Testing and Measurement of Cognitive Radio and Software Defined Radio Systems

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ABSTRACT

This paper describes an overview of Software Defined Radio (SDR) and Cognitive Radio (CR) testing and measurement issues. Challenges, opportunities, short and long term goals, and a possible path towards achieving a flexible SDR/CR testing and measurement capability are discussed. Requirements and possible ways of introducing enhanced and multi-dimensional signal analysis capability, possible new performance measures for quantifying the quality of SDR/CR transceiver, signal intelligence and new ways of monitoring radio signals in multi-dimensional electrospace are also discussed briefly in this paper.

1. INTRODUCTION

The tremendous growth in wireless industry and the diversity in wireless systems and standards have brought some challenges to the wireless community such as interoperability, global seamless connectivity, and spectral crowding. Software Defined Radio (SDR) is envisioned to be a promising solution for interoperability, global seamless connectivity, multi-standard, and multi-mode issues. SDR represents a very flexible and generic radio platform which is capable of operating with many different bandwidths over a wide range of frequencies and various different modulation and waveform formats. With SDR, the functionality of wireless devices is increased and they become more and more sophisticated. Cognitive radio (CR) provides the adaptability where the radio parameters (including frequency, power, modulation, and bandwidth) can be changed depending on the radio environment, user's situation, network condition, geolocation, and so on.

SDR and CR bring new challenges and opportunities to the test and measurement world. Testing, measuring, and verification of SDR capable devices are very challenging. The challenge is not only in hardware (requiring wideband signal analysis and generation capabilities as well as high speed ADC/DAC and fast processing capabilities), but also in software (requiring additional test vectors, performance metrics, user interface, etc.). The next generation tools should have the ability to process wide variety of waveforms and should be equipped with autonomous synchronization and detection capabilities. Especially blind identification of the waveform parameters, modulation formats, and synchronization parameters are important. In addition, understanding the transient behaviors of the transmitted signals is crucial. The measurement devices should also have cognition capabilities which can enable the device to evaluate the ability of the radio being tested (device under test, or DUT) to react to the various factors.

In this paper, testing and measurement of SDR and cognitive radios will be studied. Challenges and new approaches will be discussed. Enhanced waveform analysis capabilities will be studied. In addition to the analysis of signals in time and frequency, other dimensions like code, space, modulation, and waveform will be discussed. Moreover, new and generic performance evaluation metrics (like cyclostationarity, interference temperature, interference statistics, signal activity detection, direction finding, etc.) that are suitable for SDR and CR will be described.

2. A POSSIBLE TEST AND MEASUREMENT MODEL

Figure 1 shows a possible test and measurement model for an SDR transceiver. A transmitter or receiver can be tested at various points of the transceiver as shown in the block diagram. In addition to using signal analyzer for transmitter and signal generator for receiver testing, both of these can also be used in a combined way for functionality and protocol testing. Such a structure can also be a great model to develop an SDR test-bed. For example, signal analyzer can provide a 2-D time-frequency analysis of signal and interference. To test the behavior of the transmitter (DUT) in various interference scenarios, a signal generator can be used to generate an arbitrary interference waveform. It is expected that the SDR/CR device reacts to the interference situation properly (depending on the desired protocol). The signal analyzer and analysis software can be used to evaluate and measure the reaction of DUT to various interference scenarios. The signal analyzer can also be used to see the transient behavior of the DUT when the DUT changes the transmitted waveform as a reaction to interference or other stimulus. Hence, with such a set up, we can control the interference environment with arbitrary signal generator, and we can observe and measure the DUT behavior and performance with signal analyzer along with enhanced test and measurement software. Such a set up can also be useful for link adaptation testing and for testing other adaptive behaviors of the transmitter.

The signal generator and signal analyzer set can also be used to test any individual transmitter and receiver blocks. For example, in order to test Power Amplifier (PA) performance, signal generator can be used to generate any arbitrary signal with various peak-to-average-power-ratios (PAPR) or with various other statistics. Then, the generated RF signal can be fed to the PA and the PA output can be connected to signal analyzer to process the signal. In SDR, it is important that the signal generator can apply test signals to the digital subsystem and signal analyzer can capture signals from the digital subsystem. For example, test signals directly from signal generator (instead of a real FPGA) can be used to drive DAC (possibly after a digital signal interface module), or alternatively, a signal generated by FPGA can be fed to signal analyzer (after passing it through the digital signal interface module) to test the performance of the signal at the FPGA output.

3. BUILDING BLOCKS OF A COGNITIVE RADIO TEST AND MEASUREMENT PLATFORM

Testing and measuring SDR/CR is a very difficult process, which requires many supporting functions. Figure 2 shows some of the building blocks that would be useful for testing and measuring. The blocks required for signal generator and signal analyzer are shown separately. In addition to these individual pieces, advanced triggering mechanisms are also required between the generator and analyzer.

Signal intelligence and generic signal analysis (using blind estimation and detection techniques) could be extremely important for testing SDR transmitter, especially in doing government regulation, observing an operating network, qualification of a product, and to some extent R&D verification. Since SDR transmitters will be capable of transmitting various types of waveforms and will have the ability to change operating parameters (including modulation, bandwidth, frequency, power, time/frequency hopping pattern, etc) during the transmission, the transient analysis capability is very critical to be able to observe RF glitches, transients, and other short term abnormalities. Generic multi-antenna and multi-dimensional (time/frequency/space/angle/code) signal analysis capability will be beneficial for providing detailed information about the transmitted signal. As will be described later, the SDR testing and measurement capability also requires new metrics to accurately evaluate the performance of the transceivers. In addition to the new metrics, advanced visualization of these metrics along with proper user interface and user control mechanisms is needed. Finally, it will be very useful if the SDR measurement analysis tool has the ability to demodulate multiple signals simultaneously (multi-user detection) and separate interference from desired signal. Multi-signal separation and extraction of a signal of interest from multi-dimensional signal space helps to analyze each signal separately without the effect of other signals. As will be described briefly later, this requires advanced windowing/filtering/correlation techniques.

In signal generation side, generic signal synthesis capability is critical. The generic signal synthesis should also include the ability to provide various transient behaviors and ability to change the waveform parameters during transmission. In addition to these, it will be useful for the signal generator to be able to emulate various interference sources (co-channel, adjacent channel, narrowband, impulsive, etc) and incorporate these into the signal of interest. Emulating various impairments (IQ impairments, noise, frequency offset, sample time offset, etc), and generation of multipath channel and incorporation of the channel into the signal are also critical to test and measure the behavior of the SDR system or component under various conditions.

4. MULTI-DIMENSIONAL SIGNAL ANALYSIS

Multi-dimensional signal analysis is one of the most important building blocks for measuring SDR/CR transceivers. This involves multi-dimensional waveform awareness, signal extraction from this multi-dimensional signal space, and advanced signal analysis. For example, in Figure 3, a block diagram of time-frequency (2-D) analysis process is shown. In this specific example, the first goal is to take the time samples (a mono-dimensional vector signal that is captured in time) and obtain a two dimensional time-frequency representation of the signal. Time domain and frequency domain constitute two different ways of representing a signal. Some features of the signal are easier to represent in one domain and some others are easier in the other. Traditional oscilloscopes and spectrum analyzers are capable of providing only single dimension representation. However, wireless signals have multi-dimensional attributes with non-stationary characteristics over the transmission period and it is very difficult to provide detailed analysis using single dimensional approach.

Spectrograms are able to provide the 2-D time-frequency representation to some extent. Short-time Fourier transform, which applies pre-windowing before the transformation, provides spectral properties of the signal in short time periods (local spectrum). The performance depends on the window type and size which often results in a trade-off in obtaining a good time resolution (at the expense of bad frequency resolution) or the other way around. Recently, other techniques that provide more accurate representation of time-frequency characteristics are developed. For example, it is reported that smoothed pseudo Wigner-Ville distribution (SPWD) can provide enhanced performance compared to short-time Fourier transform [1,2]. The 2-D representation needs to be expanded to other dimensions. These other dimensions may include code domain (like code domain power used in CDMA measurements), angle domain (to provide direction of arrival, angular spread), waveform domain (to provide information about the type of signaling), polarization domain, etc. The challenge is to represent all these dimensions jointly and to develop algorithms to optimally extract features in all these dimensions.

Once an accurate representation of signal obtained in multiple dimensions (2-D in the case of the example given in Figure 3), the next step is to be able to extract the desired information from this complex plane. It is very difficult to analyze the multi-dimensional signal. However, by extracting part of this signal (for example the short transient part in time, or part of desired frequency), a detailed analysis can be performed. Signal (or feature) extraction requires accurate windowing/filtering in multiple domains. In addition, advanced triggering and/or advanced user interfaces are also required to be able to extract the desired features of the signal.

The final stage is the analysis of the extracted signal. This includes processing the extracted data and providing accurate test and measurement results as well as statistics about the signal of interest. Blind modulation analysis is one example that can be employed within this stage.

5. NEW PERFORMANCE MEASURES

In addition to the conventional measurements and analysis tools (like EVM, IQ measurements, power versus time, power spectrum, frequency offset, sample timing offset, Rho) that provide information about the DUT, SDR and CR will bring about new performance metrics and analysis options. Not only metrics or tools that can provide generic test and measurement capabilities, but also metrics that are unique for specific waveforms need to be developed. Given the vast number of possible waveforms in an SDR transceiver, providing all sorts of metrics and measures is quite challenging.

Some of the possible metrics and analysis that could be useful for SDR and CR measurements include:

- Cross-coupling/cross-talk (among RF components and high speed digital components)
- ADC/DAC impairments
- Predistortion/linearization impairments
- Time/frequency/space/angle statistics of interference and signal (like minimum bandwidth, maximum bandwidth, spectral occupancy rate, etc.
- Cyclostationarity analysis
- Generic code domain analysis
- Waveform identification (whether the signal is multicarrier signal or signal carrier signal; frequency hoping signal or not; spread spectrum signal or not)
- Auto-modulation detection
- Signal activity detection
- Direction of arrival /angle of arrival detection
- Protocol analysis
- Transient behavior measures (like spectral re-growth during transient)
- Power statistics (like peak power, average power, CCDF, PAPR, average burst width)

6. CASE STUDY: GENERIC OFDM(A) ANALYSIS REQUIREMENTS

Orthogonal frequency division multiplexing (OFDM) is a promising technology for broadband communications and has already been considered as the access technology for many current and future generation standards, such as 802.11a/g (known as WiFi), 802.16-2004/2005 (known as WiMAX), long term evolution (LTE), 802.16m, DVB-T, DAB, Multiband-UWB.

OFDM is also considered as the access technology for cognitive radio. OFDM with frequency/time multiple accessing (which is known as OFDMA) and along with multiple antenna (and MIMO) configurations allow a powerful option for flexible allocation of radio resources in a multi-dimensional time/frequency/space optimization platform. Introducing the additional dimensions of code domain and waveform domain into this picture, the future wireless systems will have a great flexibility in assigning resources optimally to users, allowing a better control on interference.

Since OFDM(A) will mostly likely be the technology for many wireless networks in the future and also due to its suitability for cognitive radio, this section is focused on some of the requirements for generic OFDM(A) analysis. The most critical part of the generic OFDM(A) analysis is the ability to estimate some of the important OFDM(A) waveform parameters and the ability to synchronize and perform extensive modulation analysis (see Figure 4). The important parameters that are required to be estimated include the bandwidth, carrier frequency, cyclic prefix size, symbol duration, FFT size, used and unused carriers, and the modulation used in each carrier. Once these important parameters are estimated, time and frequency synchronization is needed for the extensive modulation analysis. Since the transmitted frame format and training/pilot symbols are not assumed to be known, estimating channel frequency response and other important parameters like common phase offset need to be performed blindly. All these operations require extensive computational power with very fast processing capability for nearly real-time operation.

7. CONCLUSIONS

SDR/CR allows nearly limitless number of ways of generating radio signals. Accurate testing and measurement of SDR and CR devices is very crucial for the rapid penetration of these devices in the wireless market. There is a strong need for unified and generic tools that can provide as much information as possible about any arbitrary signal. The ability to automatically monitor the multi-dimensional electrospace, evaluate changes (or transients) in any domain, capture and post process the data as fast as possible is important for accurate test and measurement of the SDR/CR devices. In this paper, some of the important elements to achieve this goal are provided.

8. REFERENCES

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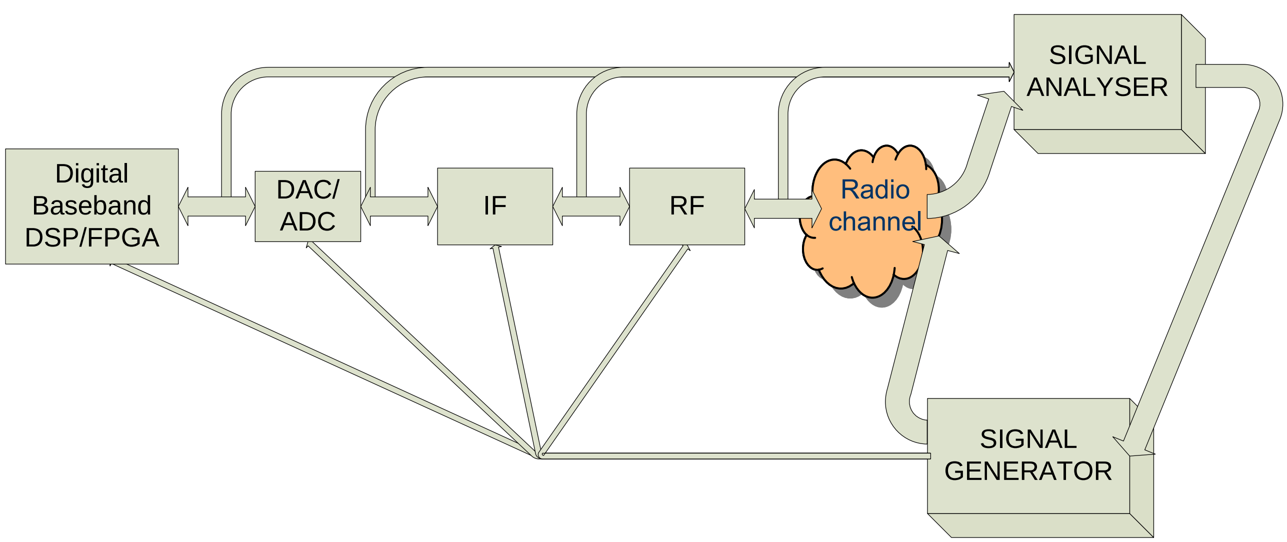

Figure 1 A possible test and measurement set-up

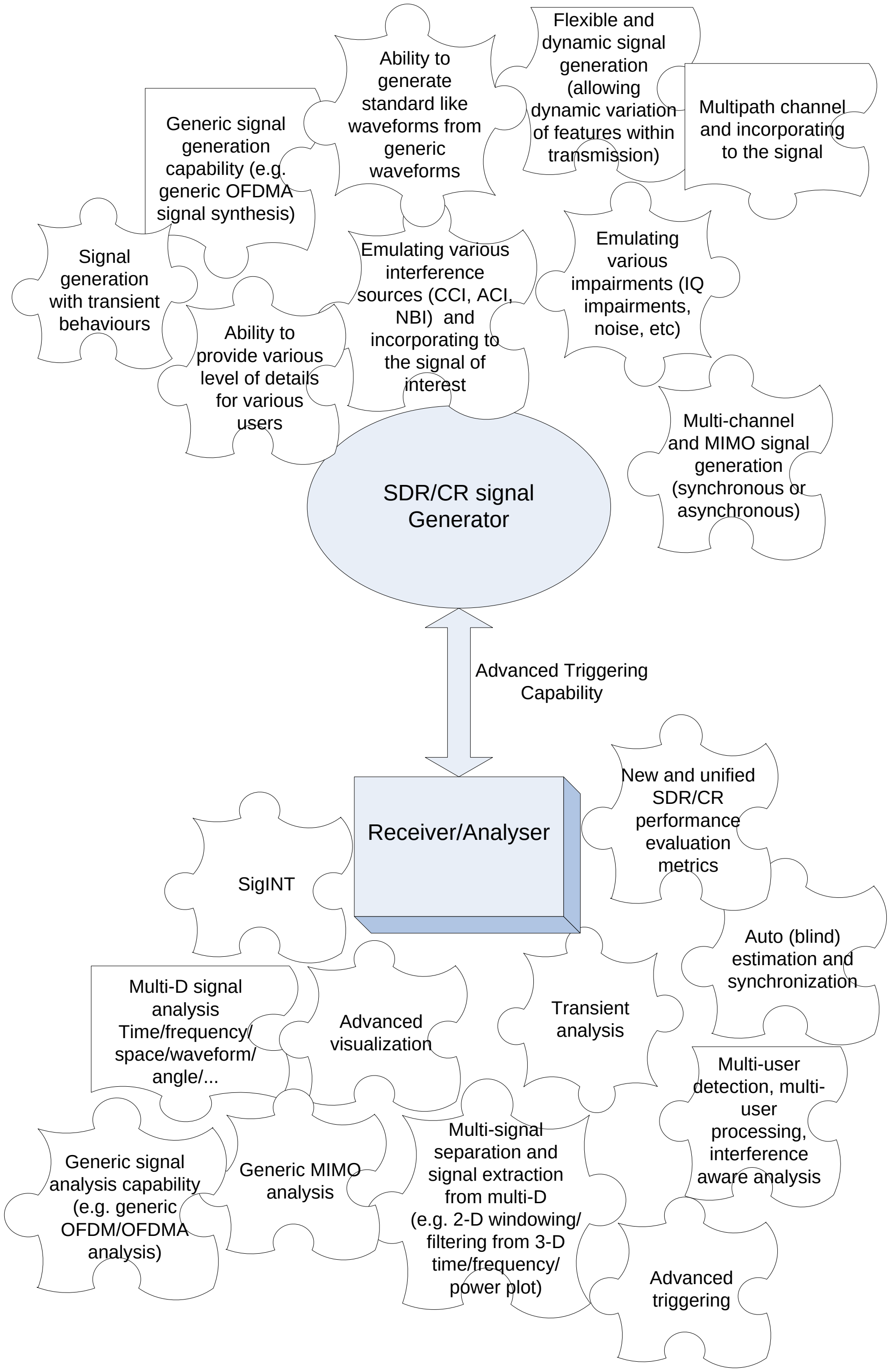

Figure 2 Some of the building blocks of a possible SDR/CR measurements and testing capability

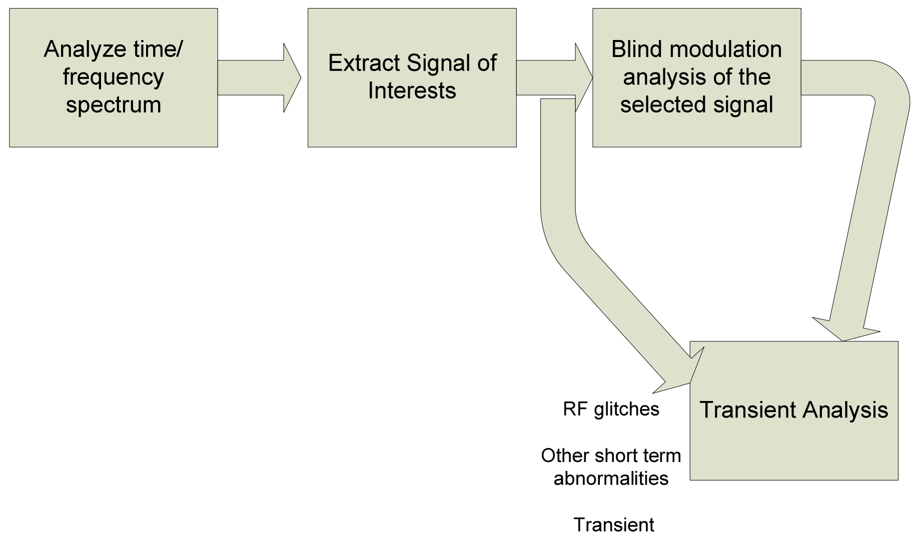

Figure 3 Time-frequency analysis process

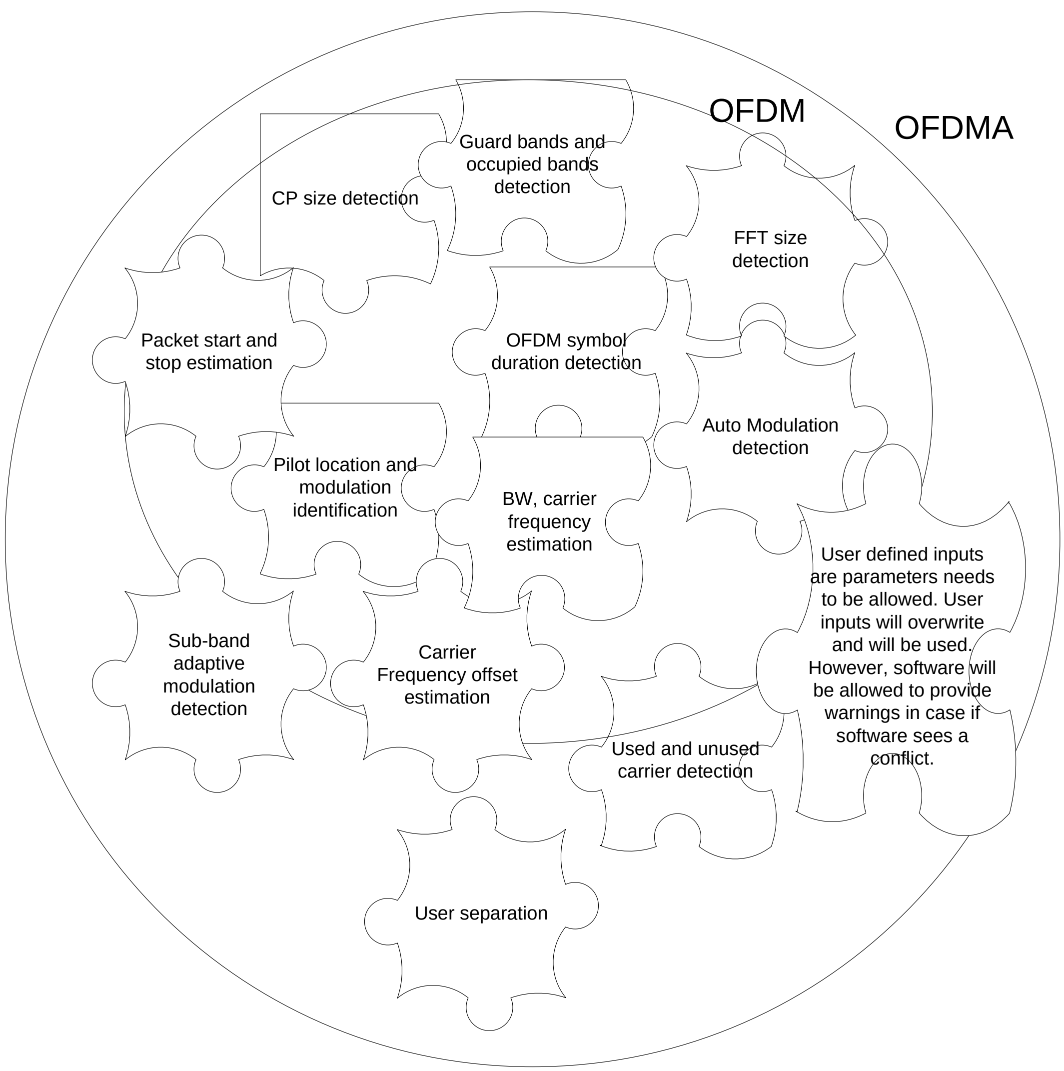

Figure 4 Some of the building blocks of a generic OFDM(A) analysis