Design Aspects of a Television White Space Device Prototype

M. A. Rahman, C. Song and H. Harada
National Institute of Information and Communications Technology (NICT),Yokosuka, 239-0847, Japan
{aziz, songe, harada}@nict.go.jp

***Abstract*—In this paper, we describe the design challenges of a recently developed television white space (TVWS) device prototype and how those were resolved. The prototype, which includes the following components: a cognitive management entity (CME), a sensing module, a geolocation device, a TV band database, a transmitter and a receiver, was designed to take part in Singapore TVWS test trial. The major features the prototype has are: cognitive functionality, spectrum sensing and database access. The technical challenges faced during its development are described in terms of wide dynamic range, adjacent channel rejection and synchronization issues of the spectrum sensor, baseband vs intermediate frequency based sensing, non white environmental noise, security regarding database access and troubles inherent in wireless environment. Performance of the prototype is also presented in terms of cognitive operations such as, success of TV signals and other incumbent detection through database access and sensing, time required for database access, sensing, channel selection, channel switching etc. Discussion regarding setting a reasonable sensing target is also presented.**

I. Introduction

Availability of frequency spectrum is one of the key requirements for wireless and mobile telecommunications. However, in any country of the world, the frequency spectrum is a limited resource. Despite this fact, the licensed spectrum over the world is under-utilized. By actively using the under-utilized portion of the spectrum, this is possible to provide many important telecommunications services. This is a branch of research that has recently received attention from researchers and regulators from various countries. Regarding the under-utilized frequency band, a term commonly used is "frequency white spaces". For example, a significant portion of the frequency band licensed to the television (TV) operators is also under-utilized and can potentially be used for other important purposes while not used by the TV operators. Those portions of frequency band are called television white space (TVWS) bands [1]−[9].

In the near future, there is a high possibility of having legal permission of unlicensed/lightly licensed use of a lot of WS spectrum in the TV bands in many countries. However, the permission is to come with accompanying requirements to be fulfilled by the TVWS devices (TVWSD). The USA has already defined the requirements [1], [2]. Many other countries such as UK, Singapore and India have developed draft requirements [3], [4]. As it seems right now, the requirements worldwide are somewhat identical that include: 1) Ability to access a database that contains information on primary TV users and/or 2) Ability to sense very low power TV signals 3) Ability to process the information received from 1) and/ or 2) and take intelligent decisions.

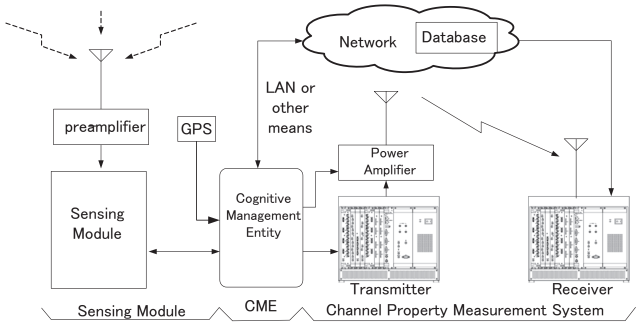

Fig. 1. NICT TVWSD prototype block diagram.

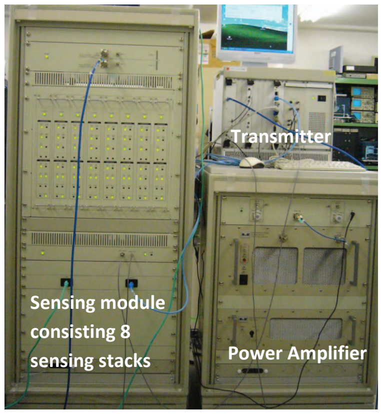

Fig. 2. The NICT TVWSD prototype hardware showing the sensing module consisting 8 sensing stacks and transmitter.

As a part of an ongoing project at NICT, recently we have developed a cognitive radio TVWS prototype [8]. In this paper, we first briefly introduce the prototype, and then mainly explain the design challenges and how those were overcome, present major functional features and relevant performance results.

II. Specification of the Prototype

A block diagram showing the component modules of the prototype and connections among them are shown in Fig. 1. The six basic component modules the prototype has are: a cognitive management entity (CME), a sensing module, a geolocation device (GPS), a TV band database (also known

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TABLE I

MAJOR PARAMETERS OF THE NICT TVWSD PROTOTYPE

Feature	Capability
Sensing	-Done every 500 milliseconds (completed within 100 ms) -8 parallel sensing stacks -Designed for sensing digital and analog TV, can also sense microphone, radio -sensitivity: -120 dBm /8 MHz for $P_D \geq 0.9$, $P_{FA} \leq 0.1$
Geolocation / Database Access	-GPS available, Real-time database access possible, every 500 milliseconds
Cognitive Decision	-Cognitive decision regarding channel selection or switching is taken based on sensing results and/or database access (by Cognitive Management Entity (CME))
Listen Before Talk	Supported (both from sensing and database access)
Detect and Avoid	Supported (both from sensing and database access)
Burst Transmission	400 ms transmission, 100 ms pause (sensing, database access)
Frequency	630 MHz to 742 MHz, Singapore TV channels 41 to 54, except 50 and 52
Tx Band Width	8, 16, 32, 64 MHz
Signal Structure	-511 PN sequence spread BPSK [2.5, 5, 10, 20 Mbps], Nyquist, roll off 0.99 -OFDM
Tx Power	4 dBm/ channel max [13 dBm for 64MHz maximum]
Power Control	In steps of 0.5 dB
Channels Supported	41 to 54 except 50, 52
Adjacent Channel Power	-48 dBm for max power transmission
NF and noise level	Below 3 dB and -100 dBm respectively

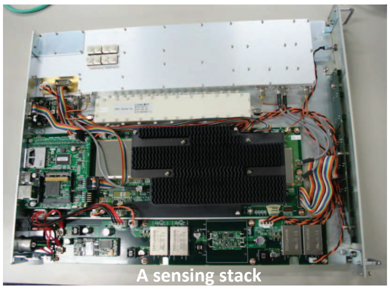

Fig. 3. A single sensing stack of the NICT TVWSD prototype.

as geolocation database), a transmitter and a receiver. Specifically, the database contains channel utilization and location information of the incumbents such as TV, personal mobile radio (PMR) localized are network and microphone. Table 1 shows the major parameters of the developed prototype. As seen, important Infocomm Development Authority (IDA) requirements are fulfilled. In 2007 and 2008 several companies developed sensing prototypes that were tested by FCC, USA for the requirements of -114 dBm/6MHz sensing level [2]. The sensing requirement imposed by IDA that is -120 dBm/8MHz translates to much lower SNR and is more difficult to reach. First of all, our sensing module of our TVWSD prototype has much better capabilities. Secondly, our prototype is a complete prototype that fulfills all the requirements by regulatory bodies for WS operation.

III. DESIGN CHALLENGES

A. *Wide Dynamic Range for Sensing*

While the sensing requirement of IDA was -120 dBm/8MHz, it is desirable that the sensor be able to sense at least -120 dBm and any power level above that, such as until the maximum limit of input (-20 dBm for the prototype). However, although it sounds easy, its actually not easy to design a sensor with such huge dynamic range. There are several challenges associated with that.

First of all, by employing a single LNA at the front end, it is not possible to support the whole desired dynamic range. Using an adaptive LNA may seem lucrative, however, is not feasible due to the following reasons: 1) increase of price 2) lack of precision and 3) increase of complexity of the feedback section for such an LNA. The solution to this part of the problem was to use two parallel connection one through a 20 dB LNA for low power inputs within -120 to -80 dBm and another with no LNA for high power inputs above -80 dBm. Here note that a gain controller is not an option here because, wideband signal is received in the input and sensing decision is to be made per channel basis.

The second challenge was how to select any one of the two input lines just mentioned. Basically, the input power level of signal is not known until the received signal is processed to some extent. So, feedback was finally needed. The good part was that a simpler feedback worked this time as compared to otherwise if an adaptive LNA would be used. The feedback was given from the CME after processing the received signal and understanding the received power level. If the calculated power would be above -80 dBm, the CME would assume higher power and command to bypass the LNA at the front end. Although this method apparently solves the problem, actually a different associated problem still exists. We will discuss this in the next subsection.

The third challenge was to produce IF signal of appropriate amplitude for the ADC in such a way not to overflow in case of high power inputs and at the same time to maintain sufficient accuracy for low power inputs. It is difficult to find a combined solution to these two problems without using an adaptive digital (voltage) gain controller (DGC). In addition to be able to sense higher power inputs, it is also desirable that the prototype be able to measure the received power accurately for the whole dynamic range. This imposes an additional requirements: to keep linearity of the DGC for desired signal to be sensed. To solve this problem, we divided the DGC operation linearity scale into two parts corresponding to LNA selection (i.e., for -120 to -80 dBm and -80 to -20 dBm). The linearity is mathematically modeled and incorporated in the CME to accurately calculate the power from outputs obtained from sensing. Due to the subdivision of the dynamic range into two, better accuracy was achieved for power measurements. Note that accuracy for lower part (i.e. power -120 dBm to -80 dBm) is better and of the order of ± 0.5 dB. The same for higher range is ± 1 dB.

B. Adjacent Channel Rejection (ACR) by Sensor

Although the front end is designed to be broadband, incumbents signals usually appear in each channel. The sensor should be able to sense and decide signal existence per channel basis. This is also crucial in the sense, once one or some channels are found vacant, the TVWSD can decide to operate in the channels. In this context, adjacent channel rejection of the sensor is of utmost importance since any leakage of the order of the sensors sensitivity or above will trigger a false alarm of detection in the adjacent channel while actually no incumbent is present. The challenges associated are multiple: 1) The transmit filters of the TV broadcasting follow relaxed design requirement with slow cut off. Hence, considerable amount of adjacent channel power is practically available for incumbents. 2) Even if we would like to cut away the adjacent channel power in the sensor by filtering, it is difficult to find a filter with such sharp cutoff in VHF/UHF bands.

There is nothing we can do to regulate the design of TV broadcast filters. Hence, we had to find a solution by using filters. Let us provide an impression of the difficulty to the reader: please note that for -20 dBm input in a channel, we needed ACR $\geq$ 100 dB to protect false alarm. While use of multiple filters in series in the front end seems to be a solution, its really not practical. In addition to the high price of the custom developed filters per channel, the size of each filter and the total number of filters needed pose a limitation. We used one filter of -3 dB BW equal to 6 MHz per channel. Although it improved the ACR, desired performance wasn't achieved. To cope with the problem, we used few SAW filters before DGC in the BW selector section and one SAW filter in the IF section. This some what solved the above problem, however, raise the following problem.

Another major challenge we faced after correcting the high adjacent channel power leakage was erroneous selection of the LNA in the front end. This is because, in the front end, a higher power input in the adjacent channel wouldn't pose any false alarm in the desired channel, however, could lead to erroneous feedback from CME to the LNA selector. Since many of the tests designed by IDA was regarding sensing in a single channel, we were giving feedback to the LAN selector based on the desired channel sensing output. However, if the desired channel has a signal with low power, while the adjacent channel has signal with high power, the CME would see the low power and would suggest employing hight gain LNA. This would lead to increased leak to the desired channel and possibility of false alarm or inaccurate power measurement. To solve this problem, we processed 8 channels output simultaneously and CME was designed to be able to calculate power in 8 channels parallelly and command to preclude the LNA once a high power signal is found in any channel irrespective of the desired channel of sensing.

C. Synchronization for Sensing

Synchronization involves time and phase (frequency). If time synchronization could be obtained, the performance of sensing would improve. From this point of view, we studied the feasibility of achieving synchronization through simulation. The main problem is that the signal to be sensed is very weak. Obtaining synchronization of such low power signal is challenging. In one sense, if synchronization is achieved, the signal has been detected. On the other hand, obtaining phase(frequency) for such low power signal is nearly impractical. Since most TV signals have repetitive structure in terms of packet or the like, achieving time synchronization could be possible. However, usually it takes relatively longer time to obtain synchronization rather than simply sensing. Still, it may be helpful to decrease sensing time during operation, if a sensor has already synchronization. In idle time, a sensor may have enough time and it may keep performing the synchronization. While in operation it may do fine tuning only.

We simulated sliding correlation and tried to identify the peak of the correlation output between signal plus noise and reference. Here one should note that performing sliding correlation is time consuming and complex. So, during usual sensing, it may not be attractive to use sliding correlation. However, sliding correlation can be used by the sensor to achieve synchronization while it is idle.

We performed averaging of the correlation output in each repetitive period. By this way, while performing sliding correlation, we gradually obtain more trustable results by noise reduction. Although, we found sensing performance improvement by achieving time synchronization that was previously reported in [5], [6], incorporating this function in hardware prototype posed further consideration. It was noted that the advantage may not be substantial if not performed in baseband. Rather the system performance is more limited by the IF based processing and its unknown carrier phase. Hence, finally this function wasn't incorporated in the prototype.

D. Baseband Vs. IF Based Sensing

As mentioned in the previous subsection, unknown carrier phase degrades sensing performance. Considering phase synchronism is difficult to achieve, an alternative to solve the problem is to perform sensing by baseband conversion. By baseband conversion, it is possible to get rid of phase asynchronism. Our simulation confirms that it provides better performance. However, IF based sensing is simpler and requires low-complexity implementation. Since, we have a plan to design ASIC in future, IF based method was used for this prototype.

E. Non White Environment Noise

Noise uncertainty is one of the most challenging problems to solve in any sensing device design. We measured the noise variance experienced by the prototype by terminating the antenna input of the sensing module by a matched terminator. We faced a situation where short term mean noise variance was small, however, the long term mean noise variance was higher than 1 dB. The long term noise variation is rather slow and repeats in several days. The reason behind this lies in the electronics involved and remained unknown to us. This long term noise variation imposed significant design constraint on us, especially, in threshold setting.

In addition to the long term noise variance, that can be verified through cable connection, in wireless environment there were interference from various sources. It was required that the prototype sensing performance doesn't significantly vary depending on the interference level.

F. Meeting Out-of-Band Emission Limit

The out-of-band emission limit imposed by IDA was -48 dBm per channel. There were no spectral mask defined either for operating channel, as well as, for adjacent channels. While transmission of upto 23 dBm was permitted in operating channel, maintaining -48 dBm in adjacent channel meant designing a power amplifier that would provide out-of-band emission with 70 dBc. This is a tremendous challenge. To achieve such goal, a huge power amplifier had to be used with massive back-off. The power amplifier was bulky, power hungry and expensive. To realize output power of 13 dBm (20 mW), with third order intermodulation, $IM_3 \approx 70$ dBc the required capacity of the amplifier was an output third order intercept point, $OIP_3 = 53$ dB implying 200 W. To facilitate smooth meeting of the out-of-band emission limit, Nyquist pulse was used instead of using commonly used root raised cosine (RRC) pulse.

G. Security in Database Access

In practice, the TV band database required for TVWS communication is supposed to be managed by third party and stored in the Internet. While accessing the database, security is a major issue during communications over Internet. It was first planned that the database server will be hosted at NICT, Japan and the CME would access it over secure shell (SSH). However, later it was pointed that SSH might not be the most appropriate model for security in this case. This was because in real deployment it would have very high client management overhead. Additionally, Internet connection to CME wasn't guaranteed for outdoor tests. Finally,we decided to use a local computer to use as a database server.

TABLE II

DETECTION PERFORMANCE OF THE NICT TVWSD PROTOTYPE.

Incumbent	Success Rate		
	Sensing ($P_{FA} \leq 0.1$)		Database Access
	-120 dBm	-114 dBm	
PAL B/G	98%	100%	100%
PAL M/N	91%	100%	100%
NTSC	94%	100%	100%
SECAM	96%	100%	100%
DVB-T	93%	100%	100%
ISDB-T	95%	100%	100%
Microphone (analog)	92%	100%	100%
Microphone (digital)	94%	100%	100%
DAB	93%	100%	100%

H. Wireless Environment

Maintain stable sensing performance over wireless environment was a challenge due to the following reasons: 1) It is difficult to have an antenna with flat gain over a wide bandwidth of 64 MHz 2) Interference from unwanted sources increase false alarm and poses difficulty to work properly with a single threshold setup.

Fluctuation in antenna gain directly translates to same amount sensing degradation. To be on the safe side, we used two antennas, one for lower half and the other for higher half of the band. This gave us relatively flat antenna gain over the bandwidth. To fight the second problem, we used advanced threshold multilevel setting techniques [6], [7].

IV. PROTOTYPE PERFORMANCE

A. Sensing and Database Access Performance

Two advanced sensing methods have been implemented in the prototype: namely correlation based method(CBM) and combined feature and energy detection. The former method is focused on analog TV sensing and the later method is focused for digital TV and other signal type detection. The sensing methods are out of scope of this paper and is described in different papers [7]-[9]. Table 2 lists the sensing performance of the prototype for various incumbent signals including TV and microphone. As seen success rate over 90% has been achieved for all incumbent signals type detection while sensing target is set to -120 dBm. If sensing target is relaxed to -114 dBm 100%, success rate can be reached. The false alarm probability was fixed at 0.1 for both cases.

Here note that, while the sensing performance achieved by the prototype is the best in current time, reliability of sensing vs. implementation complexity is a point still to consider. Especially, if we set $P_{FA} = 0.1$ and $P_D = 0.9$, although it meets regulatory requirements, user experience is a concern. If a system fails once every 10 times, the user may not like it. To solve the problem, one could go for $P_{FA} = 0.01$ and $P_D = 0.99$, however, achieving such performance for -120 dBm detection is not easily possible, especially for digital TV. Still, achieving -114 dBm/6 MHz as required by FCC is possible.

TABLE III

LISTEN BEFORE TALK AND DETECT AND AVOID TIMING

	Listen before talk			Detect and avoid		
	min(s)	max(s)	avg(s)	min(s)	max(s)	avg(s)
Sensing	0.6	1.1	0.85	0.1	1.1	0.6
Database	0.1	0.7	0.4	0.1	0.7	0.4

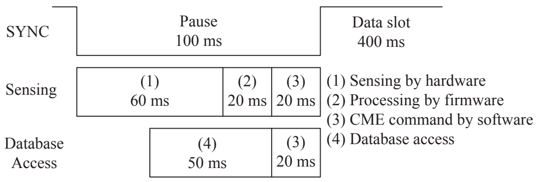

Fig. 4. Sensing and database access timings of the prototype.

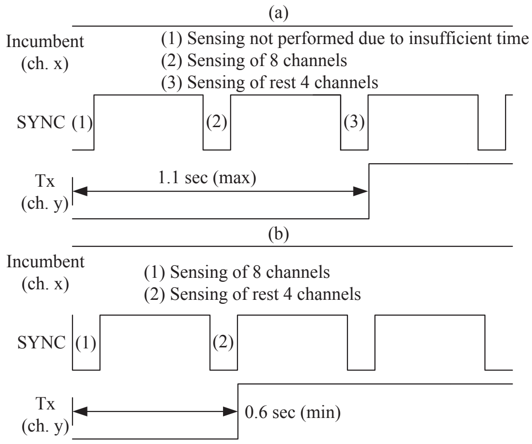

Fig. 5. Listen before talk maximum and minimum timings of the prototype.

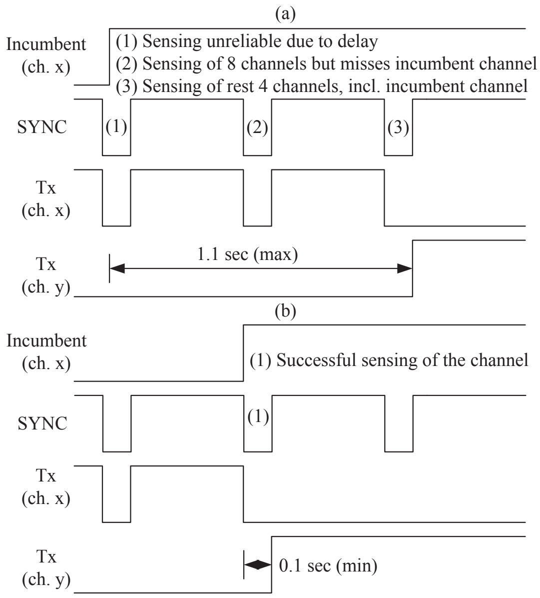

Fig. 6. Detect and avoid maximum and minimum timing of the prototype.

Based on the discussion presented above, the advantage of using the database approach becomes evident. Table 3 also shows the accuracy of data retrieval from a database and identifying a primary signal in a channel by our prototype. The accuracy is 100%. The main challenge is identifying the database and connecting to it. Afterwards, the reliability is very good. The accuracy of the decision based on information from a database also includes the accuracy of distance calculation based on GPS data. Our prototype was able to accurately calculate the distance from a primary user and take operation decision based on the criteria imposed by Singapore government.

B. Listen Before Talk (Channel Selection)

Fig. 4 shows the timing required for sensing and database access. For sensing, total required time includes time required by 1) hardware FPGA to perform sensing task [60 ms] 2) firmware to send the result to CME [20 ms] and 3) CME command to reach synthesizer to select appropriate channel [20 ms]. The total task is conveniently performed within 0.1 sec. For database access, total time for query and answer is 50 ms followed by 20 ms required by CME command to reach synthesizer to select appropriate channel. Although pausing transmission is not required for database access, which means it could be done at any time, in prototype we performed database access every 500 ms during the last 70 ms of the transmission pause.

Fig. 5 shows the minimum and maximum timing required for listen before talk by sensing based on our design. Although this term is commonly used for sensing, we also use the same term for the same function performed by looking at the database. The listen before talk timing for both sensing and database access is listed in Table 3. As seen, the operation is slightly faster though database access.

C. Detect and Avoid (Channel Switching)

In a similar manner, Fig. 6 shows the minimum and maximum timing required for detect and avoid by sensing and Table 3 lists the timing required for this function through both sensing and database access. Note that the objective of detect and avoid is sensing an incumbent in the operating channel and switching channel in case an incumbent is detected. In other words, the timing shown in Fig. 6 and Table 3 (right three columns) are channel switch time. As seen, the required channel switch time is fairly fast, which meets regulatory requirements.

D. Sensing Target Vs. White Space

Although the prototype was able to sense over 630 to 742 MHz channel (channel 41 to 54 except, 50 and 52) in Singapore, the widest 64 MHz bandwidth transmission was possible over 638 to 702 MHz channel (channel 42 to 49). Hence, wireless sensing over 638 to 702 MHz channel was of utmost importance. It was found that the existing TV signals are quite strong in this portion of the band. Basically, this part of the frequency band is supposed to be vacant in Singapore. However, neighboring countries, Malaysia and Indonesia uses

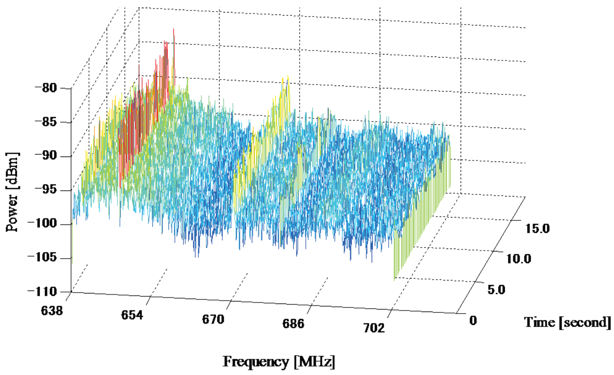

Fig. 7. TVWS Spectrum of signal pulse noise in a) an indoor facility and in b) outdoor in Singapore.

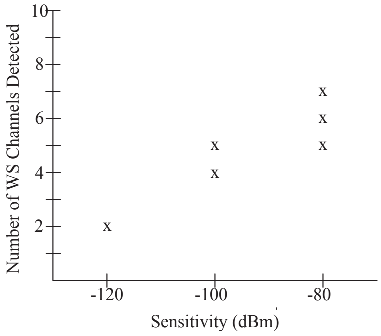

Fig. 8. Number of WS channels detected vs. sensitivity.

almost all the channels. Since Singapore is very small, TV signals from neighboring countries easily reach Singapore.

Fig. 7 shows two snap shots of the frequency spectrum taken by Rohde and Schwarz spectrum analyzer FSE in an indoor environment in Loyang Way, and in outdoor environment in Bukit Timah, Singapore. As seen, interference levels reach up to -80 dBm, especially at lower parts of the band. The higher part of the band relatively has much lower power and seems near to AWGN channel.

While we performed sensing test in indoor and outdoor in wireless environments, the prototype could easily sense the TV signals in lower part of the band since those were pretty high. Signals in the middle part of the band were lower, however, the prototype could also sense those. The prototype found channels 53 and 54 as vacant.

While the prototype was designed with a target to sense -120 dBm, the signal present in Singapore within 638 to 702 MHz was found higher than that in many parts. This is an interesting situation that a frequency band that is targeted as a WS usage cannot be used if -120 dBm sensing target is set.

We tried by reconfiguring the prototype by relaxing the sensing target (setting higher power level as sensing target). The challenge is that even by relaxing sensing target upto -100 dBm, it is not possible to get all the channels as WS. Still some parts of the band where there is higher TV power of the order of -80 dBm, becomes sensed as a channel occupied by TV.

This brings us to the question 'what would be a reasonable sensing target?' Basically by limiting the power of TVWSD, it is possible to ensure that no interference occurs to TV receivers located in Malaysia or Indonesia. So, there is no benefit to set a sensing target too low that will create the following problems: 1) make TVWSD implementation expensive 2) make finding white space difficult since already the interference caused by "real TV signal" is already high.

Fig. 8 shows the number of WS channels detected in various parts of Singapore vs. sensor sensitivity. As seen, number of vacant channels seen is somewhat linearly proportional to sensitivity in dBm. Hence, to have white spaces to use, reasonable sensing target is needed provided that interference to primary user is not caused.

Although none of the channels are being used by TV broadcasting in Singapore, some of the channels are used by microphones and some other relatively low power wireless systems. That was the interest of Singapore government to check if the sensing device has the capability to sense those. Our sensing prototype could sense all signals including microphone, digital radio, DAB, digital and analog TVs.

V. Conclusion

In this paper, we have presented the specifications of a TVWSD prototype with cognitive functionality that was recently developed at NICT, Japan. Various challenges faced during the development and how the problems were solved were discussed. The results would be helpful to telecommunications regulators to realize their TVWS regulations in a better way, as well as, implementers to understand the technology better.

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