senseless* shows that the ITM model (a.k.a. Longley-Rice (L-R) model) [14] with terrain information achieves the best safety (i.e. avoids interference with incumbents) and efficiency (i.e. increases white spaces opportunities) compared to other propagation models. In this paper, we use the ITM model with terrain information for all propagation calculations.

2.2 Spectrum Sensing

Another approach for detecting spectrum vacancy is sensing the spectrum for TV broadcasting. Several approaches have been proposed for spectrum sensing with two main categories: i) single device, e.g. [22] and ii) cooperative sensing, e.g. [3]. The main challenge with spectrum sensing is the hidden node problem where an obstruction between the spectrum sensor and the TV station causes a miss detection of the channel occupied by the TV station (Figure 2). This problem requires lowering the sensing threshold severely below the actual protection criteria, mentioned in

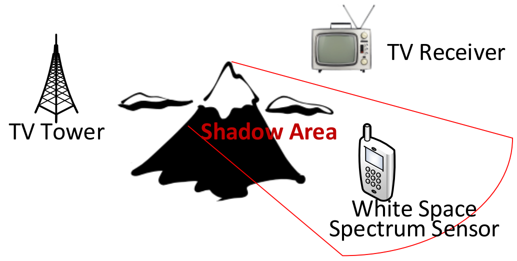


Figure 2: A hidden node case where the White Space Spectrum Sensor falls in the shadow area of the TV tower. If a sensing threshold of -84 dbm is used, the channel will be seen as vacant while a nearby TV has good reception.

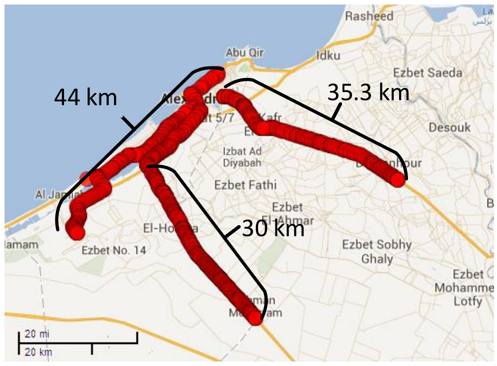


Figure 3: A map showing the measurement locations covering most of Alexandria Governorate.

Section 2.1, to ensure the protection of the incumbent receivers. For example, the FCC requires a sensing threshold of $-114dBm$ [11] which is equivalent to $26dB\mu V/m$ and the ECC proposes sensing threshold of $-120dBm$ [4] which corresponds to $13dB\mu V/m$.

Table 1 shows a comparison between the estimated radius of the coverage area of a TV station using the protection criteria (Section 2.1) and the sensing thresholds used to avoid the hidden node problem. The results in Table 1 are obtained using the L-R model assuming no obstruction in the case of using the sensing threshold, which is valid in most outdoor situations. These results show that although the sensing thresholds achieve safety, they waste white space opportunities by always assuming the worst case obstruction between the TV station and the spectrum sensor. Also, these thresholds require either really expensive sensors for accurate detection of such low thresholds, or technologies that are not commercially available yet. Motivated by these wasted opportunities, we show in the following section, that even the most accurate propagation models ensure safety but are not efficient, especially at the border of their estimated protected area. We then present a new approach for using sensory information to amend the coverage area predicted by the propagation model to accurately detect the coverage area of the TV station, which can allow lowering the sensing thresholds.

3. A LARGE SCALE URBAN STUDY

In this section, we present a large scale study that shows the inaccuracies of the L-R model as an example of one of the most complex and accurate propagation models.

Agency	Min. decodable signal power	Required sens. threshold	R_{sens}
FCC	-84 (dBm)	-114 (dBm)	1.5x R_{true}
ECC	-77 (dBm)	-120 (dBm)	2.2x R_{true}

Table 1: A comparison between the minimum power required to decode a TV signal, the required spectrum sensing threshold, and the radius of the coverage area protected by spectrum sensing R_{sens} in terms of the radius of the coverage area protected where TV reception is feasible, R_{true}.

3.1 Study Methodology

We conducted a measurement survey across the governorate of Alexandria, Egypt. The survey covered an area of around 3000 km^2 with a driving path of 190 km (as shown in Figure 3) over the duration of three months. The driving paths pass through areas with large buildings, desert, farm lands, at the edge of water bodies, and also across areas of different population densities. This terrain diversity ensures the thoroughness of testing the propagation model's accuracy.

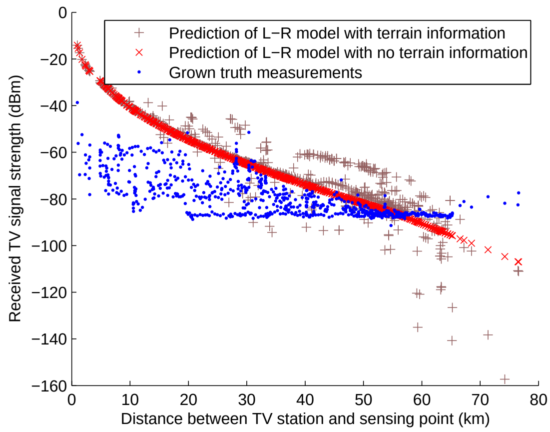
The measurement equipment consisted of a USRP N210 [8] with a WBX 50-2200 MHz Rx/Tx daughterboard. This board was fitted with a log periodic LP0410 antenna connected to a Dell XPS-L502X laptop with a battery DC/AC power inverter as a power source. Each reading was annotated by GPS coordinates obtained using a Garmin GLO GLONASS and GPS sensor. We focused on scanning the 4 active UHF analog channels by centering the receiver's frequency at the middle of the luminance portion of the signal with a bandwidth of 250 KHz. We then applied energy detection to detect the presence of TV transmission. If the received signal strength at each specified central frequency was less than or equal to -80 dBm[1], the channel is considered occupied, otherwise it is available for secondary usage.

One of the goals of the study is to measure the performance of propagation models at the border of the protected area of TV stations. For this purpose, the campaign focused on collecting measurements along several paths from the TV station to the border of the station's protected area as shown in Figure 3. Another important goal is to confirm the correlation between the predictions of the propagation model and the measurements. This observation is important in the sense that it allows the validation of new measurements based on their resemblance to predictions of propagation models.

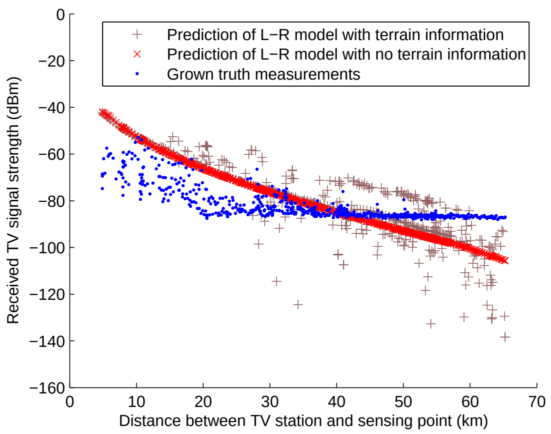
3.2 Observations

Figures 4(a) and 4(b) show the results of the measurement study. The figures show, for each point of data col-

[1]The noise floor of the USRP receiver is around -85 dBm, without the loss of the generality of our approach to any threshold we choose -80 dBm to avoid noisy readings near the noise floor.



(a) Comparison at 591 MHz.



(b) Comparison at 567 MHz.

Figure 4: A comparison between RSS field readings, L-R model predictions with no terrain information and L-R model predictions with terrain information, showing that the models almost always overestimates the signal strength.

lected, a comparison between the predicted signal strength and the measured signal strength. We use two approaches to predict the signal strength: 1) the Longley-Rice model [14] using terrain information as the most accurate propagation modeling approach, and 2) the Longley-Rice model without terrain information to model the trend of signal decaying with distance. While we plot the data for two different channels, we note, however, that due to the USRP's noise floor, no useful data was collected farther than 50 km from the TV station. Based on the collected results, we make two observations which we use later to characterize errors in the propagation model.

Observation 1: The propagation model overestimates the signal strength 97.5% of the time in the case of the channel centered at 591MHz and 94.1% of the time in the case of the channel centered at 567MHz.

Observation 2: The measured RSS readings are highly correlated with predictions of the L-R model with terrain information. These readings yield a Pearson's correlation coefficient of 0.6526 in the case of the channel centered at 591MHz and 0.6918 in the case of the channel centered at 567MHz.

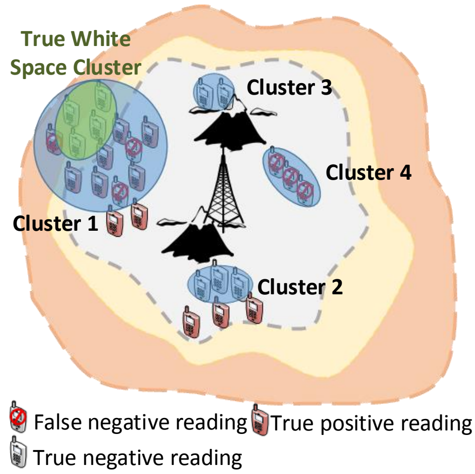


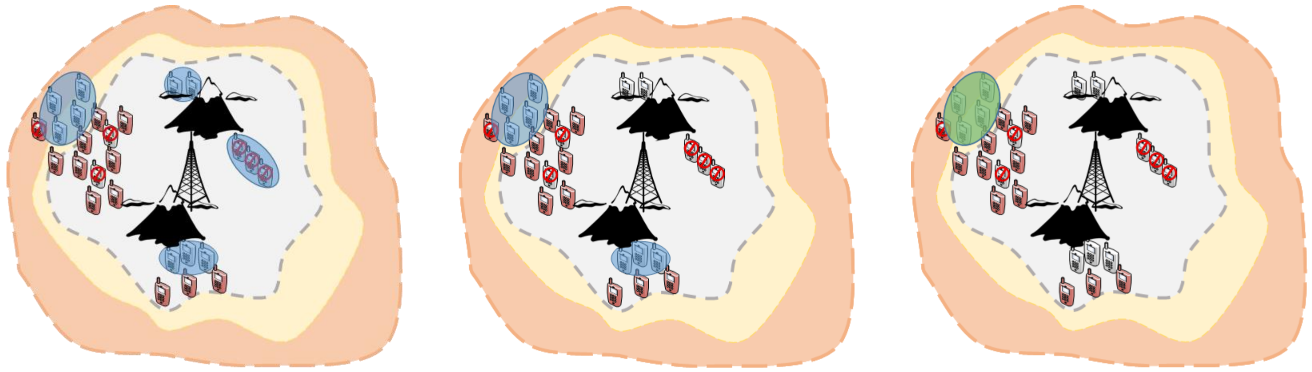
Figure 5: Different clusters of white space readings (i.e. negative readings) including both true and false negative readings.

3.3 When to Use Spectrum Sensing ?

Based on the observations made above, we argue in this section for a set of conditions that must apply to spectrum sensory readings when used to amend propagation model predictions. These conditions form a motivation for a new dynamic white space detection scheme that combines the global view of the protected area obtained from propagation models, as well as the local view of individual signal strength readings obtained from spectrum sensors. The goal of the new scheme is to overcome the two main problems facing each white space detection method: i) the hidden node problem and ii) the over-estimations made by the propagation model near the border of the protected area.

Before stating these conditions, we layout our assumptions. We assume that a set of spectrum sensing enabled WSDs are deployed throughout the area of interest and can report their location-annotated signal strength readings to a centralized geo-location white spaces database. The geo-location database also contains information about TV transmitters whose coverage area intersect with the area of interest. We chose the energy detection method for spectrum sensing [16] due to its simplicity, and because its results could be directly related to the predictions of propagation models. However, the proposed approach can be extended when feature detection approaches are used.

Initially, all collocated readings reporting the detection of white spaces for a certain channel are clustered using DB-SCAN cluster based on their geographic location (different approaches to clustering readings are further discussed in Section 4). Reported readings from WSDs can fall into 3 categories as shown in Figure 5: 1) **True Positives (TPs)** where a TV signal is rightfully detected, 2) **True Negatives (TNs)** where no TV signal can be detected and that case happens when the WSD is outside the actual protected area or when it falls in a hidden node case, and 3) **False Neg-**



(a) Remaining clusters after reducing the noisy Cluster 1 to clusters with only negative readings.

(b) Remaining clusters after removing clusters 3 and 4 that have negative correlation with the propagation model.

(c) Remaining cluster after removing Cluster 2 that is not fully contained in the protection area predicted by the propagation model.

Figure 6: Applying the three conditions to the initial set of clusters in Figure 5.

atives (FNs) where no TV signal can be detected due to malfunctioning sensors or due to the injection of malicious reports. We only cluster "negative" readings or white space readings (i.e. WSDs that report having white spaces). Clusters 1 to 4 are examples of such negative readings leading to false or erroneous clusters. Cluster 1 was formed based on both TNs and FNs that led to having a number of TPs within the cluster's geographic area. Clusters 2 and 3 were formed based on TNs that do not detect the TV signal due to a hidden node case. However, the readings in Cluster 2 exhibit a correlation with the propagation mode. Cluster 4 is formed based on a number of FNs. Our goal is to identify the "True White Space Cluster" (in green) that is merely a part of Cluster 1 and represents a number of TNs that are outside the actual protected area (in light gray).

We now state the conditions that need to be satisfied for effectively leveraging spectrum sensing. To be able to identify a set of sensory readings to be true white space readings and hence use them to amend the predictions of propagation modeling, these readings must satisfy all the following conditions:

Condition 1: Readings must be grouped into a collocated cluster, with all readings contained within the border of that cluster below the threshold of decodable signal power. *This condition guarantees ignoring noisy clusters (e.g. Cluster 1 that has TPs within its geographical area) to ensure the safety of the approach.*

Condition 2: Readings belonging to the same cluster must have a positive correlation, above 0.5, with the modeling of the signal propagation in the area covered by the cluster (Observation 2). *This condition allows for detecting malicious or noisy clusters (e.g. clusters 3 and 4 that are either FNs or TNs in a hidden node case).*

Condition 3: Clusters must not be fully enclosed within the protected area of the TV station covering their area. *This condition allows for the avoidance of hidden node problems by only modeling mispredictions near the border of the protected area (e.g. Cluster 2 that had TNs but due to a hidden node case instead of actually being outside the protected area).*

Figure 6 shows the effect of applying each of the proposed conditions on the initial clusters in Figure 5. Large clusters that include positive readings within their convex or concave hull are broken into smaller clusters, eliminating noisy clusters and ensuring the safety of the approach (Figure 6(a)). Also, The validity of the collected readings must be ensured to avoid hidden node problem cases and malicious contributors by correlating the sensory readings with the propagation model predictions based on Observation 2 (Figure 6(b)). Areas that are fully enclosed by the predicted protected area using propagation models is eliminated to ensure that all hidden node cases are detected (Figure 6(c)).

Remarks on the proposed conditions:

1. The conditions sacrifice some of the efficiency of the system's ability to detect all possible white space opportunities by ignoring the presence of false positive readings and by considering only clusters that are not fully enclosed by the predicted protected area of the TV tower. However, this sacrifice is made to ensure the method's safety by favouring spectrum incumbents.
2. The proposed conditions rely mainly on having a large number of contributors to allow for the detection of noisy clusters and prevent the formation of large faulty clusters. However, this can be prevented by the strategic placement of trusted sensors or wardriving by the operators of the geolocation database to support or even replace readings collected from contributors.

4. SPOC: SIGNAL PREDICTION AND OBSERVATION COMBINER

In this section, we present an initial attempt to design a *SPOC* system. Then, we present and discuss future research directions in order to allow for large scale deployments of the system.

4.1 SPOC Architecture

Figure 8 provides an overview of the system's architecture. The modules of the proposed system are implemented in a centralized server. WSDs communicate with *SPOC* servers through the Internet. They can also query *SPOC* for white spaces availability or submit their raw spectrum

(a) The modeling engine produces the protected area as predicted using ITM model.

(b) The Sensory readings processor collects and clusters sensory readings (the cluster above the threshold shown in dark blue and clusters below the threshold are shown in light blue and red).

(c) The fusion module infers the area represented by each cluster and subtracts them from the original protected area.

Figure 7: The three steps of *SPOC*'s operation overlaid on a map of Alexandria, Egypt where the data was collected.

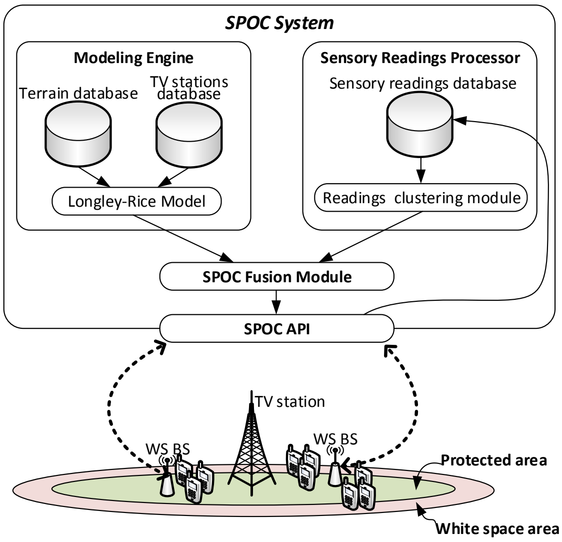


Figure 8: SPOC system architecture.

sensory readings (i.e. no sensing threshold required) in order to allow *SPOC* to obtain a more accurate view of the signal propagation. Upon receiving a white spaces query, *SPOC* considers a channel as white space if either it is outside the coverage area of any TV station working on that channel, or if it is within a cluster of readings that satisfy the conditions mentioned in the previous section. This means that from an efficiency perspective, *SPOC* performs, in the worst case, similar to conventional geo-location database.

Figure 7 shows the different steps by which the predictions of propagation models are amended using sensory readings. First, the *Modeling Engine* uses the ITM model to predict the coverage area of the different TV stations that are required to be protected by the system's administrator. A sample of this engine's output is shown in Figure 7(a). The *Sensory Readings Processor* continuously collects readings from its WSD clients, clusters those readings, and ensures that they satisfy conditions 1 and 2 (Figure 7(b)). Finally, the *SPOC Fusion Module* uses only the clusters that satisfy Condition 3 to amend protected areas predicted by the propagation model as shown in Figure 7(c). For the remainder of this section, we explain the details of each of those three steps.

4.1.1 Modeling Engine

The purpose of the *Modeling Engine* is to calculate a prediction of the coverage area of the TV signal transmitter using one of the known propagation models. In *SPOC*, we use the L-R propagation model which takes into account the nature of the terrain [9] in order to better predict the propagation of the signal. However, *SPOC*'s modular architecture allows for the usage of any propagation modeling approach which might lead to more accurate predictions [17].

4.1.2 Sensory Readings Processor

This module continuously collects readings from its WSDs clients. The *Readings Clustering Module* clusters collocated readings such that all readings contained in a single cluster are below the decodable signal power threshold. This ensures that we only have small clusters of readings all confirming the same decision which allows for ignoring some noisy readings that give false negatives. Moreover, readings belonging to the same cluster must have a positive correlation with the modeling of the signal propagation in the area covered by the cluster, which allows for the detection of some hidden node cases and the rest of malicious or noisy clusters.

We applied the DBSCAN [7] clustering algorithm to group collocated readings that are below the minimum decodable signal power. The next step is to define the border of each cluster. We define the border of each cluster using either the convex hull of all readings belonging to the same cluster (Figure 9(a)), or the alpha-shape [6] comprising the concave hull of the readings (Figure 9(b)). While concave hulls provide a safer approach, we found that by reducing the size of a cluster by adjusting the DBSCAN's parameter, concave and convex hulls did not produce different results (Figure 9(c)).

It is important to note that even smaller clusters are several tens of kilometres in length and several kilometres wide.

(a) Large cluster sizes with their coverage area inferred by calculating the convex hull of each cluster.

(b) Large cluster sizes with their coverage area inferred by calculating the concave hull of each cluster using alpha shape algorithm.

(c) Small cluster sizes with their coverage area inferred by calculating the convex hull of each cluster (concave hulls produced similar results).

Figure 9: Comparison between clustering approaches (large clusters in a and b, and small clusters in c) and cluster border definition techniques (convex hull in a and c, and concave hull in b).

This denotes the significance of using SPOC instead of conventional white space detection approaches.

4.1.3 SPOC Fusion Module

The detected cluster borders are assumed to enclose TV transmission-free areas. We use an image processing approach to fuse those areas with the area predicted using propagation models. The protected area is assumed to have a foreground color while the surrounding TV transmission-free area is assumed to have a background color to form an image. The TV transmission-free areas inferred based on spectrum sensors is then super imposed over the original image with the background color.

Edge detection [20] and basic morphology is applied on the resulting image to calculate the new border of the protected area. Hence, the module filters inferred clusters by using only the clusters that are not fully enclosed within the protected area of the TV station predicted by the propagation model. This way, the rest of the hidden node cases are detected by taking into account only the modeling mispredictions near the border of the protected area.

4.2 Discussion and Future Directions

The proposed *SPOC* system has the potential of significantly increasing white space opportunities by amending the over protective predictions of propagation models while requiring fairly high sensing thresholds. Hence, contributing spectrum sensors can have a lower complexity hardware and require less computational power. However, several challenges and directions are yet to be addressed in order to enable the large scale deployment of *SPOC*. We now present three of the most challenging problems that need to be addressed. Moreover, we realize that further analysis of the system's performance is required to define an optimal configuration of the system's operation.

4.2.1 Security

Security against malicious contributors is inherently addressed in *SPOC* by ensuring the sensory readings' correlation with the propagation model. On the other hand, further security measures must be developed in order to avoid planned massive attacks that can take into account correlation with the signal's propagation model. The work in [10] discusses several hierarchical approaches towards combining crowdsourced spectrum information.

4.2.2 Fixed Sensor Placement

The initial proposal for *SPOC* relies on a crowdsourcing approach, however, spectrum databases operators may require a more secure and reliable source of spectrum information. This motivates the development of an algorithm that can determine suitable locations that will maximize spectrum information if they had sensors. One possibility is to perform wardriving near the borders of protected regions in order to identify areas with the most deviation from the propagation model.

4.2.3 Reliability

SPOC's reliability has two components, the first is the availability of contributors. This issue can be addressed by placing fixed sensors or by providing incentives for contributors in terms of extra bandwidth. The second component is the delay incurred by the computational complexity of processing incoming readings along with the computationally expensive ITM model. Several approaches were proposed in [17] to address similar problems including precomputation (i.e. performing large scale predictions for various locations and caching them) and caching terrain information and sensory information.

4.2.4 Transmission Power Limitation

SPOC allows WSDs to operate extremely close to the border of TV stations protected areas. This can allow WSDs operating too close to those borders to cause interference at nearby TV receivers. Thus, *SPOC* must set a maximum transmission power for its client based on the white spaces assigned to them. These limits should be based on the location of WSDs with respect to the border of different TV stations.

5. RELATED WORK

Technologies used to improve white space detection efficiency has been gaining a lot of attention since the FCC ruling to allow the unlicensed usage of TV white spaces. The two main approaches for white spaces detection are geo-location [13, 17] databases and spectrum sensing. The work in [17] proposes a geo-location database that uses an improved version of the L-R model in order to enhance its efficiency in detecting white spaces. However, the accuracy of even this sophisticated L-R model has been in question within the TV broadcasting paradigm due to the need of high accuracy modeling of the coverage areas [15, 19].

On the other hand, spectrum sensing has been gaining a lot of attention, although several studies argue that single device sensing doesn't form a valuable source of spectrum information [1, 12]. These conclusions are motivated by the low thresholds required for single device spectrum sensing and the wasted opportunities by spectrum sensing as identified by the work in [13]. These conclusions motivated a large body of work on cooperative spectrum sensing, surveyed in [3]. Furthermore, spectrum sensing for detecting extra white spaces indoors was proposed in [21].

The work in [23] attempts to bridge the gap between geo-location databases and spectrum sensing through a standard model fitting procedure that amends the FCC's R6602 propagation model using spectrum sensing readings. However, focusing on the computationally efficient, but inaccurate FCC R6602 model, and relying on a simple model fitting approach, does not take into account typical white space issues like the hidden node case. Furthermore, this approach doesn't discuss security in anyway.

However, our work aims at establishing that this gap exists even while using sophisticated and accurate propagation models through a large scale measurement study. Furthermore, it bridges the same gap by using cheap and low complexity spectrum sensing with a sensing threshold over -84 dbm, to amend the prediction of the L-R propagation model.

6. CONCLUSION

In this paper, we presented a study that establishes the erroneous nature of one of the most sophisticated propagation models, the L-R model. We performed a large scale study covering an area of around 3000 km^2 showing that the model overestimates the signal power up to 97% of the time. These errors lead to an overestimation of the protected area of TV towers leading to inefficiencies in the detection of white spaces. Building on this study, we presented a characterization of spectrum sensory reading that can be used to amend the prediction of propagation models. Furthermore, we proposed *SPOC*, a system that aims at fusing the global view of propagation-modeling-based spectrum databases and the local view of spectrum sensing. *SPOC* increases the detected white space opportunities, while requiring fairly low spectrum sensing capabilities. In the end, we drew insights from our initial attempts to develop *SPOC* and presented some of the challenges and future directions that need to be addressed for the deployment of a large scale version of the system.

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