Advanced Cognitive Radio Test-bed with Carrier Aggregation in TV White Space

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ABSTRACT

Cognitive radio (CR) has been getting attention as a remarkable technology to improve spectrum efficiency by utilizing unused spectrum resources. Especially, many countries have been considering permission for CR-based spectrum usage of TV white space (TVWS). Even though TV band has favorable propagation property compared to other higher frequency bands, CR system in TVWS involves a fundamental limit on system capacity because of a restricted TV channel bandwidth. To overcome it, in this paper, we introduce new CR test-bed with capability of carrier aggregation. By utilizing carrier aggregation functionality, we can effectively utilize multiple TV channels and achieve higher system capacity. Moreover, the test-bed supports non-contiguous carrier aggregation as well as contiguous carrier aggregation. Because unused TV channels are spread over entire TV band sporadically in general, new test-bed provides noticeable performance improvement compared to the existing CR systems in TVWS. Detailed implementation of the test-bed including each functional module is explained, and functional test procedures with corresponding results are provided for evaluation.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

C.3 [**Special-purpose and application-based Systems**]: Real-time and embedded systems –*Cognitive Radio Test-bed System.*

General Terms

Design, Standardization, Verification.

Keywords

Cognitive Radio, TVWS, Carrier Aggregation, Test-bed.

1. INTRODUCTION

Cognitive Radio (CR) technology is one of the promising solutions for shortage of spectrum resources. It cognizes surrounding radio environment and dynamically optimizes its operational parameters, and consequently it can improve overall spectrum utilization. Accordingly, CR technology has drawn significant research attention from industries as well as government agencies. In this sense, a number of countries have been considering adoption of CR technology, especially in TV white space (TVWS). The US permitted CR systems to utilize unused TV band by Federal Communications Commission (FCC) [1]. The UK, EU, Japan and Korea also have been making rules on utilization of CR systems in TVWS [2],[3].

In this context, several CR system standard groups have been established with various system applications. IEEE 802.22 working group published a standard for wireless regional area networks (WRAN) for internet access in rural area [4]. ECMA-392 standard group established physical layer (PHY) and media access control (MAC) standard for personal/portable application in TVWS [5]. At that time, we developed a cognitive radio test-bed based on ECMA-392 standard [6]. It provided wireless communication services using a TV channel with cognitive capability and proved feasibility of CR system in TVWS.

Although CR system's significant spectral efficiency improvement and superior radio propagation characteristic of Ultra High Frequency (UHF) TV band, the major drawback of CR systems in TVWS is the limited system bandwidth. Due to the channelization of TV band, e.g. 6MHz in the US, a bandwidth of CR system in TVWS is limited meanwhile the conventional systems such as Wi-Fi provide relatively wider bandwidth, e.g. 20MHz. Moreover, as user's demands for high quality services increase, wireless communication systems require wider bandwidth. For this reason, IEEE 802.11 standard has been considering multi-band operation, and 3rd Generation Partnership Project (3GPP) also considers carrier aggregation to increase system capacity.

In this paper, we introduce a cognitive radio system with multi-channel operation capability. It is equipped with two radio frequency (RF) components for two channel aggregation or 2x2 multiple-input multiple-output (MIMO) operation support. By utilizing two channels carrier aggregation mode, it could provide doubly increased system capacity compare with the conventional single-channel system. Furthermore, it could aggregate not only contiguous carriers but also non-contiguous ones. Considering a strong possibility for scattered distribution of white space, capability of non-contiguous channel aggregation provides distinctive advantage for system throughput increase in realistic radio environment. The basic functionalities are based on MAC and PHY of ECMA-392 standard whereas advanced parameters and protocols are developed and applied for multi-channel operation. For CR capability, it provides geo-location database access capability, advanced spectrum sensing method, and optimized resource allocation for multi-channel CR operation.

The rest of the paper is organized as follows. The overall system architecture and configuration of the test-bed are described in

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Section II. The detailed explanations of functional modules are provided in Section III. In Section IV, functional test procedures and results for verification of test-bed capabilities are provided. Finally, the paper is concluded in Section V.

2. System architecture and configuration

The functional architecture of our cognitive radio test-bed is described in Figure 1. The geo-location database (DB) is installed separately, and the test-bed can access to the database through the conventional Internet connection. The database may provide available channel list and maximum allowed transmit power for the test-bed to utilize TVWS without harmful interference to incumbent users. The internet access method including DB access protocol is handled in higher layer part.

A distinctive feature of the test-bed is two parallel radio front end (RF) parts for supporting multi-channel or MIMO operation including PHY block which has a capability to control multiple streams of data simultaneously. Two parallel data handling processes for carrier aggregation and integrated data control for MIMO operation are implemented in PHY and MAC module. The MAC module generates and receives variable data frames according to the system mode such as MIMO and multi-channel. Separate path for spectrum sensing is designed for accurate detection of incumbent users. Cognitive capabilities of the test-bed are dealt with device management entity. It includes cognitive engine for system parameter optimization and radio resource management for efficient resource allocation.

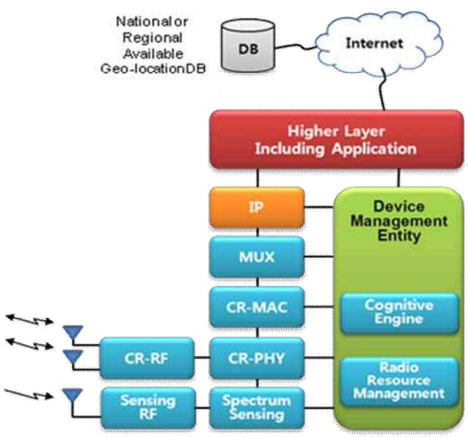

Figure 1. System architecture of test-bed

Hardware structure of the test-bed is drawn in Figure 2. It has two antennas for data paths and the other one is dedicated for spectrum sensing. Corresponding RF paths are implemented in RF board which includes reference clock divider. The RF board is connected with MAC/PHY digital board via Mictor-38 cable. A digital board contains two field programmable gate array (FPGA). The one is used for PHY module data processing and the other one is used for MAC function and spectrum sensing process. General MAC functions such as frame generation is implemented in in digital signal processor (DSP) while timing critical process such as frame check sequence is handled in the FPGA. Spectrum sensing algorithm is also implemented in MAC FPGA for easy timing synchronization between spectrum sensing and data transmission. Cognitive capabilities and resource allocation functions are implemented in central processing unit (CPU). Information exchange among CPU, DSP, and FPGA is carried out through dual-port RAM (DPRAM). Interfaces with external devices such as monitoring PC and geo-location DB are connected via Ethernet port, and CPU has a control capability for the interface.

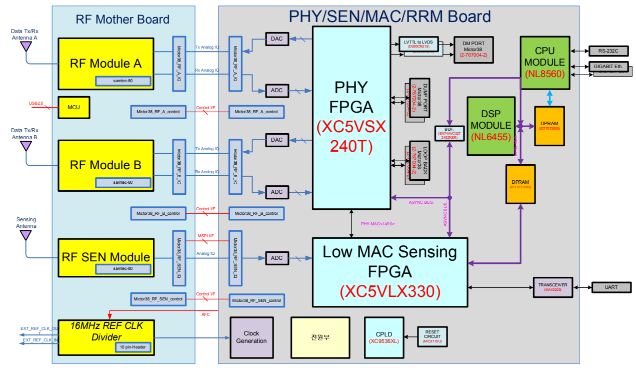

Figure 2. Hardware structure of test-bed

Images of the test-bed with hardware module layouts are listed in Figure 3. Antennas for data transmission are attached at top of the test-bed whereas spectrum sensing antenna is located aside from the test-bed to secure isolation. Multiple RF modules are shielded separately to guarantee no mutual interference even with multi-channel operation. Layout of the digital board takes into account heat and ventilation of the test-bed. External interfaces are placed on outside of the test-bed for easy monitoring and debugging.

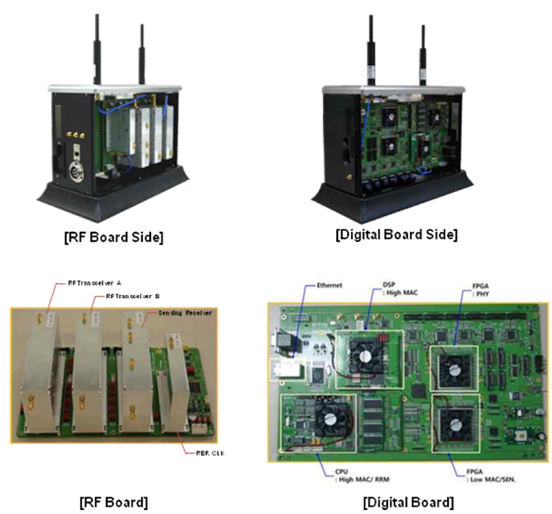

Figure 3. Hardware images of test-bed

3. FIGURES/CAPTIONS FUNCTIONAL MODULES OF THE TEST-BED

3.1 PHY

The PHY module in the test-bed supports three transmission modes of single-input single-output (SISO), MIMO (2x2), and multi-channel (2 TV channels). It is designed and developed on the basis of ECMA-392 standard, in which multiple antenna schemes are specified as an optional scheme. In order to implement the multi-channel transmission mode which is not specified in [5], we have newly defined additional preamble sequence and modified two blocks in the spatial transmission (SM) scheme which are pilot insertion and normalization of modulated symbols. So, there is no big difference between MIMO and multi-channel transmission mode in the standard point of view.

The PHY specification is based on orthogonal frequency division multiplexing (OFDM) modulation using a 128 point fast Fourier transform (FFT). Detailed OFDM parameters are shown in Table 1 considering 6MHz channel bandwidth. Each frame of PHY layer contains PLCP (Physical Layer Convergence Procedure) preamble, PLCP header, and payload. The payload includes PSDU (PHY layer Service Data Unit), tail bits, and pad bits if needed. The maximum PSDU length is 4095 bytes.

The top block diagram of PHY floating point simulator is shown in Figure 4. The floating point simulator is converted to hardware description language, and then it is used to develop the PHY module with FPGA. The binary data for transmission are encoded by channel encoding processor which includes data scrambler, Reed-Solomon(RS) encoder, convolutional encoder, puncturer, and bit interleaver. The interleaved bit stream is split into two streams when the transmission mode is either MIMO or multi-channel. Otherwise it is directly mapped to constellation points depending on modulation schemes through the first antenna path (block bold line in Figure 5). Then data constellations are allocated to data subcarriers, and 4 pilots and null subcarriers are inserted. In MIMO mode, 2 pilots are used per each antenna path. The resultant stream of constellations is subsequently input to an IFFT and cyclically extended by a cyclic prefix to prevent (ISI). The PLCP preamble is inserted in the first 1 or 3 OFDM symbols of each frame to support the synchronization, transmission mode detection, channel estimation, and tracking process. Finally, after digital filtering, the OFDM signal is delivered to the RF modules via an AD converter. The operations at the receiver are the reverse of those at the transmitter. Additional functionalities are synchronization, channel estimation, and MMSE based MIMO detection block.

The key performance of PHY module in the test-bed is represented by the achievable data rate. In [5], the maximum data rate is described as 23.74Mbps using SISO mode. In contrast, the data rate of 47.48 Mbps can be expected through multi-channel or MIMO transmission using 64QAM and 5/6-convolutional code rate. From the test in real wireless environment, we have confirmed that the test-bed can support up to 41 Mbps in PHY layer.

Table 1. OFDM Parameter

Parameters	Values
TV channel bandwidth (MHz)	6
Total number of subcarriers	128
Number of guard subcarriers (L, DC, R)	26(13,1,12)
Number of used subcarriers	102
Number of data and pilot subcarriers	98, 4
Sampling frequency (MHz)	48/7
FFT period (us)	18.667
Subcarrier spacing (KHz)	53.571
Signal bandwidth (MHz)	5.518

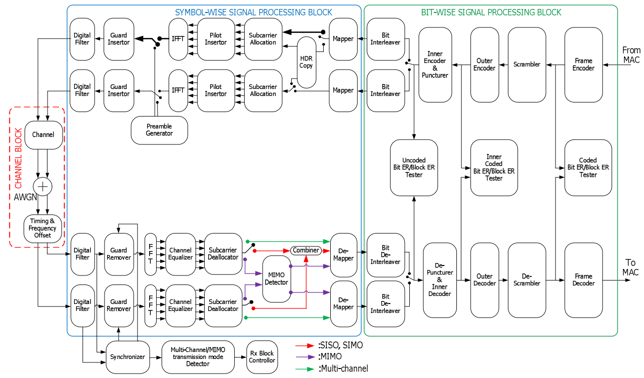

Figure 4. Top block diagram of Physical layer

3.2 MAC

The MAC module is also based on ECMA-392 standard. Super-frame structure is shown in Figure 5. The super-frame is composed of 256 medium access slots (MASs), where MAS duration is 500us. The resources in super-frame are allocated for data transfer period (DTP), contention signaling window (CSW), beacon period (BP), and reservation signaling window (RSW) for non-beaconing device. During DTP, devices can occupy a medium using three different medium access method which is Prioritized Contention Access (PCA), contention-based channel access mechanism or Channel Reservation Protocol (CRP). The MAC frame contains the MAC header which includes the frame control field, the destination address, the source address, the sequence control, and the access control filed, the FCS field, and the payload with optional the security field as shown in Figure 6. In addition, main functionalities of MAC layer for data communication, such as device synchronization, the fragmentation and aggregation of MSDUs, ARQ, dynamic channel selection, multi-rate support, transmit power control, and power management mechanisms, are specified in [5].

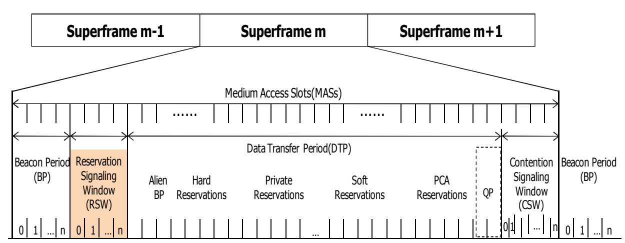

Figure 5. Super-frame structure

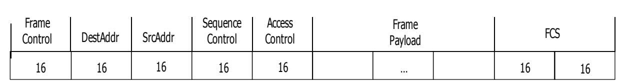

Figure 6. MAC frame format

In our test-bed, MAC module not only includes functionalities described in [5] but also supports the multi-channel transmission mode. To support multi-channel transmission mode, the MAC module interface and channel information are modified. The modified MAC module interface is multi-channel transmission mode field for each outgoing frames. In case of channel information, the channel change information element is revised to contain two RF channel number and its transmission power.

The transmitting device and the receiving device of CR system must operate on the same operating channels. For development efficient protocol of the multi-channel mode, we separated and defined the operating channels into primary and secondary channel. The primary channel is used for network management frames such as beacon frames, command frames and SISO mode data frame transmission. The secondary channel is activated when data frames are transmitted with multi-channel transmit mode. MAC module performs network management functions for all devises to share the information of operating channels. When there are changes of the behavior in the secondary channel, one device (we call the Master) among the test-bed performs network management function and requests channel change to other devices (we call the Slave) using channel change information. When slave devices receive that information element, they change the operating channels according to the channel information.

3.3 RF

The RF hardware consists of two data transceiver modules and sensing receiver module for spectrum sensing. Data transceiver module is designed for CR system using low-power under 100mW in TVWS. All of three RF modules are equipped on the RF main board including 16MHz reference clock division module. Through the reference clock division module, clock signal is shared among RF modules and digital board. The following Figure 7 is represented the entire composition diagram of the RF modules.

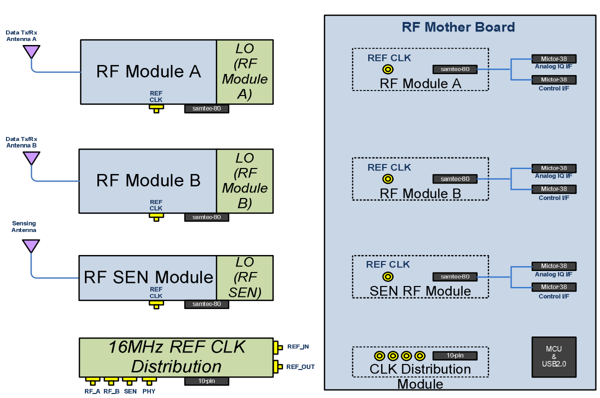

Figure 7. Entire composition diagram of the MIMO/Multi-channel CR RF module

The RF transceiver operates in UHF TV band of 470~698MHz to support the OFDM signal transmission and reception. Basically, these modules have 6MHz channel filter and optionally provide up to 12MHz for channel bonding. With regard to interface for data path between RF and PHY, a differential analog I/Q signals are transmitted to each other via mictor-38 cable. By PHY module and sensing signal processing part, the control of RF modules such as Tx/Rx conversion, PLL setting, Tx/Rx gain control using attenuator, automatic frequency control, and I/Q compensations are performed.

Unlike other communication systems, CR system changes an operating channel due to surrounding radio environments. Therefore we implemented the test-bed having the capability of fast channel switching. So the phase locked loop (PLL) lock time below 500usec is smaller than other communication system. Table 2 shows specifications of the CR RF data transceiver.

Table 2. Specifications of CR RF Data Transceiver

	Parameters	Unit	Specification
1	Frequency Band	MHz	470 ~ 698
2	Bandwidth	MHz	6/12MHz
3	Noise Figure	dB	<6
4	Max. RF input	dBm	<10
5	Max. SNR	dB	>30
6	Tx. EVM	dB	>30
7	Max. Tx. power	dBm	20
8	PLL Phase noise	dBc	<-85@1kHz <-85@10kHz <-100@100kHz <-110@1MHz
9	PLL Locking time	usec	<500

3.4 Spectrum Sensing

The spectrum sensing function is required to aware radio environment around the test-bed in real-time. In addition, some incumbent devices may not be registered to database, thus database access cannot guarantee protection of all incumbent systems from interferences caused by CR devices. Moreover, various CR system standards for TV white space have been established, and coexistence issues not only with incumbent users but also with other CR systems should be considered by utilizing spectrum sensing capabilities.

Figure 8 describes a functional architecture of the spectrum sensing module implemented in the CR test-bed. The spectrum sensing function is controlled by the MAC module. The MAC module commands the sensing module to perform spectrum sensing for desired channel with proper sensing type, sensing interval, and sensing period. The sensing control block in the sensing module interprets sensing commands and controls the sensing receiver and sensing algorithm block. According to the commands from the sensing control block, the sensing receiver receives channel data from the target channel and transfers captured signal to the sensing algorithm block.

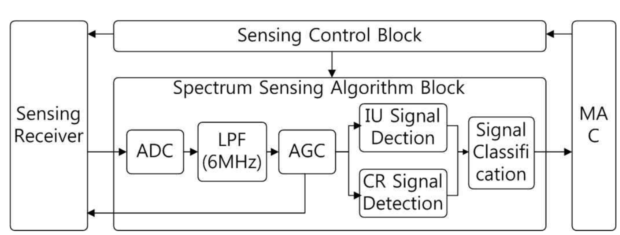

Figure 8. Functional architecture of the spectrum sensing module

The sensing algorithm block converts the received analog channel data to digital data and filters the signal with digital low-pass filter. Automatic gain control block controls gain of the sensing receiver according to the received signal power level. The channel data is transferred to two parallel signal processing blocks: incumbent user (IU) signal detection and CR signal detection. The IU signal detection block decides whether any IU signal such as digital TV, analog TV, and wireless microphone, exists in the channel. To detect IU signal, cyclo-stationary feature detection method is employed [7]. On the other hand, to detect CR signal which operates in TVWS such as IEEE 802.22, IEEE 802.11af, and ECMA-392, signal detection method utilizing spectral correlation is implemented. After both signal detection algorithms are carried out, spectrum sensing results are decided in signal classification block. Finally, spectrum sensing results are carried forward to the MAC module.

There are two types of spectrum sensing operation exist: in-band sensing and out-band sensing. The in-band sensing is used to detect presence of signal in the operating channel. When an IU signal appears in the operating channel, a CR system has to change its operating channel immediately not to make harmful interferences to the IU system. To detect a signal in the operating channel reliably, a CR system should stop its data transmission for in-band sensing duration. CR systems usually set quiet period (QP) for in-band sensing for accurate spectrum sensing results. A QP is allocated for each super-frame with length of 5.1ms. For reliable signal detection, 4 QPs are aggregated to decide signal presence of in-band sensing. Meanwhile, for multi-channel operation, the test-bed has two operating channels. In this case, the sensing module performs in-band sensing for those operating channels sequentially.

A purpose of out-band sensing is to find proper backup channels. As previously mentioned, a CR system is required to change its operating channel when an IU signal appears in the channel. Therefore, it needs to prepare candidate channels for its next operating channel. Out-band sensing is a process to exam and prepare high quality channel for its operation candidate channel. Out-band sensing is carried out for 20.4ms duration per channel according to sensing schedules controlled by the RRM module.

3.5 Cognitive Engine and RRM

The cognitive engine performs the cognitive functions in the test-bed. It carries out the process of 'geo-location database access mechanism', 'channel sensing mechanism' and 'operation channel quality decision mechanism'. Basically, cognitive engine selects the suitable channels among the available channels through three mechanisms. It also manages the channel list, in which the whole channels are classified into operating channel, candidate channel or backup channel, by using the channel status information from geo-location database or spectrum sensing module.

The geo-location database access mechanism offers an available channel lists to the CR test-bed depending on its location. Currently, there is no available public database until now. In this context, we created a simple geo-location database which has the list of available channels on the locations and is based on the protocol of IETF PAWS draft standard [8]. In Figure 9, the snap-shot of the activity between developed database and test-bed is shown. With channel sensing mechanism, the test-bed can estimates the activities of IUs and the quality of idle channels. The output of this mechanism is used to decide new operating channel when an IU is detected on current operating channel. The link quality of operating channel is decided from the result of operation channel quality decision mechanism. This mechanism judges on the quality of the current operating channel using the information of CRC error ratio and retransmission ratio during certain time. This mechanism is also used to change an operating channel when the link quality of current channel is poor.

The RRM module is developed on the CPU. This module receives flow requests from the application layer and performs call admission and resource management. If the required number of MASs is available in the super-frame, it admits the requested call and reserves the number of MASs.

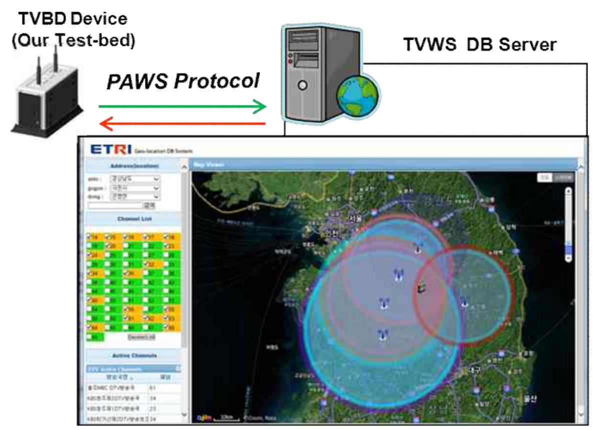

Figure 9. Snap-shot of geolocation database activity

4. FUNCTIONAL TEST OF THE TEST-BED

A setup of the test-bed for functional test is described in Figure 10. It is composed of a pair of the test-bed: a master device and corresponding slave device. A signal generator was set to generate arbitral IU signal such as TV signal and CR system signal. Two laptops were prepared to control and monitor statues of master and slave device, respectively. Virtual geo-location database was configured with a personal computer, and a diagnostic monitor (DM) was equipped for real-time monitoring of the test-bed.

We tested three functionalities to verify the cognitive functionality and performance of the CR test-bed. The first test was for process of creating a network and association between master device and slave device. And then we tested sensing capability and dynamic channel switching function when IU signal is appeared on the operating channel by a signal generator. Finally, operation test of the cognitive engine and the RRM module during data transmission and video streaming were performed.

The initial association of master and slave device came to action by beaconing process. Initial available channel list were given by geo-location DB access or spectrum sensing, and the master device choses the operating channel. The master device started beaconing on the operating channel and associated with the slave device by requesting association message. The association was completed via two way hand shake message exchanges.

Protection of IU system is a key function of the CR test-bed. In the case of IU appearance on the operating channel, the master device should immediately stops data transmission in the current operating channel and switches it to another channel provided by the cognitive engine. The channel switching operation flowchart is shown Figure 11. According to the FCC's rule and regulation, CR device should change its operating channel within 2 seconds when IU signals appear on the same channel. We measured the channel change time; it is consisted of channel sensing time, channel switching time, and variable processing time. Channel sensing time includes sensing interval according to the sensing schedule and sensing algorithm processing time. The most part of switching time depends on channel switching message exchange process between master and slave device. We have confirmed that the channel switching process takes place around 1 second of time which is enough to satisfy FCC’s requirement.

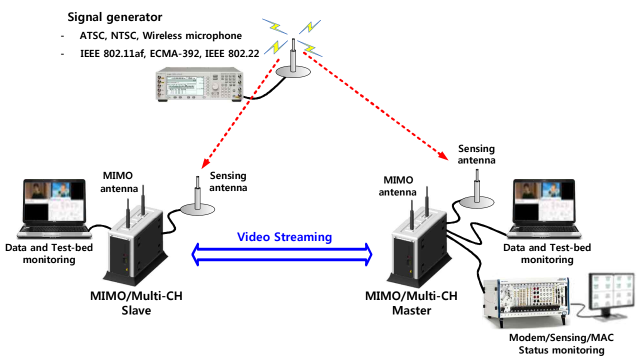

Figure 104. Functional test scenario of the test-bed

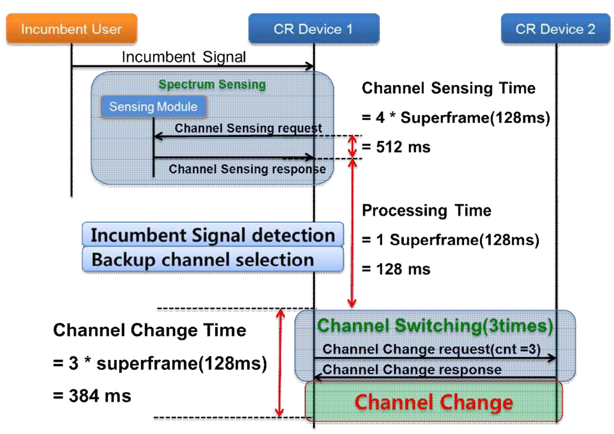

Figure 5. Flowchart of channel switching process

Snapshots of the DM configuration and illustration are shown in Figure 12. Figure 12 (A) displays system parameters and performances related with the PHY module. Followings are detailed information for each component.

①: Received signal constellation of path 1 (SISO)

②: Received signal constellation of path 2 (MIMO, MC)

③: PHY header information, e.g. modulation order

④: Operation mode: SISO, MIMO, Multi-channel

⑤: Average received SNR (signal-to-noise ratio)

⑥: Packet error rate

From figure 12 (A), we can convince that the test-bed supports multi-channel mode for highest modulation, e.g. 64QAM with reliable performance. Figure 12 (B) represents status of the test-bed related with MAC and spectrum sensing functionalities.

①: Operating channel and corresponding sensing result

②: Spectral correlation function for IU signal sensing

③: Cyclic auto-correlation function for CR signal sensing

④: Spectrum sensing history

⑤: Super-frame resource allocation

⑥: Operating channel history

We can check detailed information of spectrum results, resource allocation and utilization, and operation history of the test-bed by making use of the DM. Most of information displayed in Figure 12 (B) are updated every super-frame, thus cumulative operation behavior could be observed instantly with the implemented DM.

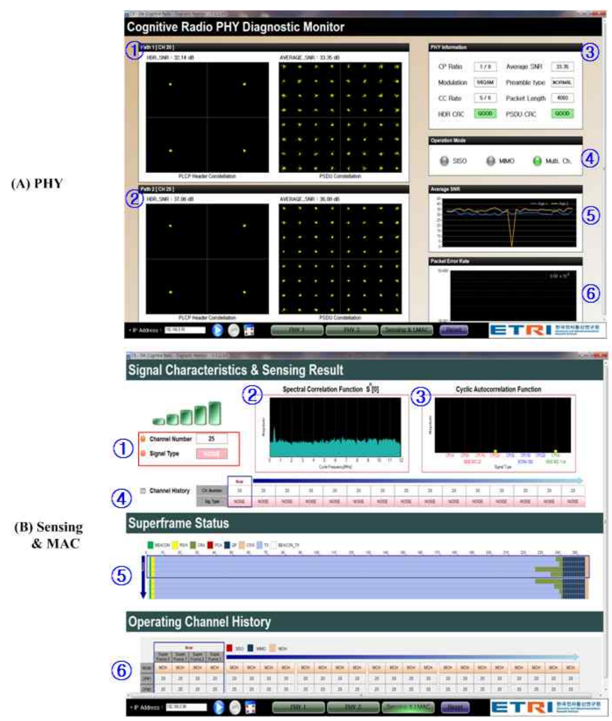

Figure 12. DM configuration and illustration

5. CONCLUSION

In this paper, we introduced a cognitive radio test-bed equipped with advanced technologies. The test-bed has proper cognitive radio capabilities to utilize TVWS without harmful interferences to incumbent users. In addition, dynamic cognitive capabilities and various system functionalities could optimize spectrum efficiency. Those capabilities were shown and proved by diagnostic monitoring equipment which also provides operation information of the test-bed in real-time. By supporting multiple carrier aggregation, it overcame a bandwidth limitation of TV band, therefore it could contribute to maximize system throughput of CR system in TVWS. Furthermore, non-contiguous carrier aggregation capability guarantees the feasibility of performance improvement in realistic TVWS environment. We convince that our CR test-bed can significantly contribute not only for research purpose in academic area but also for facilitation of CR system in business activity.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] U.S. FCC, “Second report and order and memorandum opinion and order,” in FCC 8-260, Nov. 2008.

[2] Ofcom, “Digital dividend: cognitive access statement on license-exempting cognitive devices using interleaved spectrum,” Statement, July, 2009

[3] Yonghong Zeng et al., “Worldwide Regulatory and Standardization Activities on Cognitive Radio,” in proc. of the 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum, pp. 1-9, Apr. 2010.

[4] Information exchange between systems - wireless regional area networks (WRAN) - specific requirements part 22: cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: policies and procedures for operation in the TV bands, IEEE 802.22-2011, July, 2011

[5] MAC and PHY for Operation in TV White Space, ECMA-392, Dec. 2009

[6] Antony Franklin et al., "Cognitive Radio test-bed based on ECMA-392 International Standard," 7th International Symposium on Wireless Communication Systems, pp.1026,1030, Sep. 2010

[7] Hou-Shin Chen and Wen Gao, “Cyclo-stationarity Based Sensing Algorithms,” IEEE 802.22 contrib., Doc #: IEEE 802.22-07/0133r0, Mar. 2007.

[8] IETF PAWS “Protocol to Access Spectrum Database” Available: http://tools.ietf.org/wg/paws/draft-ietf-paws-protocol/