A Protoyping Platform for Spectrum Sensing in China

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***Abstract*—Due to the increasing demand on wireless communications the idea of cognitive radio is of utmost interest. The TV white space may become the first commercial application of cognitive radio resulting from its advantageous propagation properties. It allows the usage of secondary communication systems at non-occupied frequency bands. Within this manuscript, a prototyping platform for cognitive radio applications is presented. Its underlying architecture is based on a combination of DSP and FPGA and relies on the software-defined radio paradigm. Spectrum sensing algorithms are introduced for the three predominant Chinese TV standards DTMB, CMMB and PAL-D/K. Finally, the algorithms' performance is shown in a comparison to simulation results. The focus of this manuscript is on a TV white space prototyping platform and the validation of spectrum sensing algorithms for the Chinese TV standards DTMB, CMMB and PAL-D/K.**

***Keywords*—CMMB; Cognitive Radio; DTMB; Prototyping Platform; PAL-D/K; TV White Space**

I. Introduction

In the recent decade, an increasing interest in the field of cognitive radio (CR) for wireless communication systems could be discovered. It is considered as a key technology for significantly alleviating the spectrum scarcity. One application for the CR technology is the TV white space (TVWS). It refers to non-occupied frequency bands in the TV spectrum, i.e., below 900 MHz, and is a desirable target for CR-based spectrum sharing due to its advantageous propagation properties compared to other frequency ranges on the one hand and due to its low utilization ratio on the other hand [1]. Hence, CR in TVWS will probably become the first commercial application that brings CR from concept to reality. In the United States, the FCC has already made an official request to allow unlicensed users reusing TV bands without causing interference to incumbent users [2]. In other countries, the corresponding regulatory authorities such as the CEPT in the European Union are developing regulations on the unlicensed usage in TVWS as well. Besides the regulatory authorities, standardization organizations such as IEEE 802.22 [3] have started the standardization for cognitive radio applications.

The spectrum sensing technology has been considered as a key element of CR and its application to TVWS has been widely studied. However, a variety of different TV standards exists, which may differ from country to country, especially for digital TV standards. While in North America ATSC (Advanced Television Systems Committee) is deployed, in Europe, South Asia and Africa, DVB-T/H (Digital Video Broadcasting - Terrestrial/Handheld) plays the predominant role. Further standards such as ISDB (Integrated Services Digital Broadcasting) developed in Japan or DMB (Digital Multimedia Broadcasting) developed in Korea are also used in various countries [4]. As a result, it is hardly feasible to design a universal sensing algorithm for all TV standards. This manuscript focuses on spectrum sensing for Chinese TV standards.

There are mainly three terrestrial and handheld TV standards in China: DTMB (Digital Terrestrial Multimedia Broadcast) [5] for terrestrial reception, CMMB (China Mobile Multimedia Broadcasting) [6] for handheld reception and PAL-D/K (Phase Alternating Line) [7] for analog TV. While other countries such as the USA have already stopped the provision of analog TV, the nationwide switchover from analog to digital TV will not occur until the year 2015. Therefore, the analog TV will still coexist with the digital TV for many years to come. As a result, the detection of both analog and digital signals is necessary for CR implementations.

The United States are the first and also most active country in exploiting the unlicensed usage of TVWS. The spectrum sensing technology for ATSC signals has been intensively studied. Several detection algorithms for ATSC and its analog predecessor NTSC (National Television System Committee) can be found in IEEE 802.22 standard [8]. In 2008, a sensing prototype test campaign was organized by FCC [9]. As an example, Motorola, Philips and I2R have submitted their prototype designs, which have been tested both in the laboratory as well as in the field. The results showed that the ATSC and NTSC signals can be detected correctly with a certain probability. As another widely used TV standard, DVB-T has also been intensively studied with respect to spectrum sensing. In [10], a robust sensing approach is discussed using a prototype sensor developed by Philips. Several detection algorithms for a Chinese standard, i.e., DTMB, have also

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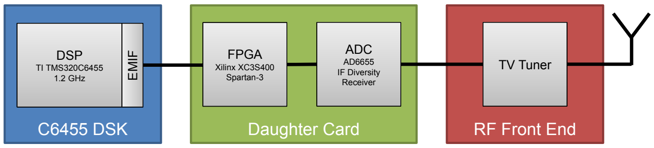

Fig. 1. Platform Overview for Spectrum Sensing Applications

been studied and published [11], [12]. The focus of this manuscript is on a prototyping platform developed by the authors and deployed for the implementation of spectrum sensing algorithms for the TVWS in China. The prototyping platform is based on the software-defined radio paradigm [13] allowing a reconfiguration of the platform by software. Besides the prototyping platform, spectrum sensing algorithms for DTMB, CMMB and PAL-D/K are illustrated including their measured performance in comparison with simulation results.

This manuscript is structured as follows. In Section II, the prototyping platform is presented, while, in Section III, the signal flow for the spectrum sensing operation is addressed. Section IV gives an overview of the Chinese TV standards DTMB, CMMB and PAL-D/K. The corresponding sensing algorithms, which are implemented on the prototyping platform, are presented in Section V. Section VI shows selected results in a comparison between the simulated algorithms' performance and the performance measured with the prototyping platform. Finally, a conclusion is given.

II. Spectrum Sensing Prototyping Platform

For the implementation of cognitive radios, an elaborated prototyping platform is essential. Already during the concept phase of this prototyping platform, modularity has been a crucial design constraint. Hence, the platform is designed in a way that certain parts can easily be replaced by more appropriate parts depending on the system to be implemented and its underlying requirements. The platform mainly consists of three printed circuit boards as illustrated in Figure 1. The base board is a DSP starter kit hosting a powerful DSP TMS320C6455 by Texas Instruments running at 1.2 GHz. This DSP is responsible for major parts of the signal processing algorithms on the one hand and for the overall platform scheduling on the other hand. Since higher-level programming languages such as C/C++ can be used for implementing signal processing algorithms, this DSP-based platform is ideally suited for rapid prototyping. Algorithms, which have been studied in a simulation environment before, can easily be implemented to run on the DSP. Furthermore, the advanced debugging capabilities of this DSP simplifies locating implementation errors.

Directly attached to the DSP is the mixed-signal daughter card. While in Figure 1 the core components required for the spectrum sensing operation are illustrated only, Figure 2 shows a more detailed block diagram of this daughter card. The daughter card can, besides the implementation presented here, also be used as a full communication transceiver. It consists

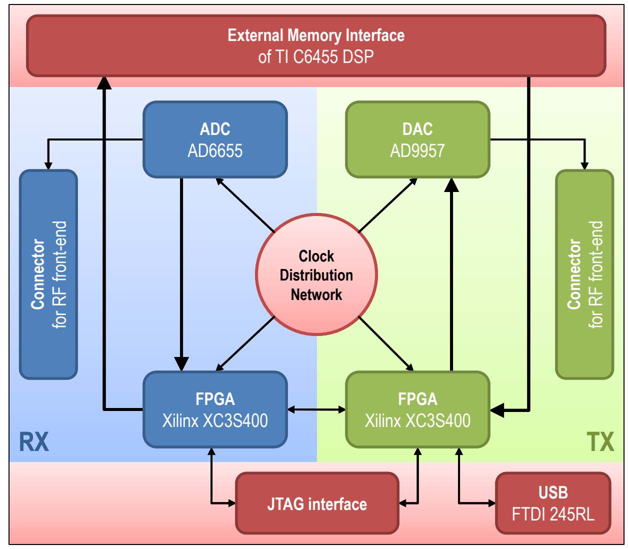

Fig. 2. Prototyping Platform: Block Diagram of the Mixed-Signal Daughter Card

of an Analog Devices AD6655 analog-to-digital converter (ADC) as well as of an Analog Devices AD9957 digital-to-analog converter (DAC). Both devices are supplied from an elaborate clock distribution network, which guarantees highly stable clocks for the overall platform. Since the focus of this manuscript is on the spectrum sensing implementation, in the following only the receiver branch of this daughter card is considered. The digitized signal coming from the ADC is directly given to a Xilinx Spartan-3 FPGA for performing further filtering and decimation operations. Furthermore, the FPGA is used for synchronizing the spectrum sensing events. The synchronization information originates from a Huawei LTE eNodeB. After some fundamental signal processing steps, the data is buffered within the FPGA and transferred to the DSP using the Texas Instrument EMIF (External Memory Interface). To reduce the overall load of the DSP, this transfer makes use of direct memory access (DMA).

The analog input signal of the ADC originates from an RF front-end directly attached to the mixed-signal daughter card. In case of the spectrum sensing prototyping platform, the RF front-end mainly consists of a commercially available TV tuner receiving the RF signal by an appropriate antenna and down-converting it to an intermediate frequency (IF) signal, which is then sampled by the ADC.

A photography of the spectrum sensing prototyping platform is given in Figure 3. It shows the three aforementioned modules with the RF front-end at the top and the DSK at the bottom. In between, the PCB of the daughter card is located. Additionally, a separate PCB is located on the right-hand side for debugging purposes and for interfacing with the synchronization entity.

III. Prototyping Platform Signal Flow

This section describes the signal flow for the spectrum sensing operation. The focus is on the digital baseband signal, which is buffered in the DSP. An overview of the signal flow gives Figure 4. Before the sensing operation starts, its parameters such as sensing interval, target false-alarm probability and TV standards to be sensed for are defined by an external spectrum management entity. Within the prototyping platform itself, a control unit is responsible for evaluating and distributing the parameters of interest. There are different operation modes depending on the a-priori knowledge about the underlying TV usage. In case the frequency band of interest may only be used by one TV standard, this information is communicated to the control unit so that only the corresponding detection algorithm is carried out. Otherwise, in case this frequency band may be used by all of the available TV standards, the control unit passes the captured data first to the DTMB detector followed by the CMMB detector and, finally, the PAL-D/K detector. The soft-decision outputs of all detectors are then processed by a combination metric to give an overall information about the presence of any of these signals. A graphical user interface (GUI) exists, which allows a simple configuration of the sensing parameters and an immediate demonstration of the sensing results.

IV. Chinese TV Standards

The intention of this section is to give a brief overview of the various Chinese TV standards. The focus is on the main aspects, which are relevant for feature-based signal detection. For a full description of the TV systems, please refer to [5], [6] and [7], respectively.

A. DTMB

DTMB, also referred to as DMB-T (Digital Multimedia Broadcast - Terrestrial), is a mandatory TV standard in China. DTMB can be used in either single-carrier or in multi-carrier mode. Three FEC (Forward Error Correction) code rates, five modulation orders and two interleaving depths are specified for DTMB [5]. A block diagram of a DTMB transmitter is shown in Figure 5.

DTMB defines three different header types with different lengths. The frame body itself has a fixed length of 500 µs. The frame structure of DTMB including the different header types is illustrated in Figure 6. The frames are hierarchically structured in a calendar day frame, a minute frame and a super frame. One superframe consists of either 225 frames with frame header mode 1 or of 216 frames with frame header mode 2 or of 200 frames with frame header mode 3.

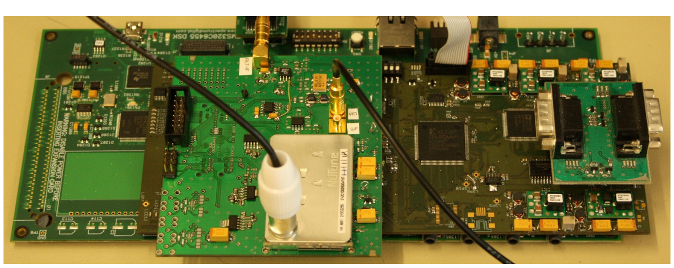

Fig. 3. Photography of the Prototyping Platform

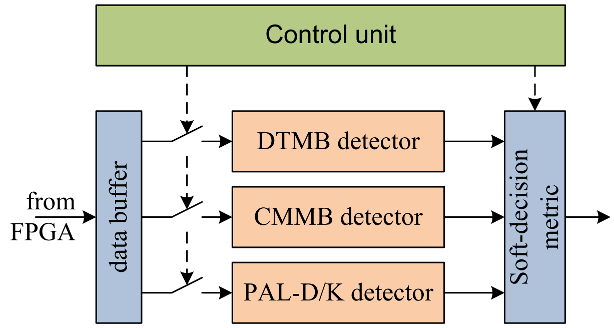

Fig. 4. DSP Signal Flow

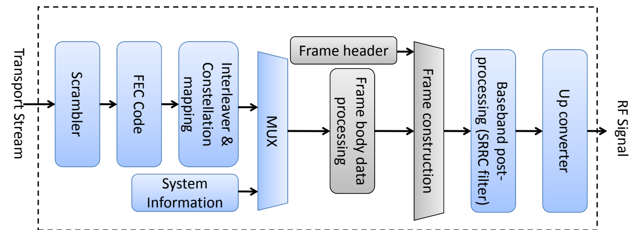

Fig. 5. DTMB Transmitter [5]

The three frame headers are generated by different generator polynomials [5], which are:

$$G_1(x) = 1 + x + x^5 + x^6 + x^8 \tag{1}$$

for mode 1,

$$G_2(x) = 1 + x^3 + x^{10} \tag{2}$$

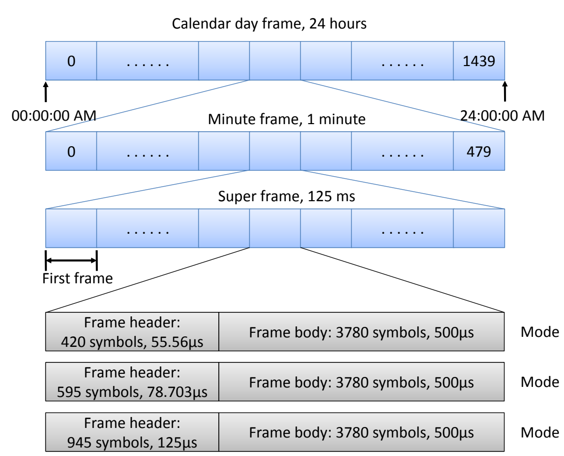

Fig. 6. DTMB Frame Structure [5]

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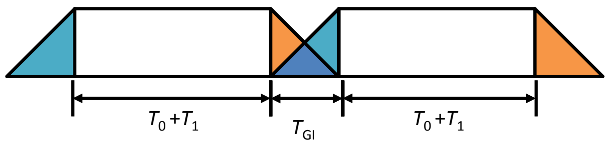

Fig. 7. CMMB Symbol Overlapping

for mode 2 and

$$G_3(x) = 1 + x^2 + x^7 + x^8 + x^9 \tag{3}$$

for mode 3. The generation of the sequence can be realized by a linear feedback shift register.

B. CMMB

CMMB is a system fully based on the well-known OFDM (Orthogonal Frequency Division Multiplexing). A combination of Reed-Solomon (RS) and Low-Density Parity-Check (LDPC) codes is used for FEC. Unlike many other OFDM systems such as DVB-T [14], the OFDM symbol of length T_0 in time-domain is not only extended by inserting a cyclic prefix (length T_1) but it is also extended by a pre-guard interval and a post-guard interval of length T_{GI} each. As illustrated in Figure 7, the post-guard interval of a certain OFDM symbol in CMMB overlaps with the pre-guard interval of the subsequent symbol [6].

In CMMB, one frame has a duration of 1 s and consists of 40 time slots. Each time slot contains one beacon and 53 OFDM symbols. The beacon contains a transmitter identification field and two synchronization signals. The OFDM symbols consist of data-bearing subcarriers as well as of pilot subcarriers. These pilot subcarriers are subdivided into continual pilots and scattered pilots [6].

C. PAL-D/K

A variety of different PAL-based standards exist, which mainly differ in the channel bandwidth or in the underlying modulation scheme. The PAL standard used in China is called PAL-D/K with 8 MHz channel bandwidth, 50 Hz field frequency and 625 lines per frame [7]. A PAL signal consists of separate video and audio parts. Within this manuscript, only the bandwidth occupied by the video part is subject to spectrum sensing. The video signal used in PAL is a CVBS (Color Video, Blanking and Sync) signal, which is an extension to the monochrome VBS (Video, Blanking and Sync) signal. A snapshot of a standard VBS signal is depicted in Figure 8. In addition to the video signal itself, the VBS signal has some additional components, which are required, e.g., for synchronization at the receiver. The black-level signal components after and before the video signal are referred to as front porch and back porch, respectively. The time values shown in Figure 8 are compliant to the PAL-D/K standard. The total duration of one line is 64 µs resulting in a line frequency of 15625 Hz [7].

V. Spectrum Sensing Algorithms

After the brief introduction to the various Chinese TV standards, this section describes the spectrum sensing algorithms. All algorithms have in common that they are based on autocorrelation of the digital baseband signal. In general, the autocorrelation function $\varphi_{ss}(t)$ of a complex signal $s(t)$ is defined as

$$\varphi_{ss}(\tau) = \int_{-\infty}^{\infty} s^*(t)s(t+\tau)dt \tag{4}$$

where $(\cdot)^*$ denotes the complex conjugation.

A. DTMB

In DTMB, the frame header appears periodically at the beginning of each frame, which can be exploited for the sensing operation. The presented autocorrelation-based sensing algorithm for DTMB can be divided into three stages:

- autocorrelation stage
- comb-correlation stage
- decision stage

A flow diagram of the algorithm is shown in Figure 9. For the autocorrelation the digitized baseband signal is multiplied with a delayed and complex conjugated version of the signal where the delay itself depends on the frame header mode. The running average filter cumulates a certain number of the multiplication output samples. Resulting from the periodical appearance of the frame header, the first stage's output is applied to a comb correlator, which is a correlation with a Dirac comb $g(t)$ with a distance Δt corresponding to the frame header period, i.e.,

$$g(t) = \sum_{k=-\infty}^{\infty} \delta(t - k \cdot \Delta t). \tag{5}$$

This stage allows collecting the energy of all frames within the sensing period. The squared magnitude of the cumulated comb-correlation output φ_{cc} is given to the decision stage. In this stage, the ratio λ of the maximum and the average of the

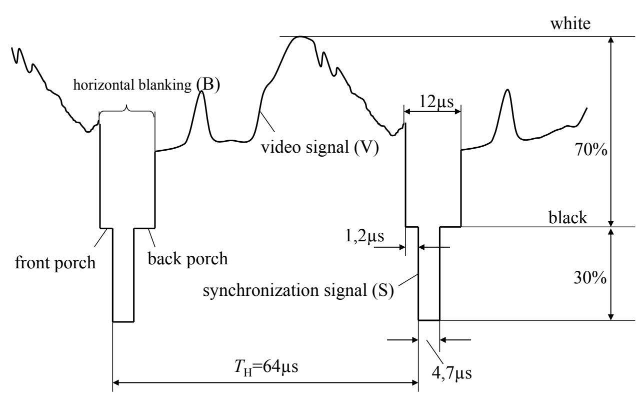

Fig. 8. VBS Signal

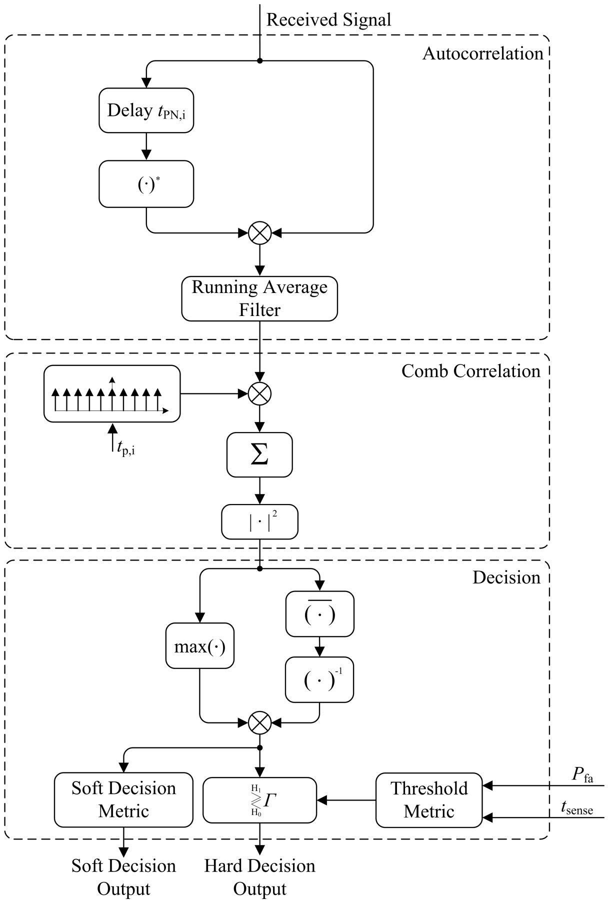

Fig. 9. Flow Diagram of the DTMB Sensing Algorithm

previous stage's output is calculated:

$$\lambda = \frac{\max\left(\varphi_{\mathrm{cc}}(t)\right)}{\overline{\varphi_{\mathrm{cc}}(t)}}. \tag{6}$$

By applying a soft-decision metric to λ, a measure for the probability of the presence of a DTMB signal is generated. Furthermore, comparing the ratio with a threshold Γ gives a hard-decision on the presence of a DTMB signal. This threshold is generated by using a threshold metric based on the available sensing interval t_{sense} and the desired false-alarm probability P_{fa}.

By using the ratio λ for making the decision about the presence of a DTMB signal, the presented algorithm is robust against dynamic range variations as well as varying signal-to-noise ratios and, thus, independent of the underlying AGC (Automatic Gain Control) implementation.

B. CMMB

The sensing algorithm for CMMB is very similar to the sensing algorithm for DTMB. As shown in Section IV, CMMB uses a cyclic repetition of certain parts of the OFDM symbol, denoted as cyclic prefix. Since this cyclic prefix equals the last part of the corresponding OFDM symbol, it is well suited for the sensing operation. The general data flow of the algorithm is identical to the DTMB algorithm depicted in Figure 9. However, the timings must be adapted according to the CMMB parameters.

C. PAL-D/K

The sensing algorithm for PAL-D/K relies on the periodicity of certain parts of the CVBS signal as depicted in Figure 8. The CVBS signal exhibits a periodic pattern of the synchronization pulses in every transmitted line of the resulting TV picture. In addition to the synchronization pulses itself with a length of $t_{\mathrm{hsync}} = 4.7\ \mu$s the front as well as the back porch with lengths of $t_{\mathrm{fp}} = 1.2\ \mu$s and $t_{\mathrm{bp}} = 6.1\ \mu$s, respectively, can be used for sensing purposes. The time between two consecutive synchronization pulses is $t_{\mathrm{H}} = 64\ \mu$s. A flow diagram of the PAL-D/K sensing algorithm is depicted in Figure 10 and consists of two stages:

- Autocorrelation stage
- Decision stage

While the delay in the autocorrelation corresponds to the periodicity of the CVBS signal, the length of the running average filter is set to t_{H} as well. This improves the sensing performance by exploiting similarities in the video signal for consecutive lines. In the decision stage, the average of the output of the autocorrelation stage is calculated. The residual parts of the decision stage are identical to the corresponding parts in the decision stages for DTMB and CMMB signals.

VI. Results

To show the overall performance of the previously introduced algorithms, a comparison between the simulation results and the results measured with the prototyping platform is given. The TV signals are generated by a Rohde & Schwarz signal generator. The signals are sent to the prototyping platform for detection. Additionally, the actual signal power is measured using a Rohde & Schwarz power meter. The parameters used for the simulations as well as for the measurements are as follows: The bandwidth used for all TV

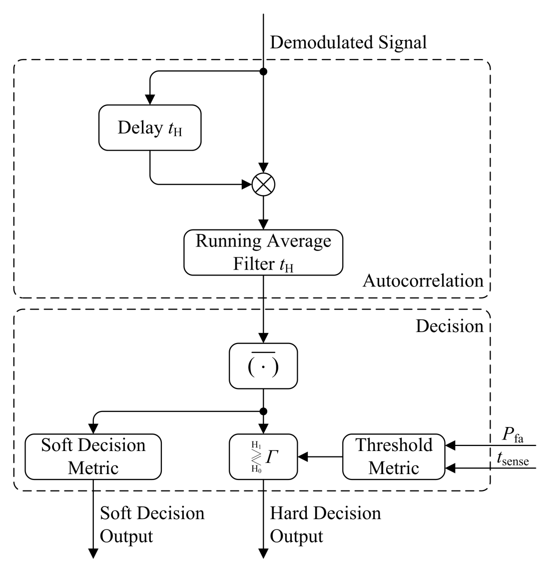

Fig. 10. Flow Diagram of the PAL-D/K Sensing Algorithm

standards is 8 MHz and the sensing interval t_{sense} is set to 20 ms. The target false-alarm probabilities are 10% and 0.1%, while the target detection probability is 90%. For the simulations, a noise figure of 8 dB is considered. Figure 11 shows the detection probability P_{d} versus the received signal power p_{rx}. The considered DTMB signal uses frame header mode 1. The blue curves show the simulation results for a false-alarm probability of 10% and 0.1%, respectively. The red curves show the corresponding measurement results. For the target detection probability of 90%, the measurement results are 3 dB to 4 dB worse than the simulation results. Thus, with the given algorithms, a sensitivity of approximately -110 dBm and -108.5 dBm can be reached in the presented hardware setup. There are several reasons that could result in such degradations. The simulations assume a perfect AGC while in the real system the maximum gain is limited by the tuner module leading to an increased quantization noise in case of very low signal powers at the input of the tuner. The TV tuner shows highly unstable behavior in terms of amplitude and phase when the input signal is very weak. Such a property results from the fact that the tuner is designed for receiving TV signals at significantly higher power levels. The required sensing sensitivity is much higher than the TV receiver sensitivity. This causes unexpected distortion when the signal level is below the target receiver sensitivity. This aspect is also the reason why autocorrelation algorithms are favorable compared to cross-correlation algorithms. Cross-correlation algorithms suffer more seriously from such distortions of the tuner, leading maximally to the same overall performance as the autocorrelation algorithms although in simulations such cross-correlation algorithms perform better than their autocorrelation counterparts. However, the computational complexity of cross-correlation implementations is much higher and, hence, autocorrelation algorithms are preferred.

Further reasons for the difference between the simulated and measured sensing results are effects such as frequency offsets and amplifier non-linearities in the RF stage, which cannot be avoided in hardware implementations and may lead to significant performance degradations. However, these effects have not been considered in the simulations.

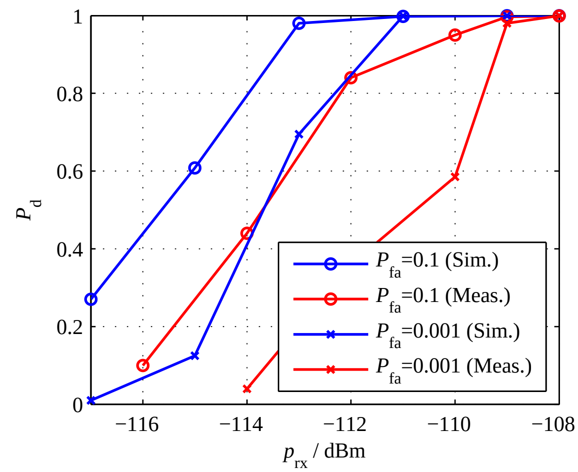

Fig. 12. Simulation and Measurement Results for CMMB

The simulation and measurement results for the TV standard CMMB are plotted in Figure 12. Again, a degradation of the measurement performance of almost 3 dB compared to the simulation performance can be identified. With the implemented algorithms, a sensitivity of -111 dBm ($P_{\text{fa}} = 10\%$) and -109.5 dBm ($P_{\text{fa}} = 0.1\%$), respectively, can be reached for the given target detection probability.

In case of PAL-D/K, the measured performance is much worse than the simulated performance as shown in Figure 13. For PAL-D/K, further signal processing steps are necessary to extract the CVBS signal from the received PAL signal. These signal processing steps need to be carried out before the sensing operation. However, they are implemented in a way to minimize the processing latency rather than for utilizing the dynamic range most efficiently. This leads to a significant

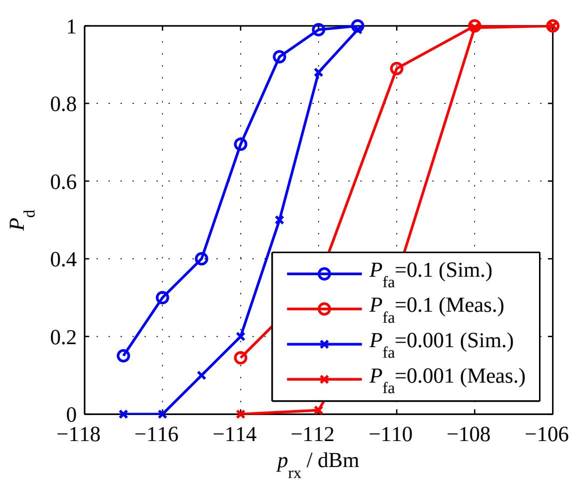

Fig. 11. Simulation and Measurement Results for DTMB

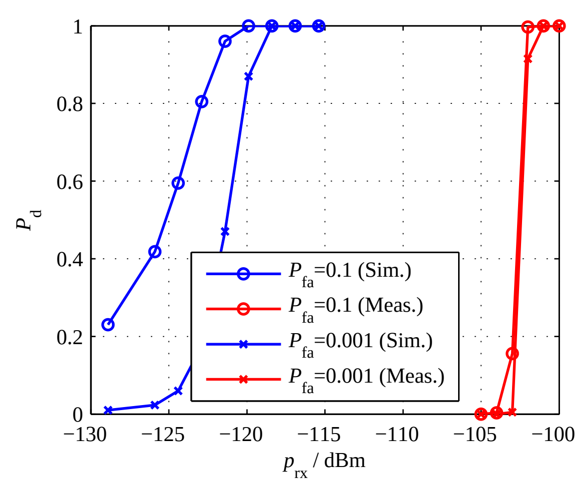

Fig. 13. Simulation and Measurement Results for PAL-D/K

performance degradation in comparison to the simulation results, which are based on floating-point calculations without any constraints regarding the dynamic range. The sensitivity for PAL-D/K is approximately -102 dBm.

VII. Conclusion

In this manuscript, a prototyping platform for spectrum sensing was presented and its underlying architecture was illustrated. Furthermore, an application of cognitive radio for TV white space in China was addressed. Therefore, spectrum sensing algorithms for the three predominant TV standards in China, namely DTMB, CMMB and PAL-D/K, were presented. Those sensing algorithms have been validated on a prototyping platform. The prototyping platform itself as well as the underlying signal flow were highlighted. It was shown that a signal detection even at very low input levels is possible with that platform. For a false-alarm probability of 10% and a detection probability of 90%, a sensitivity of -110 dBm can be achieved for DTMB. For CMMB and for PAL-D/K, -111 dBm and -102 dBm, respectively, can be achieved.

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