Exploring White Spaces in Metropolitan Cities: A Measurement Study in Hong Kong

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***Abstract*—This paper presents a large-scale TV spectrum measurement study in 30+ urban and rural locations in Hong Kong. Both indoor and outdoor measurements have been taken at each location. Previous measurement studies usually involve only a few geographical locations in a city. We find that the wireless environment in a metropolitan city like Hong Kong is rather complicated, and we need to measure a substantial number of representative locations in order to obtain a comprehensive understanding of the TV white-space feasibility.**

Based on our measurements, we analyze the white-space opportunities from different aspects including white-space distribution, white-space rate by different thresholds, etc. Our results show that different areas in Hong Kong observe very different white-space availability patterns. The closer to the downtown, the less white-space opportunities. In particular, the averaged outdoor white-space ratios in urban, sub-urban and rural areas are 44.1%, 55.9%, and 60.9%, respectively. In addition, the switch-over from digital to analog TV in a few years will release additional up-to 35% of the TV spectrum as white spaces in Hong Kong. The indoor white-space ratios in urban, suburban and rural areas are 67.9%, 74.7%, and 73.3%, respectively, which are much higher than the white-space ratios in outdoor scenarios. We also find in indoor environment there exist more contiguous vacant TV channels than in outdoor environment, which can be exploited to better support high-rate wireless communication. We believe our results are useful for understanding the white-space opportunities in metropolitan cities.

I. Introduction

In recent years, the demands for spectral capacity are increasing rapidly to provide high data rate wireless communication. The license-exempt spectrum supply cannot catch up with the vast increasing demand, resulting in the bottlenecks in wireless broadband access. According to Federal Communications Commission (FCC)'s rule [1], white-space devices can access vacant TV channels using geo-location database or spectrum sensing for efficient spectrum utilization. It is shown in previous research [2] that wireless signal transmission using the TV spectrum outperforms those using 5GHz and 2.4GHz band in terms of superior propagation and penetration ability. Deployment of white-space devices has attracted much attention recently for its high economic value especially in metropolitan cities. Characterizing cities' spectrum usage pattern is essential for regulators to make proper decisions and establish a solid foundation for further research.

In this paper, we present a large-scale TV spectrum occupancy measurement study in Hong Kong. Hong Kong has a typical metropolitan city environment such as concentrated population and high building density. There are two principal reasons that make TV spectrum occupancy distribution in Hong Kong complicated: 1) Over 70% terrain in Hong Kong is hilly or mountainous with steep slopes, and there are high density buildings in urban area, which have significant influence on the TV signal propagation. 2) Dozens of TV towers distribute unevenly in different districts which have their local coverage areas. This indicates that a large-scale measurement is needed for a complete understanding of the TV spectrum occupancy distribution in Hong Kong.

To detect the TV signals accurately, we choose feature-based detection scheme. Analog TV signal is detected by its signal feature pattern in frequency domain. For digital terrestrial television in Hong Kong, it has removed the pilot tone but use pseudo noise (PN) sequences as guard intervals, so the PN correlation detection method is chosen in our project. As compared to the energy-based detection technique commonly adopted in previous studies [3], [4], [5], [6], our scheme achieves higher detection accuracy and is robust to noise.

Our study results in the following three main contributions. First, this is the first large-scale measurement study in a metropolitan city. 30+ locations have been chosen in our measurement that cover all the 18 districts in Hong Kong [7]. Both outdoor and indoor has been measured at each location. We observe the outdoor white-space ratios in urban, sub-urban and rural areas are 44.1%, 55.9%, and 60.9%, respectively. This suggests that the closer to the downtown, the less outdoor white spaces. We also find the outdoor white-space ratio is correlated with population density in Hong Kong. In high population density areas, there always exist less available TV channels. In addition, we estimate that the switch-over from digital to analog TV will release additional 35 percentage of the TV spectrum as white spaces, which is more than 110MHz spectrum.

Second, we find the indoor white-space ratios in urban, suburban and rural areas are 67.9%, 74.7%, and 73.3%, respectively, which are on average 18% higher than the white-space ratios in outdoor scenarios. Different from the outdoor white space distribution, there is no significant white-space ratio decrease in urban area. This means we still have a lot of white-space opportunities in urban areas that have the largest spectrum demand. Additionally, there are also a substantial amount of contiguous vacant channels in indoor scenarios as compared to the outdoor scenarios. Prior research has shown that using aggregate contiguous channels in wireless communications improves throughput [8], [9]. The indoor scenarios thus provide a better dynamic spectrum access environment

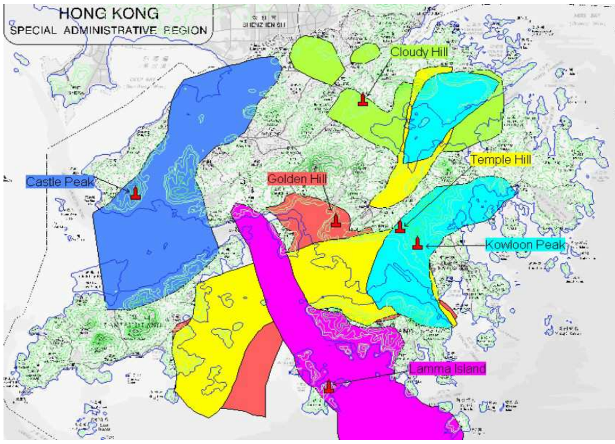

Figure 1: Estimated coverage of principal transmitting stations [11].

Figure 2: A map showing the 31 diverse measurement locations, covering all the 18 districts in Hong Kong [7]. Each measurement location corresponds to a droplet-shape marker on the map.

for white space devices than the outdoor scenarios.

Third, we study the accuracy of the model-based white-space identification approaches in this paper. FCC's ruling on September 2010 has removed the mandatory requirement of spectrum sensing, and there is trend towards using geo-location and database to identify white spaces based on propagation models. By comparing the modeling results checked from Microsoft's online White Space Finder [10] with our measurement data, we find substantial white space loss in modeling results. This suggests that the field measurement can give us more reliable results and spectrum sensing is still indispensable in some cases. More accurate models can be introduced or fine-tuned using our measurement results.

The rest of the paper is structured as follow. Section III describes measurement locations and methodology in data collection and detection algorithms. Section IV contains the observations from our outdoor measurement including the white space distribution and in-depth analyses. Section V then presents the analysis results of indoor spectrum opportunities. Finally we summarize our observations and conclude in Section VI.

II. Related Work

There have been several spectrum surveys in other cities such as Chicago [3], New York [12], Singapore [5], Guangzhou [4] and Vienna near Washington [13]. According to their measurement results, there exists abundant white-space networking potential in those cities. Those measurements paid more attention on the time-varying nature of spectrum usage and deployed only a few and fixed locations for the measurement. However, wireless environment in metropolitan cities are complicated because TV signal propagation is influenced by terrain situation as well as blocking of high density buildings. The uneven distribution of TV towers may influence the spectrum usage pattern in different districts as well. In this case, we need measurements in a large number of various locations to obtain a good understanding towards white-space opportunities in metropolitan cities.

Since the mandatory requirement to use spectrum sensing is discarded due to sensing efficacy, the geo-location and database query has been widely studied these years. [14], [15] have discussed the feasibility of adopting geo-location and database access for white space query. [16], [17] have studied the white space availability in Europe and US by geo-location and modeling. In our work, the calculated results in different models are compared with our measurement data. We find that the model-based approach fails to identify many vacant TV channels. This suggests that in a metropolitan city with complicated radio environment, spectrum sensing based approach may give us more accurate white-space availability results.

The indoor white space opportunity has rarely been explored, although over 70% of spectrum demand comes from indoor environment [18]. [19] presents an evaluation of spectrum occupancy in both indoor and outdoor scenarios at one particular location. In [20], an experimental spectrum sensor test bed is constructed to study indoor radio environmental map. However, these evaluating studies are small-scale and there are limited observations on the characteristics of the indoor environment. We analyze the indoor white-space opportunities at multiple locations in a metropolitan city in this paper.

III. Large-Scale Measurements in Hong Kong

A. Objective

We take a large-scale measurement in Hong Kong in order to have a complete understanding of TV spectrum usage characteristic in metropolitan cities. As show in Fig. 1, which is the estimated coverage map of principal transmitting stations in Hong Kong provided by Office of the Communications Authority of Hong Kong (OFCA) [11], there is vast difference in TV signal coverage between rural and urban areas caused by the uneven distribution of transmitters. Over 70% of Hong Kong's terrain is hilly to mountainous and there exist the largest number of skyscrapers in the downtown. In this case, enough number of measurement locations have been chosen in our project. For more accurate identification on the low

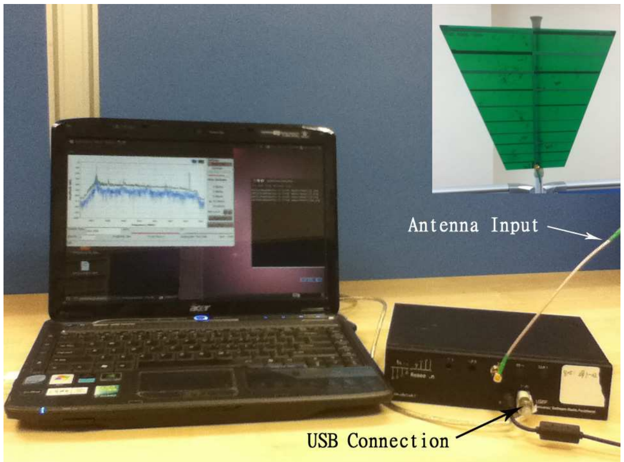

Figure 3: Photograph of the measurement device.

energy signals, we adopt feature detection on TV signals which performs well even at low SNR. We present the measurement details in the following.

B. Measurement Locations and Methodology

In this paper, 30+ locations have been measured including Hong Kong Island, Kowloon peninsula and New Territories (Shown in Fig. 2). These locations have covered all the 18 districts in Hong Kong [7], which have different terrain and population characteristics. For example, the urban area such as MongKok has the highest density population in the world. While in some remote areas such as Yuen Lang, the population and building densities are much lower.

We choose open areas for outdoor measurements at each location and the indoor measurements are taken inside various commercial buildings nearby. We measure the indoor / outdoor spectrum usage pattern at three time instants, one in the morning, one at noon and one in the evening at the selected locations. The time interval between two adjacent measurements is four hours. In each measurement, we scan all 42 analog and digital TV channels with frequency range of 470-860 MHz in Hong Kong. In this paper, we focus on the spatial characteristics analysis of the white space distribution and the broadcasting time table can be checked from database, so we didn't take long period measurements in our project.

C. Tools and Equipments

The hardware equipment used for measurement consists of a USRP [21], a Log Periodic PCB Antenna and a laptop computer shown in Fig. 3. The USRP board coupled with a TVRX receiver-only daughter board is suitable for receiving signals from 400 to 860MHz which covers the TV band in Hong Kong. GNU Radio [22] is chosen as the software platform to process the received signals. Analog and digital TV signal detection algorithms are performed to detect the existence of TV signals robustly in the software platform.

After performing FFT on the PC, the output signals from USRP and GNU Radio is a relative value in dB which should

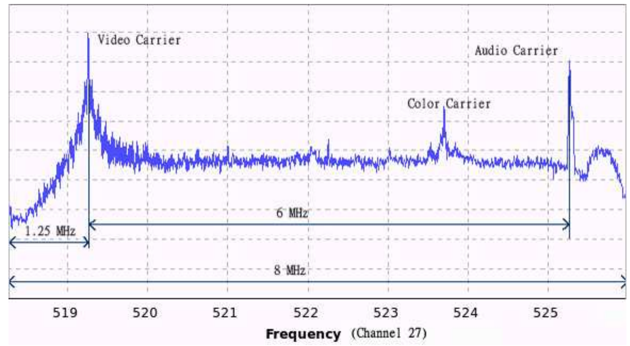

Figure 4: Analog TV signal frequency pattern.

Frame header (420, 595, or 945 symbols)	Frame body (system information and data) (3780 symbols)

Figure 5: Signal frame structure of the DMB-T.

82 (217) symbols in front synchronization	PN 255 (511)	83 (217) symbols in rear synchronization

Figure 6: Frame header structure, PN420 (PN945).

be calibrated into absolute power level at the antenna input. Prior to measurement, the following procedure should be done.

- A RF signal generator is connected to USRP as standard signal source input and the recorded power levels measured by USRP are provided.
- The difference between the signal generator and the USRP output is recorded.
- The calibration value is then added to the measured values in which case we can read absolute power level in dBm from laptop.

After these settings, we can construct a flexible and reliable spectrum analyzer which can meet all the requirements for our measurements.

D. TV Signal Detection Algorithms

Energy detection has been adopted widely as the most convenient way for white space detection [23]. However, the performance of energy detection drops when the signal is at low SNR. In Hong Kong, there exist dozens of principal and fill-in transmitting stations. Some distant TV transmitters may visible with very low power level which cannot be identified by energy detection accurately. Additionally, spatial variation may exist widely in urban environment, which means the building constructions may cause unexpected signal attenuation even on small scales. The energy detection method performs badly when detecting such low power signals. For more accurate detection, we adopt feature detection to identify the existence of TV signals.

Two algorithms have been designed to detect analog and digital TV signals respectively. (1) Analog TV signal (PAL) is identified by its signal feature which is the location of its video carrier and its peak energy level in frequency domain as

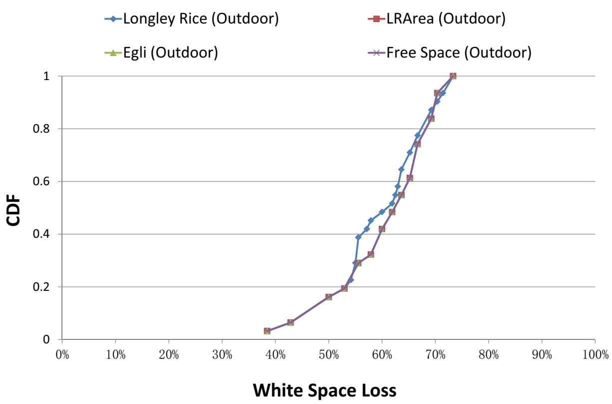

Figure 7: White Space Loss in outdoor environment.

shown in Fig. 4. Detection based on video carrier location is robust against noise uncertainty since the position of the peaks can be pinpointed with accuracy even if the amplitude is low due to fading. We use a 2048 point FFT with the FFT bin size 3.9 KHz to get good accuracy in signal pattern detection. The device achieves a minimum discernible video amplitude sensitivity of -114 dBm.

(2) Digital TV (DMB-T) in Hong Kong adopts Time-domain synchronous OFDM (TDS-OFDM) technique as the digital multi-carrier modulation method. Instead of cyclic prefixes, pseudo noise (PN) sequences are inserted as guard intervals. In this case, the typical DTV pilot tone detection does not work in Hong Kong. There are three frame header modes defined in DMB-T Standard as shown in Fig. 5 and Hong Kong adopts mode 3. Observed that the PN sequence consists of one front synchronization, one PN255 sequence and one rear synchronization (shown in Fig. 6), and the front and rear synchronizations are cyclic extensions of the PN255 sequence with the length of 217 symbols 6, the existence of DMB-T signal can be detected by the correlation of the PN sequences.

These two detection algorithms have been proved to be robust even under low SNR in our test. The TV channel power is recorded for further signal energy analysis.

IV. Outdoor Measurement Results and White Spaces Opportunity Analysis

A. Model-Based Approaches Under-Estimate White Spaces Availability

FCC recommends to use a model-based approach for identifying white spaces for its low-cost and reliable protection for primary users [1]. The estimated receiving TV signal powers can be calculated by different propagation models with several parameters as the input, such as the distance between transmitter and receiver, transmission power and the terrain information. To verify the accuracy of white space modeling, especially in metropolitan cities such as Hong Kong, we use an online WhiteSpaceFinder [10] provided by Microsoft, from which we can check available TV channels at particular locations upon the model-based approach. The parameters of the WhiteSpaceFinder uses for calculation are provided by OFCA open database [11]. We then compare our ground-truth measured data with the modeling results, with four typical propagation models are used for the calculation, namely Longley Rice, LRArea, Egil, and Free Space.

By this comparison, we find all the TV channels estimated to be vacant are indeed free to use; hence, there is no false alarm. However, the model-based approach fails to identify many vacant TV channels.

We define a metric, called *white space loss*, as follows:

$$\left(1-\frac{\text{number of unused channels a model estimates}}{\text{number of unused channels}}\right)\times 100\%. \tag{1}$$

It represents the percentage of vacant channels that are not identified by a model at a location. The cumulative density function (CDF) of the indoor and outdoor white space losses are shown in Fig. 7. Observed from this figure, more than 50% of outdoor white spaces cannot be found, which are very significant losses.

This heavy white space loss can be explained that the mountains and the dense tall buildings have big influence on the signal propagation which make the modeling result inaccurate. More sophisticated indoor/outdoor models are needed for accurate white space estimation. This suggests that in some metropolitan cities, the white space environment is much more complicated than we have recognized before. The ground-truth measurement can give us more reliable result and outdoor models need to be modified as well.

B. Outdoor Measurement Results

Via our large-scale measurement, we have a more complete observation on the existing white space opportunities compared with previous measurement work. Fig. 20 in the appendix shows the fraction of utilized TV spectrum out of the evaluated 42 channels at 31 locations. These results have been averaged by three time instant results. As shown in the figure, the spectrum usage ratio ranges from 29% to 69%, makes the white spaces distribute uneven in different districts. This confirms our intuition that the measurement deployed at limited locations can not reveal the complete radio environment in a metropolitan city. Many more details have been presented in our work. We will make in-depth analyses in the following subsection.

C. Outdoor White Spaces Opportunity Analysis

1) Outdoor White Space Distribution: As has been discussed before, the white space distribution is quite uneven in Hong Kong. In particular, we first group the 18 administrative regions into three areas, namely urban, sub-urban, and rural, according to the population density [7] and show the result in Fig. 9. The downtown area is inhabited by high-density population and fewer people live in rural area. Outdoor measurement result details at 29 locations are presented in Fig. 8. Note that two locations that influenced by TV signals from adjacent city Shenzhen have been removed. Fig. 8 illustrates how the white space distribute from the most remote areas to the downtown of Hong Kong. Obviously, the closer to the

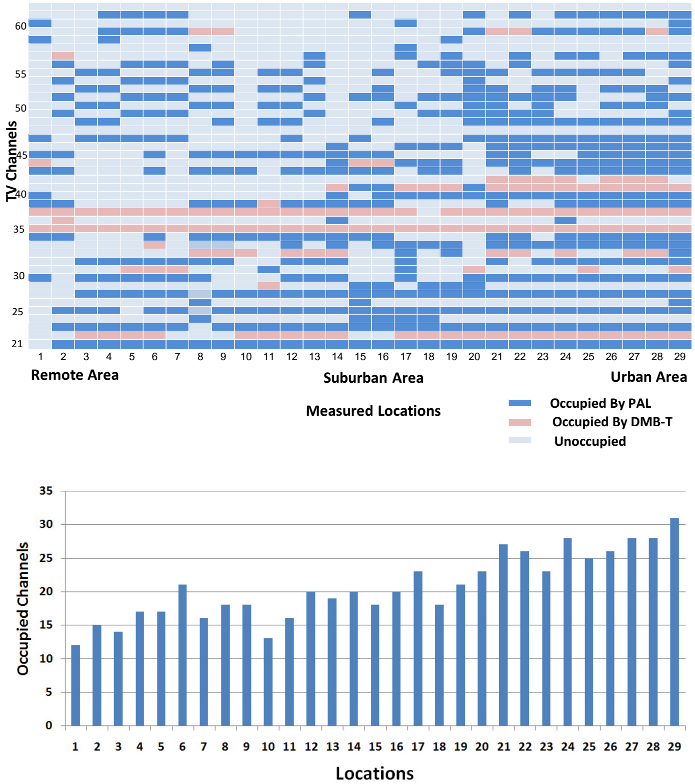

Figure 8: White space distribution details and occupied percentage statistics (Outdoor). In our measurement, we can receive several TV signals from adjacent city Shenzhen at two locations in rural area. So we exclude these two locations in this figure, resulting 29 locations presented.

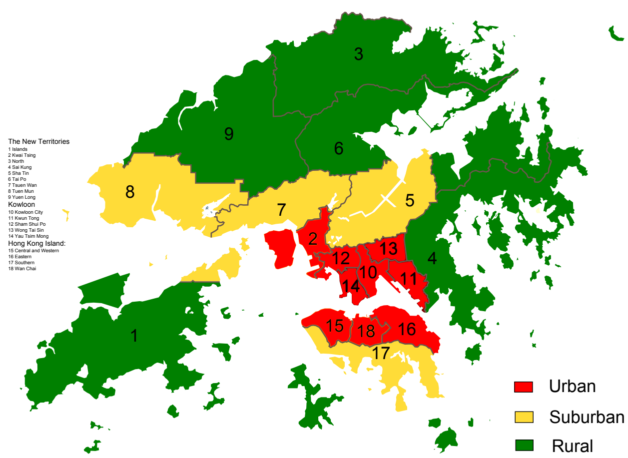

Figure 9: Urban, sub-urban and rural areas in Hong Kong.

remote areas, the sparser occupied channels distributed, while in downtown the TV channels are heavily occupied. We make a quantitative analysis on the three areas and calculate the white space rate respectively. The analysis result shows below:

- Urban area - The locations in North Hong Kong Island and Kowloon Peninsula are the areas heavily occupied by TV signals. The average white space availability ratio is 44.1%.
- Suburban area - This area includes East Kowloon, Tsuen Wan, Shain and South Hong Kong Island. From Fig. 9 we can find those districts distribute around the urban area and the average white space is 55.9%.
- Rural area - This area includes most of the remote districts in Hong Kong including North New Territories, Yuen Long and Tai Po. All the locations in this area have very low TV spectrum usage ratio with the overall white space 60.9%. These remote districts are usually covered by only one or none principal transmitting station.

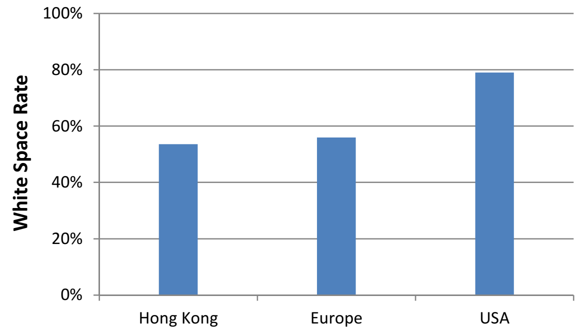

Figure 10: White space ratio in Hong Kong, Europe and USA.

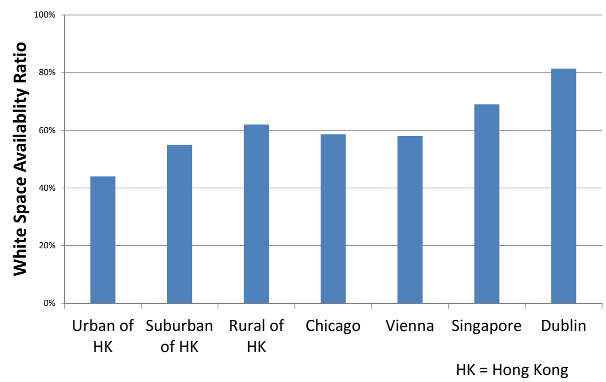

Figure 11: Comparison of white spaces in different cities.

The overall white space in Hong Kong is 53.6%. From this quantitative analysis we confirmed our intuition that the closer to the downtown, the less white space opportunities in outdoor environment.

2) White Space Findings Compared with Other metropolitan Cities: More in-depth analyses on the complicated white space distribution will be present in the following. First of all, we are interested in how the white space availability in Hong Kong is compared with US and Europe that have been widely studied. Note that US has completed the digital switch-over in 2009, so we have chosen those data in US collected after the transition. We present the comparison of Hong Kong's white space with Europe [16] and US [17] and show the result in Fig. 10. From this figure we can see the white space opportunity in Hong Kong is similar to Europe but less than US. That's possibly because of the completed digital transition in the US.

Then we compare the white space of Hong Kong with other metropolitan cities such as Chicago [3] and Vienna [13] (near

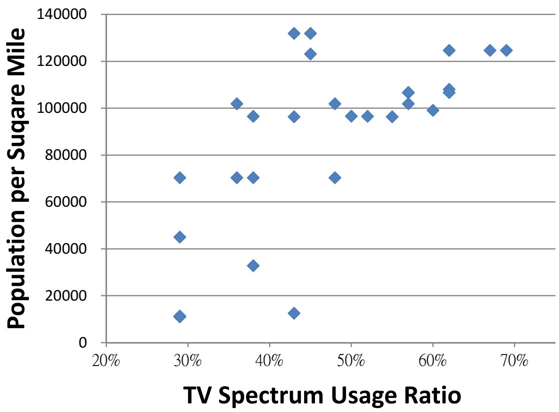

Figure 12: Spectrum usage ratio vs population densities of measured locations.

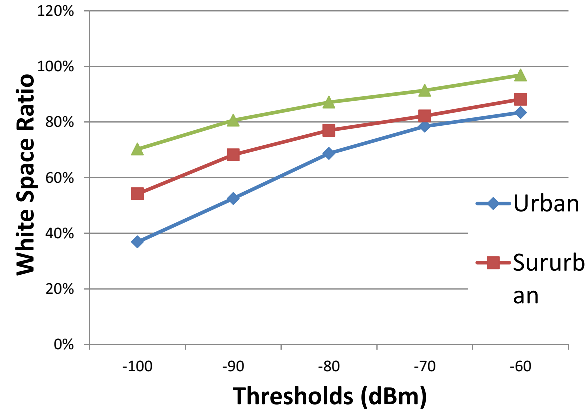

Figure 13: White-space ratio by thresholds.

Washington DC) in US, Dublin [24] in Europe and Singapore [5] in Asia. There have been several measurement papers [24], [5], [13], [3], so we check the white space ability in those cities from existing literature. Due to that the previous measurements were taken at one particular location in those cities, we present the white space ratio of Hong Kong as urban, suburban and rural results separately in the comparison (shown in Fig. 11).

Fig. 11 shows that the urban area of Hong Kong has the lowest white-space ratio, which is also the area with the highest population and building density in the world. Similar with Hong Kong, in Chicago and Washington there also exist large number of skyscrapers and about 58% of TV spectrum is utilized. Before the digital transition, the white-space ratios in these two cities were about 45%. Dublin is the smallest city in the comparison and it has the highest white-space ratio. We have the intuition that in more metropolitan cities, the less white spaces exist. But surprisingly, in Singapore with the highest population density among these cities except Hong Kong, the TV spectrum occupancy ratio is as low as 30%. After checking the broadcasting table we find Singapore is a quite small country which surrounded by Malaysia and Indonesia, so the 11 VHF channels and 42 UHF channels for TV broadcasting have been shared by all the three countries. Singapore is a very unique case among these cities.

3) White-Space Ratio by Thresholds and Correlations with Population Density: Intuitively, in high population density areas, there exist more principal and fill-in transmitters which may occupy more TV channels. Our previous result also shows the white-space ratio in urban area is much lower than the sub-urban and rural areas. Then we study the correlation between white spaces and population density based on all our measured data. We check the population density [25] around our measured locations and the spectrum usage rates at those locations, then show the result in Fig. 12. We can observe the trend that the higher population density, the more spectrum been utilized. In order to guarantee the broadcasting service quality in high building density urban area, more principal and fill-in transmitters cover this area which makes the number of available channels reduced. This seems to be a disappointing result that in those districts with more population and spectrum demands, less extra available spectrum can be provided.

The white-space ratio can also be determined by the threshold. [26] has mentioned the various sensing levels that depend on the source of TV transmissions. As [14] described, the transmitter type can be used to set different detection thresholds and potentially open up more white spaces. We show the white spaces of urban, sub-urban and rural areas by different thresholds in Fig. 13. The white-space ratio increase significantly when we raise the threshold. When the threshold is up to -60 dBm, which is the typical receivable threshold for TV receivers, over 80% of TV channels are defined to be vacant. Meanwhile, we can observe that there are always more white spaces in rural area than urban and sub-urban areas no matter how to adjust the threshold. FCC adopts -114 dBm as the detecting threshold which is a very strict requirement. In this case, we can avoid the interference and guarantee the wireless communication of primary users.

4) Discussions of the Digital Switch-Over in Hong Kong: US has completed its digital transition from analog to digital TV broadcasting on June 2009 which has released approximate 100MHz contiguous channels for auction [27], [6]. In UK, previous analysis also shows about 80 MHz wide of available spectrum in channels 31-40 [16] after transition. At present, analog and digital televisions are broadcasting simultaneously in Hong Kong, and channel 47 and 62 have been reserved for DTT and mobile TV [11]. Analyzed from the TV broadcasting table provided by OFCA [11] and our measurement result in Fig. 8, four analog broadcasting channels (Jade, Pearl, Home and World) occupy over 80% of current utilized TV spectrum. While at the same time, three digital multiplex channels broadcast 11 TV channel contents, for 3 or 4 TV contents have been ”compressed” into one channel which have saved much spectrum resource. Another advantage of digital TV is the single frequency network it adopts which makes radio spectrum utilization more efficient compared to traditional multi-frequency network transmission of analog TV. There are huge differences in spectrum utilization performance between analog and digital TV broadcasting.

Based on these observations, we expect the white-space availability changes in the following way in Hong Kong after the switch-over: Only 19% of TV channels will be utilized in

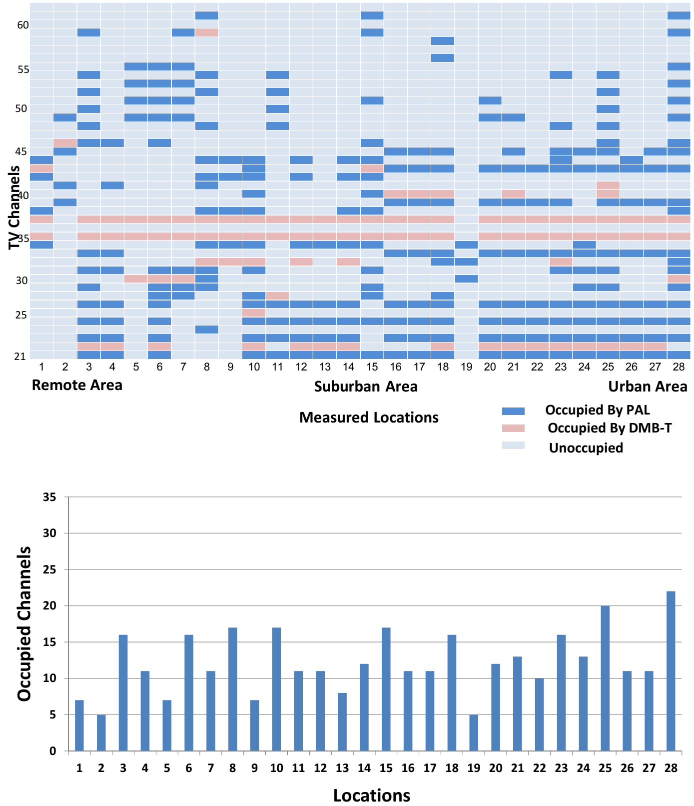

Figure 14: White space distribution details and occupied percentage statistics (Indoor). 30 indoor locations have been measured in our project, and we have excluded two locations that are influenced by TV signals from adjcent city Shenzhen. 28 locations are presented in this figure.

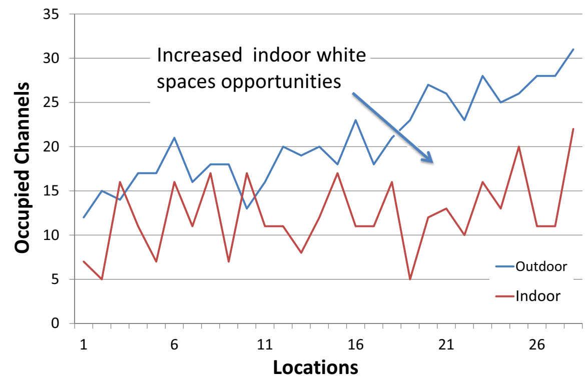

Figure 15: Indoor / Outdoor white space opportunity comparison.

urban area after the transition and this percentage will reduce to 14% and 13% in suburban and rural area, which means over 80% of TV band will be released. The digital TV can be broadcasted in signal-frequency network. So the utilized spectrum pattern can be rearranged to be neater and make the available channels contiguous. New digital channels and services may be introduced as well which depends on local TV stations and OFCA. Overall we expect the TV spectrum utilization ratio will be much lower after the transition.

V. Indoor Measurement Results and White Spaces Opportunity Analysis

A. Indoor Measurement Results

Another opportunity that has not got fully explored is indoor white spaces. As has been studied, over 70% of spectrum demand comes from indoor environment [18]. However, few papers have discussed it. To fill in the gap, we perform large-scale indoor measurement studies along with the outdoor measurements and in-depth analyses of the indoor opportunities will be present. Our result shows the indoor white space availability is a very different story as compared to the outdoor scenario in HK, including higher white space percentage, larger number of contiguous channels and lower received signal power. In short, there are more indoor white space opportunities which have not been fully explored.

Fig. 21 in the appendix shows the indoor white spaces measurement result and the indoor spectrum usage percentage ranges from 8 to 55%. Compared with outdoor result in Fig. 20, we find the overall usage percentage decreases for 20%, which produces many more white spaces. The overall indoor white space is 72% and the indoor white-space ratios in urban, sub-urban and rural areas are 67.9%, 74.7%, and 73.3%, respectively. We will make deeper analyses in the following.

B. Indoor White Space Opportunity Analysis

1) Indoor / Outdoor Comparison and Indoor White Space Opportunity Exploration: As has been discussed, when closer to the downtown, more channels have been occupied by TV signals in outdoor environment. But observed from Fig. 14, which is the detailed indoor measurement result, the indoor spectrum usage percentage doesn't show significant increase from remote areas to the downtown. We present both the indoor/outdoor spectrum usage ratio and show the white space opportunities in Fig. 15, from which we observe that the difference of spectrum usage ratio creates new opportunities for spectrum access, especially in urban area. This is also the region with the largest spectrum demand. The indoor white spaces in urban, suburban and rural areas are 67.9%, 74.7% and 73.3% respectively, with much smaller variation compared with 44.1%, 55.9% and 60.9% in outdoor environment. The overall indoor white space capacity has increased for 18.4% compared with outdoor scenarios. We have the conclusion that large numbers of scarce spectrum resources have not been fully explored in indoor environment.

2) Indoor White Space Characteristics and Opportunity Analysis: Before presenting the analysis result, we first choose a typical urban environment in Admiralty and show the measurement result in Fig. 16 (Outdoor) and Fig 17 (Indoor). The vertical axis is the measured energy level in each channel and three time instant results are presented in the figure. Comparing these two results, the indoor signal strength is 5 to 25 dB lower than the outdoor signals. In this case, weak signals (lower than -80 dBm) in several channels attenuate to be too low to be detected, which create large scare of contiguous available channels between channel 46 and 62. This provides an ideal environment for wireless broadband communication.

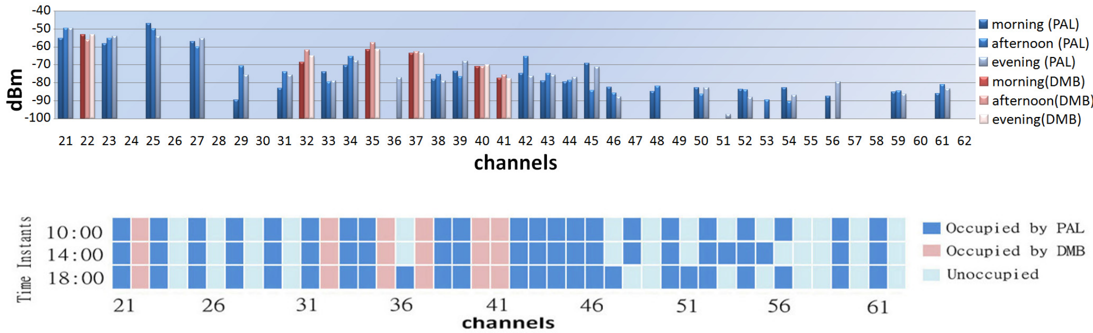

Figure 16: Outdoor measurement result in Admiralty.

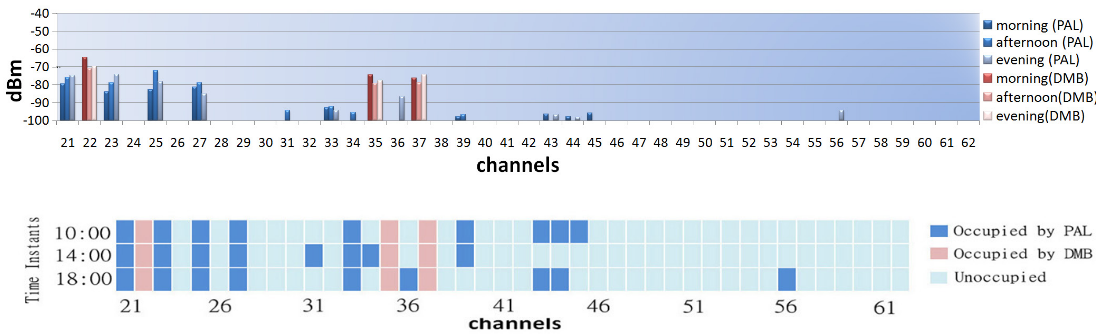

Figure 17: Indoor measurement result in Admiralty.

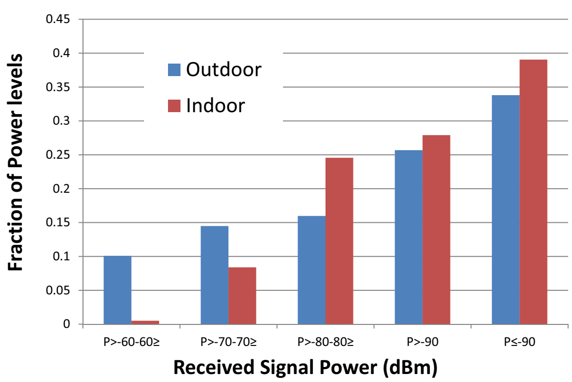

Figure 18: Fraction of received signal power levels.

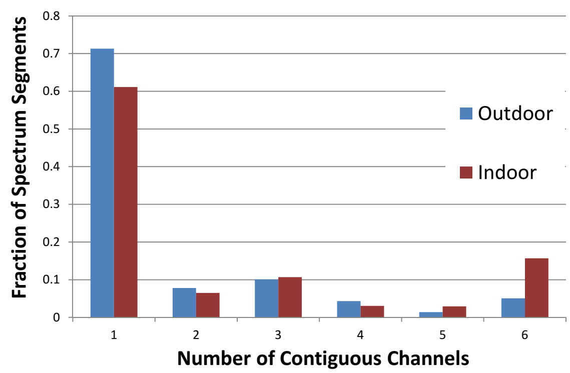

Figure 19: Fraction of contiguous channels.

Then we summarize the received signal strength at all locations and compare the indoor / outdoor powers in Fig. 18, from which we can observe significant signal attenuation in indoor environment. Over 90% of the indoor signal strength falls below 80 dBm, which is lower than the minimum receivable power level of TV sets. The walls of buildings play an important role in blocking the TV signals and make indoor environment much better for white space communication compared with the outdoor. One characteristic of indoor white spaces is there is no fixed signal attenuation pattern indoors. As been tested in [20], it is really challenging to build radio environment maps for indoor environments due to the complex characteristics of these environments in terms of propagation models, and their dynamics. In our indoor measurement, significant spatial variation occurs. The signal strength may drop to very low level even in small scale. The indoor white spaces are determined by the outdoor radio environment, the building structure as well as users' location inside the building, which make the white space solutions for indoor use extremely challenging.

Lastly the fraction of contiguous available channels calculated by all the collected data is summarized. Shown in Fig. 19, the fraction of 6+ contiguous indoor channels is three times larger than outdoor. As we know, with wider transmission bandwidth, we can provide a better wireless communication environment. Prior research has shown that aggregating contiguous channels improves throughput [8], [9]. Our result indicates in outdoor environment, most available channels are fragmented, while in indoor environment, more contiguous available channels exist.

3) Advantages of indoor white spaces: As we have shown, the indoor white-space ratio is 18.4% higher than outdoor, and the "quality" of the indoor white spaces is much better as well. The signal attenuation releases lots of contiguous available channels indoors which are ideal for wireless broadband communication. Considering that Hong Kong has the largest number of high-density skyscrapers in the world and in these internal spaces there exist large and fast increasing spectrum demands, we believe the potential of indoor white spaces has been under-estimated before. More research can be done for fully indoor white spaces exploration.

VI. Conclusions

In this work, we carried out a large scale TV spectrum occupancy measurement study in Hong Kong. Compared with model-based approaches commonly adopted in geo-database white-space identification systems, we find that the measurements can give us more accurate white space availability information in metropolitan cities. We choose 30+ locations in all 18 districts in Hong Kong and carry out both indoor and outdoor measurements. We observe that in urban area, the outdoor white space availability ratio is 44.1%, and this ratio in suburban and rural areas are 55.9% and 60.9%, respectively. The indoor white-space ratios in urban, suburban and rural areas are 67.9%, 74.7%, and 73.3%, respectively, which are much higher than the white-space ratios in outdoor scenarios. We also find in indoor environment there exist more contiguous unused channels than in outdoor environment, which can be exploited to support wide-band wireless communication. We believe our results and observations are helpful for understanding the white-space feasibility in metropolitan cities.

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Appendix

Fig. 20 and Fig. 21 show the detailed outdoor and indoor measurement results at the 30+ locations. The outdoor spectrum usage ratio rangs from 29% to 69%, with overall 50% of spectrum utilized at all locations. In indoor sceniro, the spectrum usage ratio ranges from 7% to 57%, with average 30% spectrum utilized. Comparing these two results, we see that there are roughly 20% vacant more spectrum that are

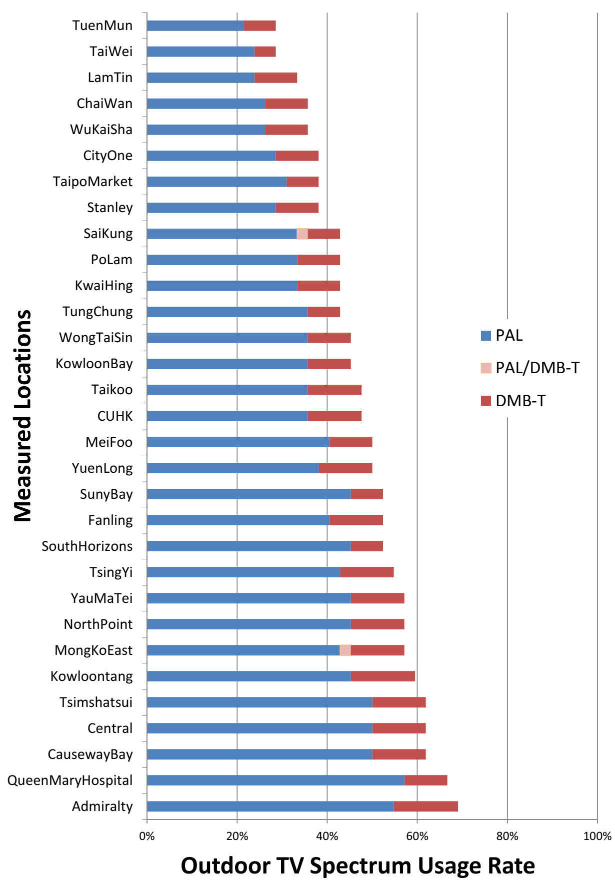

Figure 20: Multiple locations measurement result (Outdoor).

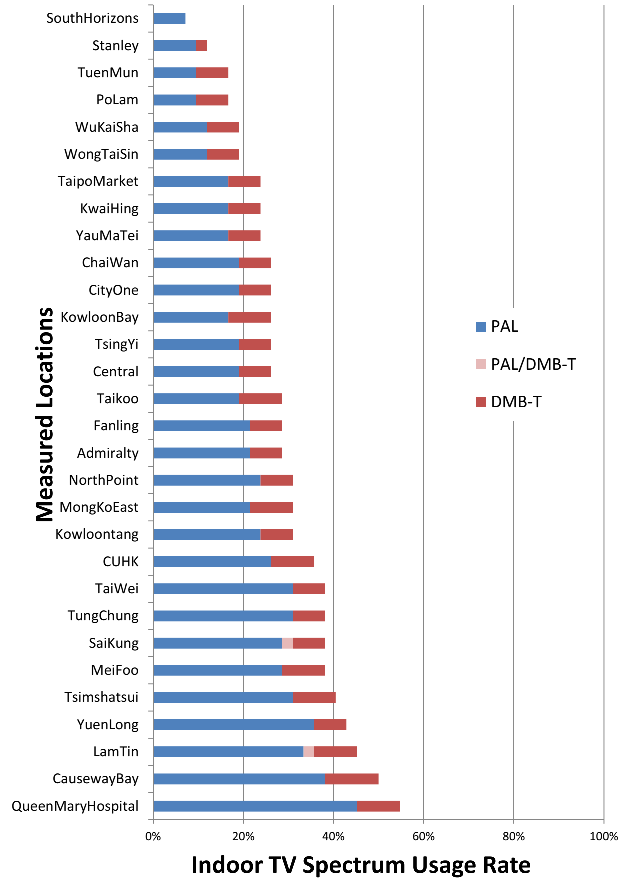

Figure 21: Multiple locations measurement result (Indoor).

white spaces in the indoor scenarios than in the outdoor scenarios..

Another observation is that analogTV signal occupies a large fraction of the spectrum. Only 10% of the total TV spectrum is used by digital TV channels (shown in red in the figure, and the fraction in pink means both analog and digital TV signals have been detected). In several years, analog TV broadcasting will switch-over into digital in Hong Kong. According to our analysis in Section IV-C4, after the switch-over, over 80% of TV spectrum that is originally occupied by the analog TV channels will be released. This suggest there will be even more white spaces available for exploration in Hong Kong after the switch-over.