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Spectrum Sensing in Cognitive Radio using Reconfigurable Antennas: A Literature Review

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***Abstract*— Cognitive radio (CR), including software defined radio enabling technology, is suggested to realize a flexible and efficient usage of spectrum. In this paper, we present a review of the recent advances in spectrum sensing in CR. For the front end Radio frequency (RF) transceivers hardware design and algorithms are reviewed. Reconfigurable antennas for spectrum sensing are discussed. Multi-antenna systems are highlighted with an advantage of overcoming multipath effects. We also give insight into learning aided sub-band selection to determine a free channel.**

***Index Terms*—Cognitive radio, spectrum sensing reconfigurable antennas, multi-antenna system, Q-Learning.**

I. INTRODUCTION

Wireless technology is necessary to support the mobile user. Adaptive and efficient use of spectrum is an important issue to optimize this for the maximum number of users. Cognitive Radio is a new class of radio that is able to reliably sense the spectral environment over a wide bandwidth from 2 GHz to 11 GHz, detects the unused spectrum, and use the spectrum for transmission with minimum interference to the primary user [1]. The main feature of CRs is their ability to observe their communication environment and independently adapt the parameters of communication scheme to maximize the quality of service (QoS) for the secondary users while minimizing the interference to the primary user [2]. In CR cycle, the CR monitors spectrum bands, captures their information, and then detect the spectrum spaces, shown in Fig. 1. The characteristics of the spectrum spaces that are detected through spectrum sensing are estimated. The appropriate spectrum band is chosen according to the spectrum characteristics and user requirements. Once the operating spectrum band is determined, the communication can be performed over this spectrum [1]. Fig. 2 illustrates the CR scenario. It consists of two users, primary user (PU) and secondary user (SU). Each user knows only his channel and the unused spectrum through reliable and adequate sensing. The SU or cognitive user will listen to the channel, if sensed idle, will transmit during empty spaces.

According to FCC, Ultra-wide band (UWB) refers to radio technology with a bandwidth exceeding the lesser of 500 MHz or 20% of the arithmetic center frequency. FCC has authorized the unlicensed use of UWB in the frequency range from 3.1 to 10.6 GHz. The FCC power spectral density emission limit for UWB transmitters is -41.3 dBm/MHz. And the emission limit for UWB emitters may be significantly lower, -75 dBm/MHz in other segment of the spectrum [4].

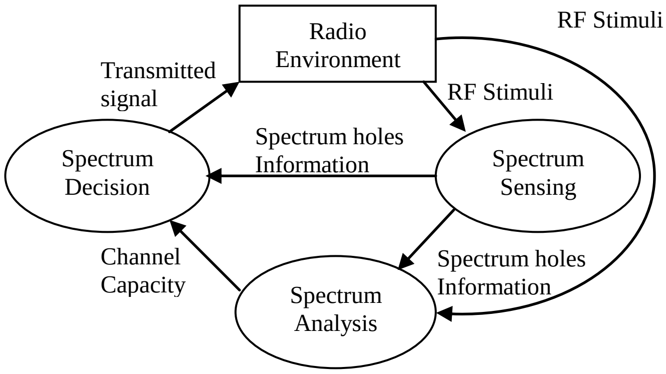

Fig. 1: Cognitive Radio Cycle

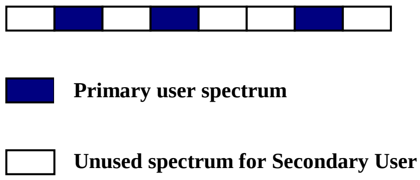

Fig. 2: Cognitive radio scenario

II. CR TRANSCEIVERS

CR implements dynamic spectrum allocation polices by allowing SU to access spectrum bands licensed to PU while avoiding interference with them [2]. Therefore there will be more constraints on the antenna design at the front end; also there is need for development of algorithm for sensing the complete spectrum and autonomously to adapt to particular situation through cognitive engine.

A. Antennas for cognitive Radio

Two main approaches of sharing spectrum between primary users (PUs) and secondary users (SUs) exist: spectrum underlay and spectrum overlay. In the underlay approach, SUs should operate below the noise floor of PUs, and thus contingent constraints are imposed on their transmission power. Ultra-wideband (UWB) technology is very suitable as the enabling technology for this approach. In spectrum overlay CR, SUs search for unused frequency bands, called white spaces, and use them for communication.

UWB antennas are used for underlay CR and also for channel sensing in overlay CR. For communication in overlay CR, the antenna must be frequency reconfigurable or tunable.

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Single- and dual-port antennas for overlay CR can be designed. In the dual-port case, one port has UWB frequency response and is used for channel sensing, and the second port, which is frequency reconfigurable/tunable, is used for communicating. In the more challenging single-port design, the same port can have UWB response for sensing and can be reconfigured for tunable narrowband operation when required to communicate over a white space [2].

B. Guidelines to design UWB antennas

(i) The proper selection of the patch shape. Round shapes and round edges lead to smoother current flow and, as a result, to better wideband characteristics.

(ii) The good design of the ground plane. Partial ground planes, and ground planes with specially designed slots, play a major role in obtaining UWB response. Keeping a full-ground plane is possible, but in that case an elaborate work has to be done on the patch design.

(iii) The matching between the feed line and the patch. This is achieved using either tapered connections, inset feed, or slits under the feed in the ground plane.

(iv) The use of fractal shapes, which are known for their self-repetitive characteristic, used to obtain multi and wideband operation, and their space-filling property, which leads to increasing the electrical length of the antenna without tampering with its overall physical size.

A combination of these guidelines can be used to design an antenna for UWB sensing. An example is illustrated here as described by the authors in [9].

The UWB design presented in [9] features a micro-strip feed line with two 45^O bends and a tapered section for size reduction and matching, respectively. The ground plane is partial and comprises a rectangular part and a trapezoidal part. The patch is a half ellipse with the cut made along the minor axis. Four slots whose location and size relate to a modified Sierpinski carpet, with the ellipse as the basic shape, are incorporated into the patch. The geometry of this antenna is shown in Fig. 3. Four techniques are applied for good impedance matching over the UWB range: (1) the specially selected patch shape, (2) the tapered connection between the patch and the feed line (3) the optimized partial ground plane, and (4) the slots whose design is based on the knowledge of fractal shapes.

As a result, this antenna has an impedance bandwidth over the 2 − 11GHz range, as shown in Fig. 4, and thus can operate in the bands used for UMTS, WLAN, WiMAX, and UWB applications. It has omni directional radiation patterns due to the partial ground plane.

The effect of ground plane on the performance of the CR UWB antenna is described in [10]. It is proved that it is possible to obtain an ultra wide impedance bandwidth using either a partial ground or a ground plane with optimized large slot. A photo of both versions is given in Fig. 5. One has partial ground plane and the other has a ground plane with a large slot.

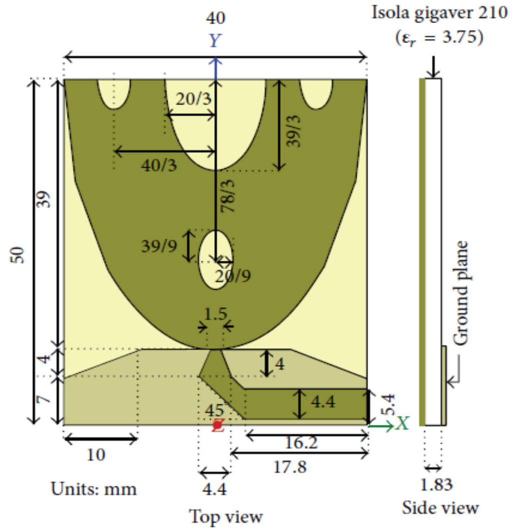

Fig. 3: The configuration of UWB antenna as in [9].

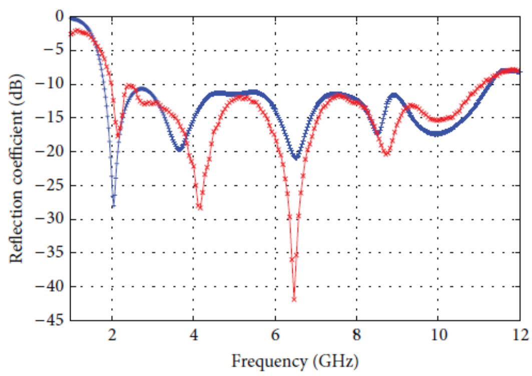

Fig. 4: Reflection Coefficient of the UWB antenna in Fig. 3.
Blue ----→ simulated
Red -----→ Measured

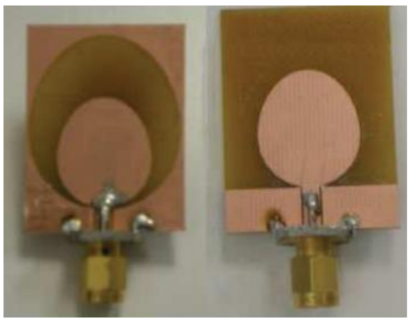

Fig. 5: UWB antennas with optimized ground planes [10].

III. RECONFIGURABLE ANTENNAS

Reconfigurable antennas have the ability to radiate more than one pattern at different frequencies and polarizations and they satisfy the requirement for increased functionality like direction finding, beam steering, radar control and command. Reconfigurable antennas can be achieved through many techniques that alter electromagnetic fields of the antennas effective aperture by redistributing the currents. The authors

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in [3] have a lot to describe on this concept. An extract has been summarized here.

Reconfigurable antennas can be implemented through;

i). RF-MEMS, PIN diodes, varactors – electrically reconfigurable

ii). Photoconductive switching elements – optically reconfigurable

iii). Altering the structure of antenna – physically reconfigurable

iv). Smart materials such as using ferrites and liquid crystals – substrate characteristics reconfigurable.

A pictorial representation is shown in Fig. 6.

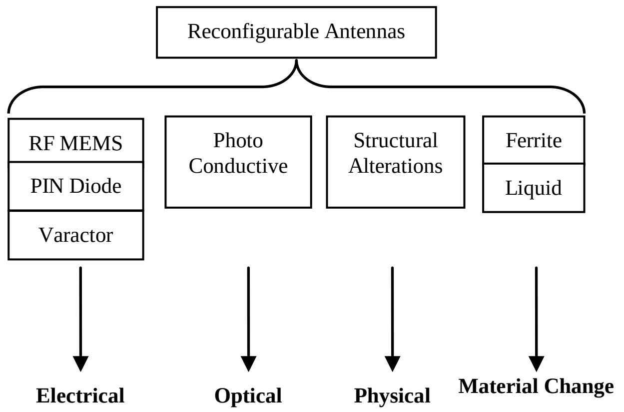

Fig. 6: Implementation of Reconfigurable Antennas [3].

Advantages of using reconfigurable antennas [5] are summarized below.

1. Ability to support more than one wireless standard by minimizing cost, volume representation, simplifying integration and providing good isolation between different wireless standards.
2. Lower front end processing – no need for front end filtering, good out of band rejection.
3. Best candidate for software defined radio – capability to adopt and learn, automated via a microcontroller or FPGA.
4. Multifunctional capabilities – change functionality as the mission changes, act as a single element or an array, provide narrow band or wide band operation.

Reconfigurable antennas are required to cover different wireless services that are spanned over a wide frequency range. So a frequency reconfigurable antenna is required for a CR system. A CR system is able to communicate efficiently across a channel by altering its frequency of operation based on the constant monitoring of channel spectrum [3].

Three key parameters for a CR antenna designer;

1. Isolation between the two ports of the sensing and reconfigurable antennas
2. Dimensions of the CR antenna system substrate Omni directional / reconfigurable radiation pattern.

The authors in [6] propose two structures incorporated together into the same substrate. The first structure is an ultra wideband (UWB) antenna covering the spectrum from 3.1–11 GHz for channel sensing. The second structure is a frequency reconfigurable triangular-shaped patch for establishing communication with another RF device. The antenna reconfigurability is achieved via a rotational motion. Fig. 7 shows sensing antenna structure.

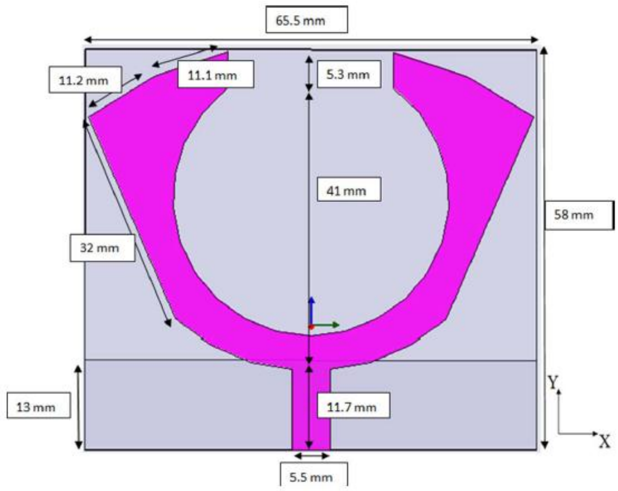

Fig. 7: Sensing antenna

Fig. 8 shows the return loss of the sensing antenna. The return loss shows coverage from 3.3–11 GHz, making it suitable for channel sensing in cognitive radio systems. For an antenna to be suitable for channel sensing, it should possess an omni directional radiation pattern. The antenna structure investigated in this section satisfies this requirement. The computed radiation pattern in the X-Z plane at 4.5 (thin line), 7.5 (thick line), and 10.5 GHz (dotted line) is shown in Fig. 9. It is essential to note that the addition of the rounded shape just after the strip line feed-line is responsible for producing the required wide bandwidth for the antenna. This rounded shape has the effect of making the antenna input impedance close to 50 for the band from 3.3–11 GHz. This antenna structure also shows a resonance at 1.9 GHz.

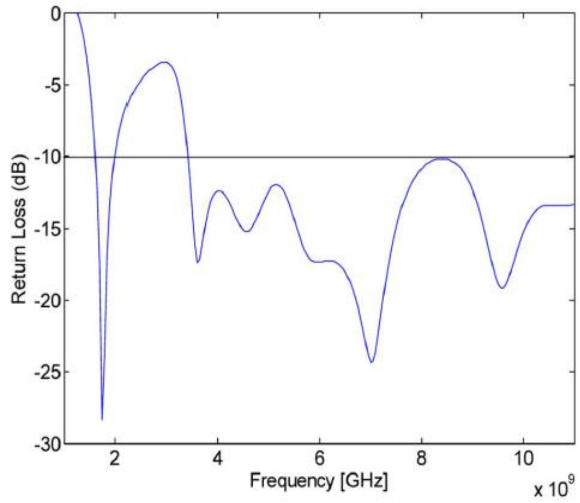

Fig. 8: Return Loss of Sensing antenna.

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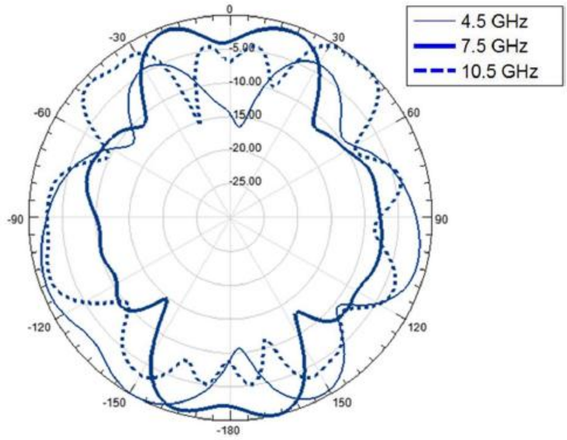

Fig. 9: The normalized radiation pattern of sensing antenna.

The "reconfigurable communicating" antenna structure is summarized in Fig. 10. By rotating the antenna patch by 180, a different structure is being fed by the micro-strip line. This rotation will produce different resonances, making the antenna suitable to communicate at the frequency specified by the "sensing" antenna. The antenna top layer consists of two triangular-shaped patches that are separated by a given distance. Similar to the "sensing" antenna, this structure is fed via a micro-strip line and has a partial ground. Since this antenna is incorporated with the "sensing" antenna, its substrate size was taken to be the same as the "sensing" antenna. Its ground dimension is taken to be 18 mm X 9 mm so that it will not affect the radiation from the patch of the "sensing" antenna. The process of rotation is shown in Fig. 11; the structure shown in the left corresponds to position 1, and the structure shown in the right corresponds to position 2. The return loss for the communicating antenna is shown in Fig. 12. This antenna has the property to tune from 5.3–9.15 GHz (position 1) to 3.4–4.85 GHz (position 2). The computed radiation pattern in the X-Z plane at 6.65 GHz for position 1 (thick line) and at 4 GHz for position 2 (thin line) is shown in Fig. 13. For both positions, the antenna satisfies the omni directional property.

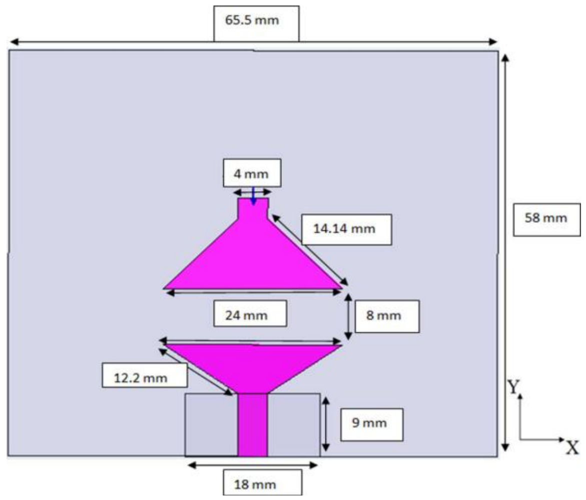

Fig. 10: The "reconfigurable communicating" antenna structure.

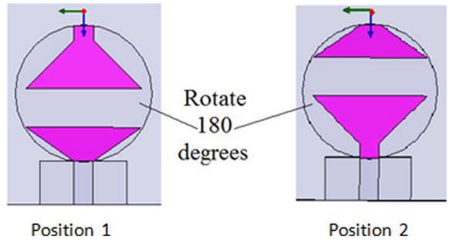

Fig. 11: The process of rotation.

The return loss for the communicating antenna is shown in Fig. 12.

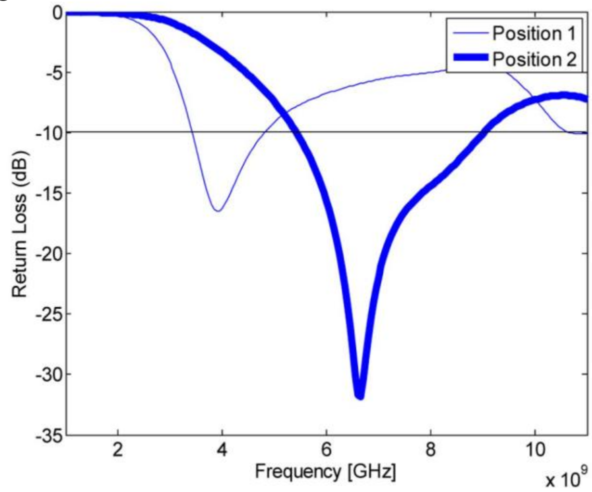

Fig. 12: Return loss of reconfigurable communicating antenna.

This antenna has the property to tune from 5.3–9.15 GHz (position 1) to 3.4–4.85 GHz (position 2). The computed radiation pattern in the X-Z plane at 6.65 GHz for position 1 (thick line) and at 4 GHz for position 2 (thin line) is shown in Fig. 13. For both positions, the antenna satisfies the omni directional property.

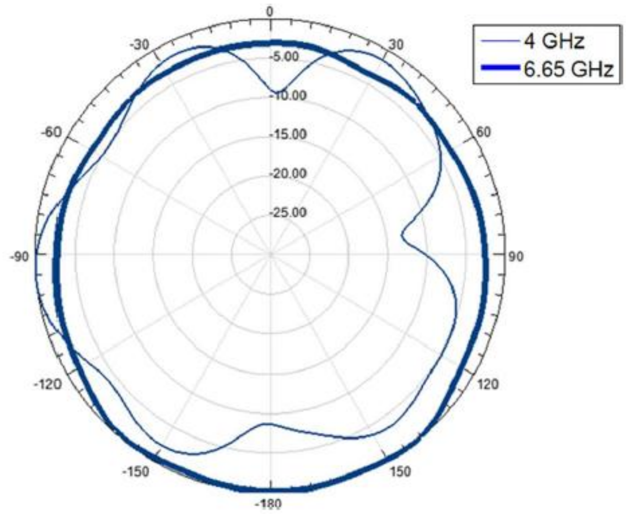

Fig. 13: The normalized radiation pattern for positions 1 and 2.

The complete cognitive antenna structure, embedding sensing and reconfigurable communicating antenna structure is shown in Fig. 14 as proposed by the authors in [6]. Since the "sensing" and the reconfigurable communicating" antennas

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are both incorporated into the same substrate, it is crucial to look at the coupling between them. For both positions, the transmission between the two antennas is below -10dB for the whole band of interest.

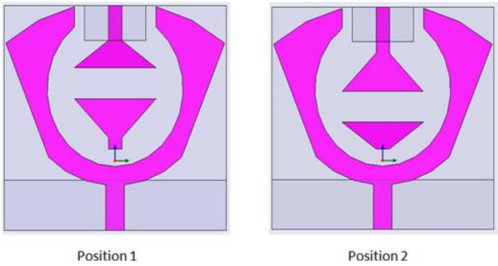


Fig. 14: The cognitive antenna structure.

IV. MULTI-ANTENNA SYSTEM

A multi-antenna system can be used for spectrum sensing and communication purpose. A multi-antenna system consists of a UWB antenna for spectrum sensing in a wide band from about 2 GHz to 11 GHz, another antenna is a narrow band antenna for determining the specific or a group of free channels, and one more antenna for communication purpose. This third antenna must be able to transmit over a narrow band anywhere between 2 to 11 GHz. A more detail on the multi antenna systems are presented in [3].

One such antenna is proposed by the authors in [7], a rotatable antenna for CR. These antennas are physically reconfigurable structures. Fig. 15 shows such an antenna. The left module is a UWB sensing antenna, and the right module is a rotatable antenna for communication purpose.

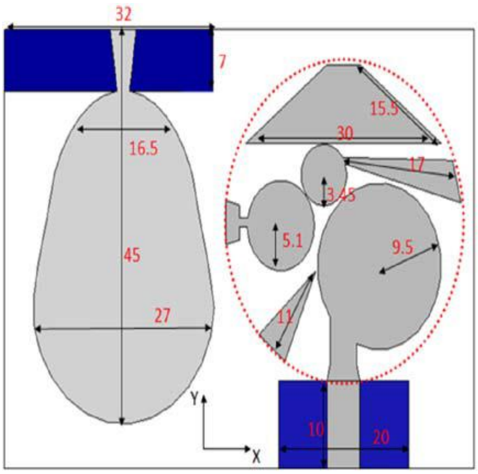


Fig. 15: Rotatable reconfigurable multi-antenna [7].

The frequency tuning is obtained by physically altering the patch shape. A stepper motor can be used to rotate a set of patch antennas built on a single circular substrate [7]. The contact between the feed line and the rotating circular patch is a 50Ω overflowing strip line. The shapes on the circular patch each have different frequency of radiation; hence each rotation will provide connecting shape and frequency. The stepper motor can be fit at the back of the rotatable section. Fig. 16 shows a prototype of such an antenna.

Fig. 16: Fabricated prototype of Fig. 15 [7].

In another approach, for multi-antenna systems the authors in [14], [15] present techniques to overcome multipath effects. Multiple Input Multiple Output (MIMO) techniques are applied to CR networks to improve spectral efficiency. In one of the scenarios it can be assumed that the system comprises a single-input single-output (SISO) primary user (PU) pair and a multi-input single-output (MISO) secondary user (SU) pair. Fig. 17 illustrates the system model of one such scenario.

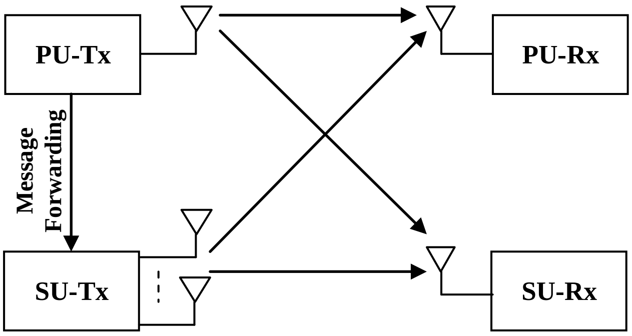
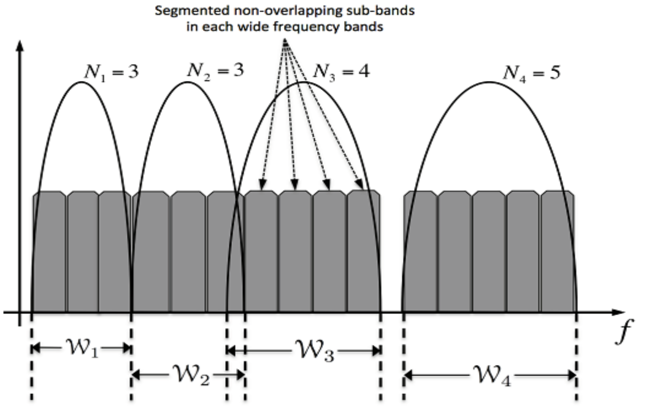


Fig. 17: System Model.

The SU transmitter is equipped with *M* transmit antennas, and only a single antenna is at the PU transmitter. Multiple antennas at the PU transmitter are not considered, as the focus is on the operation of the SU transmitter. Further, the number of antennas at the PU transmitter does not affect the interference to the SU receiver. It is also assumed that the receivers for both the PU and SU are equipped with a single receive antenna. Fading occurs in each channel. And the fading channels remain constant during a time slot. The main goal here is to determine the optimal beam forming vectors and power ratio in order to maximize the rate of the SU while meeting the rate requirement of the PU in MIMO antenna system. The proposed MIMO technique [14] in CR outperforms the conventional MIMO techniques in general. As the number of antennas is increased, the performance of the proposed algorithm diminishes. The spectral efficiency of the CR networks increases over the solution of optimization problem.

V. LEARNING AIDED SUB-BAND SELECTION

Spectrum sensing is a fundamental task for Cognitive Radios to detect spectrum opportunities and to know the surrounding RF environment. Several sensing algorithms are proposed for sensing the primary user signals in narrow and wide band frequencies [8] & [11]. In narrow band, a CR senses a particular channel or a particular set of channels, to determine the existence of primary signals. The decision making will reduce to binary hypothesis testing problem to determine whether a particular channel is idle or busy [12]. The authors in [13] have proposed three sub-band selection policies to find spectrum opportunities considering the hardware requirements and time delays. Wide band sensing refers to simultaneous sensing of a frequency band containing multiple narrow band channels. An illustration of wide frequency bands and further segmented sub bands in each wide band frequency is shown in Fig. 17.



The total number of sub bands: NB = N1 + N2 + N3 + N4 = 15.

Fig. 17: Relation between wide band and sub bands.

The three sub band selection policies as proposed are; 1) a myopic sub band selection policy based on the channel Markov models; 2) a myopic sub band selection policy based on the channel sub band Markov models to reduce the complexity; 3) a Q-learning technique is proposed to avoid the necessity of the Markov properties. It is assumed that in each several frequency sub bands the CR can only perform spectrum sensing in one sub band at a time.

The two Markov-based sub-band selection policies may achieve good results. But, the performance may vary depending on the RF environment. The required Markov knowledge may not be easy to obtain in some cases. On the other hand, the Q-learning policy achieves reasonable results in all test cases, with a much lower computational effort without any knowledge of the channel/sub-band Markov models. As a result, application of the Q-learning technique in the wide-band spectrum sensing problem is valid. In order to achieve the autonomous operation of the CR in practical RF environments, the CR may adopt a certain Machine-learning technique to fine tune the parameters of the Q-learning method.

VI. CONCLUSION

In this paper we have reviewed antennas requirement for Cognitive Radios. The reconfigurable antennas promise a novel approach for sensing ultra wide band spectrum and also to transmit over any narrow sub band. A UWB antenna can sense the complete spectrum for white spaces. Another antenna meant for communicating purpose would transmit over these white spaces. On the other hand the communication antenna must be frequency reconfigurable to transmit at any frequency. The frequency reconfiguration can also be achieved by using smart materials as substrate for antenna design. The sensing antenna must be continuously sensing the spectrum and provide the spectrum holes to the communicating antenna. The multi-antenna system can be a solution to the problem of transmitting at different frequency bands. The challenge in future scope is to have a connection among the UWB sensing antenna, narrow band channel sensing antenna and the communicating antenna and to integrate sensing with communicating.

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