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COGNITIVE RADIO RESEARCH AND ANTENNA IMPLEMENTATION CHALLENGES

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ABSTRACT:

The leapfrogging developments in communication & technology are leading to connect the world into a global village. The rewards of the connectivity, are however, deeply marred by the improper utilization of the resources available i.e. radio spectrum. It was reckoned that the effective utilization of the electromagnetic spectrum leads us to think interms of under used spectrum, thereby relieving demand in congested bands. This has been clearly manifested and utilized by the recent cognitive radios. Cognitive radio (CR) inclusive of software defined radio (SDR) has been proposed as the mean to the efficient use of the spectrum by exploiting the existence of the spectrum holes. Cognitive radio technique is based on the dynamic frequency selection (DFS) and with this functionality, CR checks on the availability of a channel before using it. It works to ensure that the channels are evenly loaded to reduce interference. To achieve this capacity for spectrum agility, also optimizing for power, modulation, range and other communication parameters, an extremely flexible radio frequency (RF) front end is vital. As such, the antenna front end challenges are immense as CR can be operated any where in the frequency spectrum. This paper, while attempting to evaluate these emerging trends, emphasizes

upon the dire need for antenna technologies that are needed. This paper also draws attention to enhance the operation of the antenna arrays, mechanisms and practices.

1. Introduction

The electromagnetic spectrum is a natural resource, the use of which by transmitter and receivers is licensed by governments. The federal communications commission (FCC) published a report prepared by the spectrum-policy task force in November, 2002 aimed at improving the way in which this precious resource is managed in the United States. Among the task force major findings and recommendations, some of the frequency bands in the spectrum are largely unoccupied most of the time and some of them are partially occupied while some are heavily used. This has made to think interms of the spectrum holes. A spectrum hole is a band of frequencies assigned to the primary user, but at a particular time and specific geographic location, the band not being utilized by the user. The spectrum utilization can be improved significantly by making it possible for a secondary user who is not being serviced to access a spectrum hole un occupied by the primary user at the right location and time. One of the prominent solutions for the effective utilization of the spectrum is by using the CR. The concept of a cognitive radio was termed by Joseph Mitola in 1999. CR is a radio that can monitor its local radio environment and /or its geographical position, and using this data, adjusts its characteristics in order to optimize its performance and its operating frequency to take advantage of unused spectrum and or adapt its transmitted power, modulation scheme or other waveform parameters to reach an acceptable compromise between quality of service and spectral requirements

Cognitive Radios need antennas that cover a wide frequency range and they serves as transducers between electromagnetic wave traveling in free space and guided electromagnetic signal in the front end circuit. As such they play a critical role in the performance of CR systems to attain the maximum effective range. The antennas commonly used for wireless handsets also can be used with a cognitive radio, such as monopole, diamond and round diamond, bi-conical dipole etc., The antennas that are in current usage are digital antenna elements that use front end down conversion and digitization, frequency, waveform, polarization agility, beam steering and beam forming techniques, smart intelligent antennas using different signal processing techniques. But they suffer from the noise interference, cost, gain bandwidth considerations, size etc.

In an effort to improve the speed and quality of two-way radio communication, there is an immense need of developing self-adapting, re configurable antenna for cognitive radios. These radios detect those channels that are in use and those that are not. Rather than traditionally modifying the signal processing methods of cognitive radio, changes will be made to the antenna itself. This technology involves in developments of ultra wide band (UWB) systems; enhancement of current orthogonal frequency division multiplexing (OFDM) based wireless communication systems. This necessitates studying and improving the multiple-antenna transmission and multiple-antenna reception (MIMO) wireless communication systems and the application of MIMO to OFDM Systems.

In this connection, an antenna catering the needs of high efficiency, small profile of the antennas could be achieved by a reconfigurable antenna which covers the desired band instaneously with improvement in signal to noise ratio (SNR) of RF front-end, reducing the cost and eliminating the need for duplex filter, also the antenna pair is electronically reconfigurable based on the frequency information from the digital signal processor (DSP), the modified RF Front-End architecture is a promising technology for the Cognitive Radios. The fundamental gain-bandwidth limitations of electrically small antennas prevent a small antenna from having high efficiency and wide bandwidth simultaneously. In the age of miniaturization, especially in the wireless communications, a promising solution to this limitation is to introduce reconfigurable antennas that can be tuned electronically to different frequency bands with both high efficiency and narrow instantaneous bandwidth. This technology not only simplifies current RF Front-End architectures, but can be reprogrammed on demand to transmit and receive RF signals in any desired frequency band. This novel Front-End architecture can really be helpful in effective realization of mobile communications using the Cognitive Radio.

2. Cognitive Radio

A software radio is a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals according the SDR Forum. A CR is a software-defined radio that possesses the attributes of being RF and spatially aware with the ability to autonomously adjust to its environment accordingly such as frequency, power and modulation. The above ideal concept is well represented by the Software Defined Radio architecture paradigm proposed by J. Mitola in which the analog blocks are limited to Power Amplifier. The CR has the potential to significantly improve the efficiency with which RF spectrum is used. On the other hand it might search for under used spectrum, thereby relieving the demand in congested bands. It also dynamically optimize its waveform configuration, thereby allowing more intensive re use of spectrum either through improved resilience to interference received from other spectrum users or reduced interference caused to other users

The Federal Communications Commission (FCC) has identified the features that cognitive radios can incorporate to enable a more efficient and flexible usage of spectrum:

a. Frequency Agility: The radio is able to change its operating frequency to optimize its use in adapting to the environment.

b. Dynamic Frequency Selection (DFS): The radio senses signals from nearby transmitters to choose an optimal operation environment.

c. Adaptive Modulation: The transmission characteristics and waveforms can be reconfigured to exploit all opportunities for the usage of spectrum

d. Transmit Power Control (TPC): The transmission power is adapted to full power limits when necessary on the one hand and to lower levels on the other hand to allow greater sharing of spectrum.

e. Location Awareness – The radio is able to determine its location and the location of other devices operating in the same spectrum to optimize transmission parameters for increasing spectrum re-use.

f. Negotiated Use – The cognitive radio may have algorithms enabling the sharing of spectrum in terms of prearranged agreements between a licensee and a third party or on an ad-hoc/real-time basis.

The different performance measuring power parameters include frequency, power, antenna, transmitter bandwidth, modulation schemes. This means that the said radio has to deal with different RF spectrum and base band varieties at the same time, thus requiring a more robust, efficient and reconfigurable hardware architecture. The introduction of this revolutionary paradigm poses many challenges across all layers of a cognitive radio system design like spectrum sensing, interference management, resource allocation, RF design and implementation issues.

a. Sensing: One of the defining functions of a cognitive radio is the ability to sense the radio channel in order to find opportunities in spectrum and adapt the radio parameters. Recent measurements have shown that the spectrum usage is concentrated on certain portions of the spectrum while significant amount of the spectrum remains un used. These holes can be classified into three types.

a. Black spaces, which are occupied by higher power interferes some of the time,

b. Grey spaces, which are occupied by low power interferes,

c. White spaces, which are free, no one send information this band, but is occupied by

natural and artificial forms of noise eg: thermal noise, transient reflections.

The biggest challenge related to spectrum sensing is in developing sensing techniques which are able to detect very weak primary user signals which being sufficiently fast and low cost to implement.

b. Interference management and resource allocation: Spectrum utilization can be improved by making a secondary user to access a spectrum hole unoccupied by the primary user at the right location and the right time. In current cognitive radio protocol proposals, the device listens to the wireless channel and determines, either in time or frequency, which part of the spectrum is un used. It then adapts its signals to fill this void in the spectrum domain. Thus, a device transmits over a certain time or frequency band only when no other user does.

2.1 Implementation Issues: To achieve this capacity for spectrum agility, also optimizing for power, modulation, range and other communication parameters an extremely flexible RF Front End is vital. As such, the antennas in the Front End challenges are immense as CR can be operated any where in the frequency spectrum.

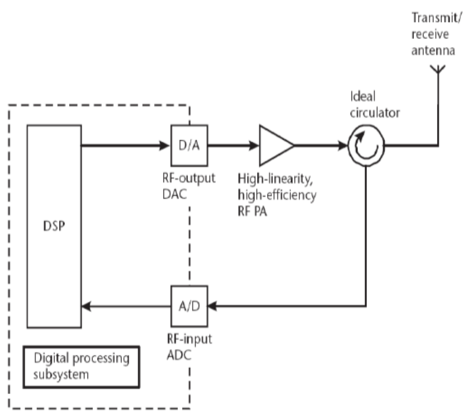

Fig.1. Block diagram of the RF front end of a CR

<u>RF Design:</u> A primary technological concern in cognitive radio architectures, whether it be for wideband sensing procedures or wide band multi band communication mechanisms is the ability to design linear and spectrally agile components and architectures in the radio frequency front end of the transceivers.

<u>System on chip implementation:</u> Designing the digital base band processing of such extremely agile system is a very challenging task. The required processing power is huge in most of the functional unit and the memory needs and memory bandwidths are also usually very high. But the most two most difficult aspects are probably: the partitioning of the system in hardware and software processing units. The challenges are those of a real-time constrained application in the context of a multi processor System on Chip architecture and the antenna systems.

The first SDR architecture was proposed by Mitola and Maguire, in which the RF and analog processing are reduced to only a pair of data converters, thus providing the maximum flexibility and programmability through the digital processing block. This idealistic approach, however, suffers from the poor tolerance of to the interferers. In many wireless applications, a small desired signal could be accompanied by several large in-band signals created by nearby transmitters of the same communication standard or out-of-band blockers caused by any transmitter. At times, these blockers could be as much as about 100 dB larger than the desirable received signal, which, due to the lack of any filtering in this idealistic approach would demand an impractical dynamic range of about 100 dB on the ADC. This long-term requirement is very far beyond the limits of the technology available as will be shown in ADC/DAC challenges sub-section. Research on high-performances ADC/DAC is going on with significant progress, especially with hybrid-filter bank and time-interleaving architectures.

In order to operate on very wide band or multibands simultaneously, parallel processing is employed from antennas to analog to digital interfaces. Multi antennas are necessary for multi-input-multioutput (MIMO) operation and/or multibands operation. After antennas, a passive module is used for switching or duplexing, RF filtering, and impedance matching between antennas and power amplifiers (PAs). This module is composed of a range of submodules in order to cover a wide bandwidth or enable simultaneous communications. Then multireceiver (Rx) and multitransmitter (Tx) are followed before a multi-ADC/DACs module. A high performance and very flexible digital baseband carries out not only all conventional processing for modulation and demodulation, coding and encoding, and so forth, but also digital filtering, dc offset cancellation, digital automatic gain control, calibration and correction of analog errors and non linearities. Combining with control plane and sensor, a feedback from baseband to RF front-end and transceiver are necessary to boost the performance of the analog part.

The challenges of RF front-end and transceiver in the short-/midterm are to reduce the off-chip and passive components, increase their frequency-agility, minimize the power dissipation, and reduce area. Hence along with the RF Front end Transceiver challenges; there are other issues like base band and spectrum sensing algorithm implementations. The most challenging task is located in the RF front-end design, in particular low NF, high linearity, and wide dynamic range:

$$SNR_{min}[dB] = P_{min}[dBm] - NF[dB] + 174[dBm/Hz] - 10\log10B[dB \cdot Hz]. \quad (1)$$

The equation (1) above represents the relation between the minimal SNR value (SNR_{min}) for a given algorithm and the minimal sensing sensitivity or threshold (P_{min}), the NF of the receiver (NF) where B is the channel bandwidth to be sensed.

2.2 Spectrum Management Issues:

The Opportunic Sperctrum Access methods adopted methods adopts the modern techniques may be better understood by the classification as shown in Fig 2

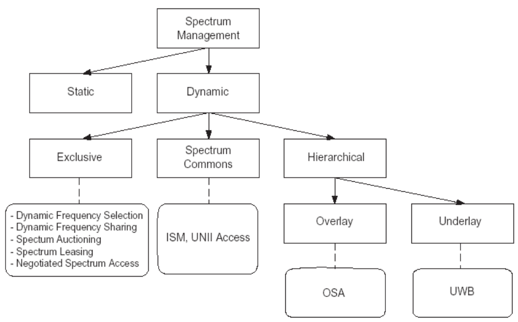

Fig 2. Modern Spectrum Management classification

The major challenges that are included in the design of the spectrum management are classified into computation related problems like decision, learning and adoptability with all layers of protocol stack, architecture related challenges related to equipment , testing and physical layer, protocol related problems, signaling, security and medium access control etc.

2.3 RF Transceiver and circuit design.

The issues related to the design of wideband signal paths and the decades-wide synthesis of carrier frequencies of more importance. Cognitive radios pose challenges at all levels of abstraction along with the RF and analog design issues are to be considered in the transceiver circuit design. The receive signal path of a cognitive radio must deal with two issues: (1) broadband characteristics, i.e., a relatively flat noise figure (NF) and gain, and adequate input matching across two to three decades; (2) nonlinearity and local oscillator (LO) harmonics. The design of Low Noise Amplifier must emphasizes the use of multiple inductors complicates the routing and increases the area.

The receive path must achieve decades-wide bandwidth with high linearity and adequate input matching while suppressing the effect of Local Oscillator harmonics. The Local Oscillator path must provide a carrier frequency spanning two or three decades. Also, the receiver architecture must be chosen to reduce the spectrum sensing time. An LNA topology can cancel the input capacitance by means of inductive behavior provided by negative feedback. In addition, a carrier synthesis technique using a bimodal oscillator is desirable that can cover multiple decades. It is preferred that RF-assisted spectrum sensing by block down conversion can increase the probability of finding an available channel.

3. Antenna Technology for the CR

Cognitive radios need antennas that cover wide frequency range. Antennas serve as transducers between electromagnetic wave traveling in free space and guided electromagnetic signal in circuits. As such they play a critical role in the performance of CR systems. The maximum effective range could not be accomplished by ignoring the antenna (3). An effective antenna solution increases the range and corresponding coverage of a CR. There are many characteristics of antennas that determine whether the antenna is efficient or not. Some of the most important characteristics of antennas are gain, size, radiation pattern, bandwidth and voltage standing wave ratio (VSWR).

The emerging concept of SDR enables new flexible platforms, capable of providing re programmable hardware and supporting optimal adaptive algorithm for pre distortion. The optimal algorithm for adaptive RF linearization is not known. It is very likely that there will be different algorithmic techniques depending on the mode of operation rather than a single one. The Multiple-input, multiple-output (MIMO) techniques for wireless channels, involving the use of multi-element antenna arrays at both the transmitter and receiver increases the performance, capacity of the communication systems and networks along with the advanced ADC and DAC's. Three basic types of MIMO techniques are envisaged for use in MIMO CR schemenes:

a. Spatial multiplexing and closed loop techniques (STBC), which includes beamforming techniques.

b. Code Division Multiple Access (CDMA) systems usually involve forward error correction (FEC) to reduce sensitivity to multiple access interference.

c. Space time turbo coded turbo parallel interference cancellation (ST-TuC-turbo-PIC) which reduces the bit error rate performance.

3.1 Adaptive MIMO and CR:

The adaptive antenna systems approach communication between a user and base station in a different way, in effect adding a dimension of space. By adjusting to an RF environment as it changes (or the spatial origin of signals), adaptive antenna technology can dynamically alter the signal patterns to near infinity to optimize the performance of the wireless system.

Adaptive arrays utilize sophisticated signal-processing algorithms to

Continuously distinguish between desired signals, multipath, and interfering signals as well as calculate their directions of arrival. This approach continuously updates its transmit strategy based on changes in both the desired and interfering signal locations. The ability to track users smoothly with main lobes and interferers with nulls ensures that the link budget is constantly maximized because there are neither micro sectors nor predefined patterns. The adaptive MIMO for CR implementation of wireless communications system includes a barrier in the RF part of the transceiver (including antenna and ADC/DAC) and in the base band processing.

3.2 Reconfigurable Antenna Arrays in CR:

The reconfigurable antennas are a new concept antenna which dynamically alters the electrical or physical configurations. The reconfigurable antenna could be automatically reconfigured to satisfy the frequency band and gain requirements of different applications by using an antenna or antenna arrays. In this manner, several antenna systems could utilize a common antenna aperture, resulting in considerable saving in size, weight and cost. In the design and synthesis of antennas, the goal is to find a radiating structure that meets a set of performance criteria that usually include gain, maximum side lobe level, beam width, input impedance, and physical size. The difficulties of realizing the reconfigurable antenna are how to design the reconfigurable antenna and how to use the feasible optimization methods to find the suitable configurations to meet the needs of carious applications.

Advances in reconfigurable RF front ends, particularly reconfigurable antenna arrays afford a new hardware dimension for optimizing the performance of wireless communication systems by adapting the array configuration to changes in the communication environment. The reconfigurable antenna system consists of antenna arrays of multiple elements, RF front end of multiple RF chains, array processing sections.

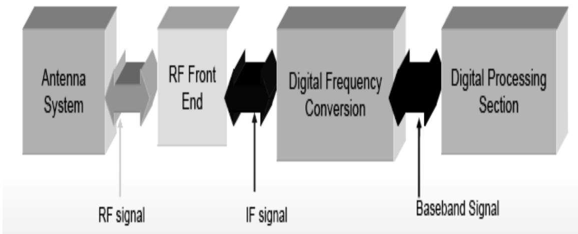

Fig 3.Block diagram of Reconfigurable antenna system

3.3 Implementation issues of Reconfigurable arrays for CR

The implementation of reconfigurable arrays mainly based on the software and hardware boundaries need to be defined and appropriate interfaces at the boundaries.

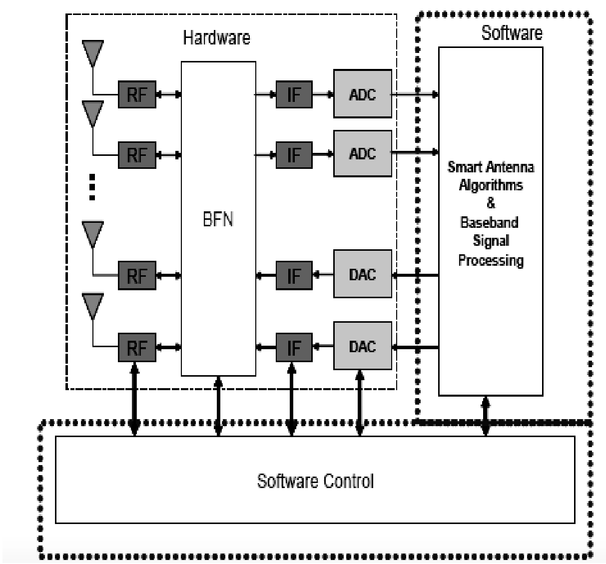

Fig 4. A system level view of the RF Front end of CR

The basic implementation of the reconfigurable antenna array system includes

a. RF front end: It should be capable of convert RF energy to suitable IF in the receive mode and IF energy to RF in the transmit mode, replication of RF chain for each antenna element
b. Digital Frequency conversion: This converts IF signal into complex base band signal in the receive mode and translates the complex base band signal into IF signal in the transmit mode.
c. Digital processing section: It collects the signal of an individual antenna array, and includes the beam forming of the collected signals.

The advantages of such system are its small size, high efficiency selective bandwidth, reconfigurable. This methodology simplifies the antenna design, reduces the requirements for analog filtering in the RF front end.

3.4 The Role of the Antenna

There is a need for antennas that can make a cognitive radio (CR) system work with other devices across multi-bands, multi-standards or multi-channels. Since these new devices must both learn and adapt to their RF environment for the purpose of establishing seamless communication with other RF devices, Antennas also be designed to learn and adapt or reconfigure themselves and at the physical layer, the defining characteristics of the envisioned system include a) cognition: the ability of spectrum sensing across multi-bands, multi-standards and multi-channels to detect and classify RF activities of interest, and the ability to decide in which band and under what standard the radio needs to establish communication with a chosen RF device via learning and reasoning, and b) reconfigurability: the ability to adapt RF communications parameters such as standard, carrier frequency, power transmission, modulation format, coding scheme and data rate entirely in software, without having to change hardware. To be able to autonomously detect and establish communication with another RF device in its range, the RF device should be able to monitor and sense its RF environment to detect RF activity, classify a detected RF activity as one of several possibilities, and establish communications in appropriate modes. Due to impairments inherent in the wireless channel as well as ambient noise, it is possible that a cognitive radio device that a cognitive radio device can either mistakenly detect or miss an RF device in its range as well as misclassify a detected device.

Antennas design need to be able to change the direction of the main lobe on a real time basis and at different frequencies. Although there is no such thing as an "intelligent" or "smart" antenna, the cognition and learning part of cognitive radio is currently being tackled by communication and computer scientists. Their emphasis, however, is in the area of detecting and characterizing the communication channels properties, such as frequencies, transmission rate, modulation etc. There is another level of learning and cognition for which the antenna and RF engineers are better suited. A certain level of "intelligence" can be built into the radio device using several algorithms (such as neural networks, particle swarm optimization, support vector machines, and genetic algorithms, to name a few) in order to develop the next generation of responsive circuits and cognitive radio required to develop a real-time reconfigurable radio device. The aim is to have a device with "intelligent" antennas that can recognize their environment, collaborate between themselves during sensing and communication, reconfigure their radiation, polarization, or frequency and even self-tune themselves based on changes in their environment or operational mission.

4. Conclusion and Future Scope:

Extending the availability of today's radio spectrum is a natural interest of the design engineers. With a more flexible regulatory frame work, cognitive radios will improve coverage, capacity and quality of service to future radio networks. The usage of reconfigurable antenna arrays will reduce the complexity of the RF front end architecture of CR. Reconfigurable antennas would benefit all transceiver architectures and system simulations and measurements of hardware prototypes indicate that there could be well significant performance enhancement and cost reductions associated with this approach. The reconfigurable antenna that we have broad boarded to date all use PIN diode or FET switches. These Switches are far from ideal and significantly reduce the radiation efficiency of the antennas. Furthermore, these devices also exhibit non linearities that contribute to harmonic and inter modulation distortions in both transmit and receive chains. However, RF MEMS switches appear poised to become viable alternatives in their near future to minimize these undesired effects. These switches are virtually ideal in terms of insertion loss and isolation, and their linearity is better than GaAs devices. Currently, reliability and packaging issues concerning these devices are being resolved and low cost production techniques are being developed. Based on these developments, we expect to be able to evaluate the performance of the reconfigurable antennas realized with RF MEMS switches in the near future. Implementing the reconfigurable antennas with MEMS technology will increase the performance and tuning range of an electronically small antenna. Hence we expect that the further simplification in the scenario for all current wireless frequency bands including GSM, PCS,DPS, GPS, ISM and so on and will enhance the applications of the Cognitive radio environments.

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