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Review Article

Recent Advances on Radio-Frequency Design in Cognitive Radio

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With the growth of mobile data applications, the spectrum allocation is becoming very scarce. To ease congestion and boost speeds, cognitive radio (CR) is currently seen as a major solution and expected to be the key player in the new wireless technologies. In this paper, we will start by introducing the cognitive radio systems, followed by exploring the challenges in designing RF engine, along with an investigation of its antennas, amplifiers, oscillators, and the components that are expected to operate over a wide range of frequencies.

1. Introduction

With the increasing demand for high data rates requiring high resources, such as energy and frequency bandwidth, cognitive radio (CR) is thought of as a very promising solution. The basic operating principle of CR device relies on a cycle of observation, analysis, and decision and an opportunistic access to the available bandwidth. Hence, a CR device, usually referred to as secondary terminal, has to firstly sense the existence of a primary transmission and opportunistically transmits whenever a frequency/time slot is vacant. If the authorized (primary) terminal restarted transmission, the secondary terminal jumps off into a different band or alters its transmission parameters so that it does not affect the primary transmission [1].

In practice, the cognitive radio devices are expected to sense the occupancy of any channel at any band in the entire spectrum and autonomously adapt to the primary transmission [2]. This continuous (or discontinuous) sensing process on a large bandwidth imposes different constraints on the radio-frequency front-ends of the secondary terminal. More precisely, these requirements constrain strict issues on antenna design, low noise amplification, frequency synthesizers providing a carrier frequency from tens of megahertz to about 10 GHz, mixing spurs, and spectrum sensing. Broadband and tunable antennas, multiband amplifiers, RF filters, broadband direct-conversion mixers, baseband filters, and ADCs/DACs are needed to realize software-defined cognitive radio equipment. These RF components are expected to operate over a wide range of frequencies [3].

In cognitive radio, a reconfigurable radio front-end can be programmed to transmit, steer to any band, tune to a channel of any bandwidth, and receive any acceptable modulation scheme. The ability to design linear and spectrally agile components and architectures in the radio-frequency front-end of the transceiver is considered a primary technological concern in cognitive radio architectures.

The objective of this paper is to revise the major concerns of the front-end design of a CR system including the antennas, amplifiers, and oscillators. In the literature, very few works have investigated the design issues of the CR front-end from end-to-end. Moreover, a complied review of the different constraints has been very little tackled. We cite, for instance, the work in [4] as a first attempt to harmonize all these constraints. Hence, this paper belongs to the research works which could be used as a reference for the RF engineers working on CR. To complete this work, we detail and investigate the challenges to overcome in the next few years in order to design a complete and smoothly tunable RF front-end for CR applications.

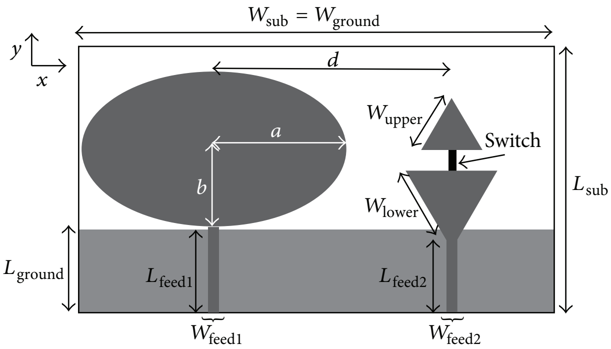

Figure 1: A proposed sensing and communicating antenna configuration in [5].

2. Antennas for Cognitive Radio

Cognitive radio communication is envisaged to be a new paradigm of methodologies for enhancing the performance of radio communication systems through the efficient utilization of radio spectrum. A key enabler for realization of a cognitive communication system and one of its main challenges is the capability of reconfigurability in the underlying hardware and the associated protocol suite. From the antenna design perspective, the demand for multiwideband antennas which can be easily integrated with the communication system is continuously increasing. Reconfigurable and frequency agile architectures are mostly designed nowadays in order to solve the broad frequency allocation and to reduce the number of functional blocks. Intensive work has been done in designing antennas for cognitive radio applications. The use of wideband antennas for spectrum sensing and narrowband antennas for transmission has been proposed by the research community [16, 17]. The sensing and transmitting antennas could be also found in the structure, as shown in Figure 1.

In general, there are three different categories of reconfigurable antenna:

(1) Frequency reconfigurable antennas: the frequency of the antenna is tuned to have single multifunctional antenna as a small terminal for many services, with radiation pattern remaining unchanged while the frequency is changing [18–20].

(2) Radiation patterns reconfigurable antennas: the antenna can steer its radiation patterns beams to different direction. The frequency remains unchanged while the radiation pattern changes upon the system requirements [21–23].

(3) Polarization reconfigurable antennas: providing an additional degree of freedom to improve link quality as a form of switched antenna diversity with improved signal reception performance in a multipath fading environment [24].

So far, reconfigurable antennas for cognitive radio communications can be classified into three types: electronically reconfigurable antennas, mechanically reconfigurable antennas, and optically reconfigurable antennas.

Table 1: Operating bands achieved when switches are ON/OFF [6].

Switch 1	Switch 2	Switch 3	Switch 4	Frequency band (GHz)
ON	ON	ON	ON	2.50–3.40 and 3.81–5.32
ON	ON	ON	OFF	2.49–4.26 and 5.90–6.25
ON	ON	OFF	ON	2.49–4.36
ON	ON	OFF	OFF	2.50–4.38
ON	OFF	ON	ON	3.79–6.71
OFF	ON	ON	ON	3.82–6.38
OFF	OFF	ON	ON	4.06–6.36

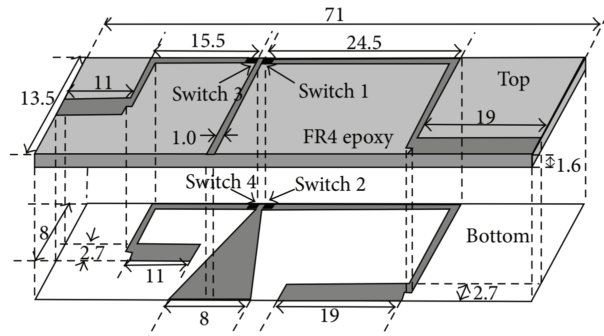

Figure 2: A proposed sensing and communicating antenna configuration in [6] (dimension is mm).

2.1. Electronically Reconfigurable Antennas. Electronic reconfigurability is usually achieved by incorporating switches, variable capacitors, lumped components such as PIN diodes, varactor diodes, MEMS switches, or phase shifters in the topology of the antenna [6, 7, 25–30]. An example of a frequency reconfigurable antenna for cognitive radio is proposed in [25]. The sensing and communicating antenna are positioned at the same one volume, with a printed hour glass shaped coplanar waveguide (CPW) fed monopole sensing antenna operating at 3.9 GHz to 11 GHz, accomplishing the UWB characteristic. The reverse side of the substrate contains the communicating antenna designed to operate from 5.15 GHz to 5.35 GHz. Another broadband antenna designed for a frequency and radiation patterns reconfigurability for cognitive radio is investigated in [6] and shown in Figure 2. The antenna consists of two branches. The left branch involves a short transmission line and a short dipole, and the right branch involves a long transmission line and a long dipole. By setting switching pairs of the four controlling switches, mutual coupling between a dipole and a nearby transmission is disturbed. The currents on the transmission line will be unbalanced, and hence radiation will occur. An example of a summarizing table of such reconfigurability of the proposed antenna in [6] is shown in Table 1.

In [26] PIN diodes are used in the design of a reconfigurable C-slot microstrip patch antenna that can operate in dual-band or in very wideband mode. A dual-band reconfigurable double C-slot microstrip patch antenna is also proposed in [7] and shown in Figure 3. Two PIN diode switches are used here to generate a dual-band and wideband by changing the states of the PIN diode. The antenna can operate

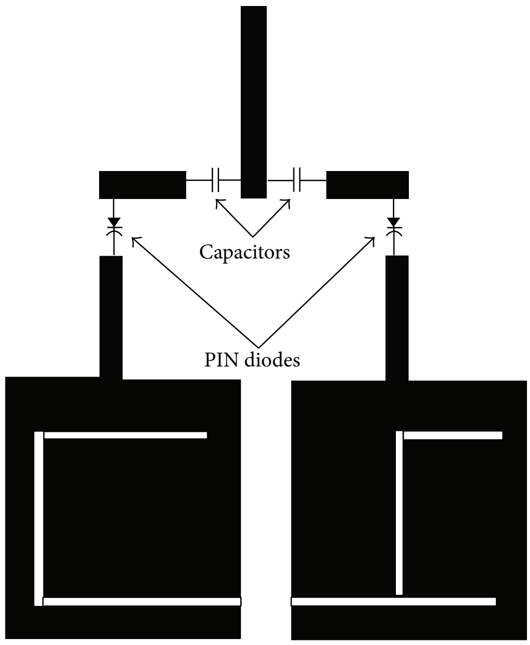

Figure 3: A proposed sensing and communicating antenna configuration in [7].

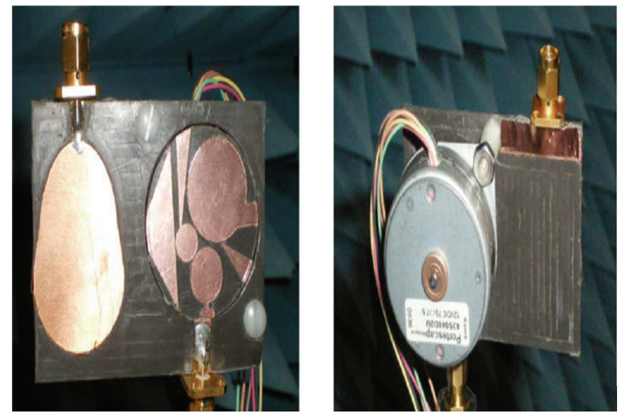

Figure 4: Implemented front-end using rotatable controlled reconfigurable antennas [8].

in dual-band or in very wideband mode in 5, 6, and 7 GHz bands. The wideband mode can be obtained when both switches are in the ON state.

In [27] a quad-band antenna for cognitive radio is presented. It has a direction radiation pattern in four frequency bands, covering most of the spectrum used for existing wireless applications. MEMS switch is used to adjust the operating frequency of the quad-band antenna. A two-element antenna array was further developed to increase the antenna gain for base station applications.

A dual port sensing and communicating antenna design for cognitive radio system is also presented in [28]. A tunable narrowband frequency operation is also proposed in [29]. An SMV1405 varactor is used to adjust the length of an open loop resonator (OLR) based band-stop filter. GaAs field-effect-transistor (FET) is used in [30] to design an UWB microstrip monopole antenna with reconfigurable multiband function. In [31], a novel design of a reconfigurable miniaturized planar spiral monopole antenna suitable for TVWS applications is reported. By inserting a tunable inductor on the spiral monopole and modifying its inductance, frequency reconfigurability is attained.

2.2. Mechanically Reconfigurable Antennas. Mechanic reconfigurability is usually achieved by incorporating some physical alteration of the antenna structure using a rotational movement. The advantage of this method is that no biasing circuits for switch activation are needed, which might affect the antenna performance. An example of this implementation is shown in [32]. The antenna presented consists of two structures incorporated together into the same substrate: the first structure is an ultrawideband (UWB) antenna covering the spectrum from 3.111 GHz for channel sensing, and the second structure is a frequency reconfigurable triangular-shaped patch for establishing communication with another RF device. The frequency reconfigurability is achieved via a rotational motion, for which the rotating part of the antenna is responsible to produce the required frequency tuning. By rotation of the antenna with different rotation angles different resonances are produced, making the antenna suitable to communicate at the frequency specified by the "sensing" antenna.

Another example of this implementation in the design of a cognitive radio front-end is presented in [8] using also rotatable controlled reconfigurable antennas. The frequency agility is also achieved via a rotational motion of the antenna patch controlled by a stepper motor mounted on the back of the antenna structure. This is shown in Figure 4. In [32], an UWB sensing antenna is presented with slotted polygon shaped patch with partial ground on the reverse side of the patch. The frequency configuration is achieved by rotational movement of the triangular-shaped patch communicating antenna.

Moreover, in [33], a frequency reconfigurability of an antenna for cognitive radio is also achieved via rotation motion of a part of the antenna patch. The rotating part has the form of a circle and contains four different shapes for which each shape corresponds to a different antenna structure. With every rotation, a different antenna structure is fed in order to produce a different set of resonant frequencies. Using the same rotation mechanism, a multiband reconfigurable antenna is presented in [34] using different rotating slot configurations of the antenna.

2.3. Optically Reconfigurable Antennas. Additional work has been done on the design of optically reconfigurable antennas [9, 35–41]. An example of a photoconductive switch that uses an η-type silicon switch doped with phosphorus to increase its conductivity is proposed in [35]. A frequency and radiation pattern reconfigurability has been achieved by effectively changing the dipole arm length. Optical-fiber cables are used to feed the printed dipole antenna. Another example of optically controlled frequency reconfigurable

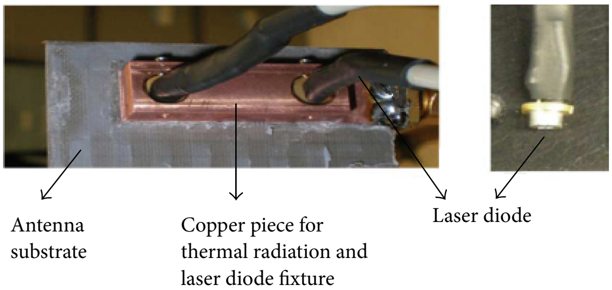

Figure 5: Integration of the laser diode into the antenna structure [9].

microstrip antenna is also presented in [36]. Moreover, field-effect-transistor- (FET-) based electronic switches used with optical control are proposed in [37] to control planar arrays of electrically small metallic patches.

Furthermore, dynamically changing the material properties of parts of an antenna can significantly alter the antenna performance. This is possible through changing the conductive properties of some materials through an electric current or optical signal. In [38] a frequency reconfigurable rectangular patch antenna is achieved using LED that is used to alter the conductivity of the semiconductors used. The variable conducting material changes the resonant frequency of the patch by increasing or decreasing the size of the patch [38].

Another work that reduces the complexity of the systems negating the need for optical-fiber cables [39] is proposed in [9]. The design is based on integrating laser diodes within the antenna structure, as shown in Figure 5. This technique does not require any biasing lines for switch activation purposes in the antenna radiating plane, as is the case with RF MEMS [40] or PIN diodes [41].

3. Amplifier Design for Cognitive Radio

3.1. Power Amplifiers. Amplifiers are basic building blocks in electronics communications systems. For the transmitter design in cognitive radio applications, in order not to interfere with the primary user and operate at multistandard frequency range, a high power gain is required, and thus a broadband linear power amplifier (PA) is desired. It must provide a high output power, simultaneously assuring a wide bandwidth, high efficiency, and linearity behavior.

The power amplifier, which is a crucial element of wireless transmitters, consumes a large portion of energy in RF circuits during transmission. Consequently, an efficient PA design with high efficiency capabilities is required. As the system requirements vary, the specific constraints on the amplifier design also vary considerably. There are, however, common requirements for nearly all amplifiers, including frequency range, gain flatness, output power, linearity, matching, and stability. Often there are design trade-offs required to optimize any parameter over the other, and performance compromises are usually necessary. Different classes and modes of operation were defined, each achieving certain criteria in such performance metrics. Popular examples are the basic classes such as Classes A, B, C, D, E, and F PAs. Because of their highly versatile circuit function, PAs have always been the first to benefit from developments in the device and semiconductor technologies, which helped in defining even new techniques for operation like the Doherty amplifiers and Class J PAs to meet the requirements imposed on PAs due to the evolution of new communication systems and standards as CR systems.

When the PA is driven towards saturation, the nonlinear distortion will increase significantly. On the other hand, the highest PA power efficiency is obtained at the saturation point. In fact, there is a trade-off between the power efficiency of the PA and its linearity. The nonlinear behavior of the PA leads to spectral regrowth of its out-of-band output signal and, as a result, to adjacent channel interference (ACI). The ACI power is a nonlinear increasing function of the PA input power. Therefore, it is important to consider the PA nonlinear behavior of the CR transmitter and the resulting ACI power for allocating power in CR networks by noting the interference temperature limits. The CR system design should be aware of the nonlinear behavioral model of the PA and of the other users constraints in the environment.

There are several methods to develop wideband PAs:

(i) The traveling-wave and distributed amplifier topologies have excellent characteristics in terms of bandwidth, gain flatness, and input voltage standing-wave ratio, so that they are widely used for broadband PA development [42, 43].

(ii) The multistage LC combination technique is proposed [44] to improve the GaAs HBT PA in order to be used in broadband wireless applications from 3.3 to 3.6 GHz.

(iii) The push-pull PAs can reach wide bandwidth using broadband transformers [45–47].

(iv) The shunt-feedback technique and multisection distributed matching networks are demonstrated to be useful in [48].

Several works have been proposed in designing power amplifiers for cognitive radio applications. In [49], a broadband PA is demonstrated in InGaAs HEMT technology using load impedance tracking. The power-added efficiency and the 1 dB compression point of the PA are better than 20% and 21.4 dBm, respectively. A wideband power amplifier for the application of intelligent cognitive radios is proposed in [10]. In this PA design, the broadband frequency response is enhanced using transformer matching network and resistive feedback. As shown in Figure 6, series stack topology is used to achieve the broadband load impedance match by discussing the constraints of stack PA in both GaAs and CMOS methods. The main difference between these two PAs is the feed point. In the first one, transformers are employed using RF input at the bottom and ground at the top. In Figure 6(b), the RF feed point is upside-down compared to Figure 6(a). Due to the fact that these two PAs are voltage combined, the total biasing current is controlled by the transistor. To verify the design models, a high efficiency broadband PA in commercial 0.18 m CMOS process with the best PAE of 30% and the 1 dB compression point of 20 dBm is established. This

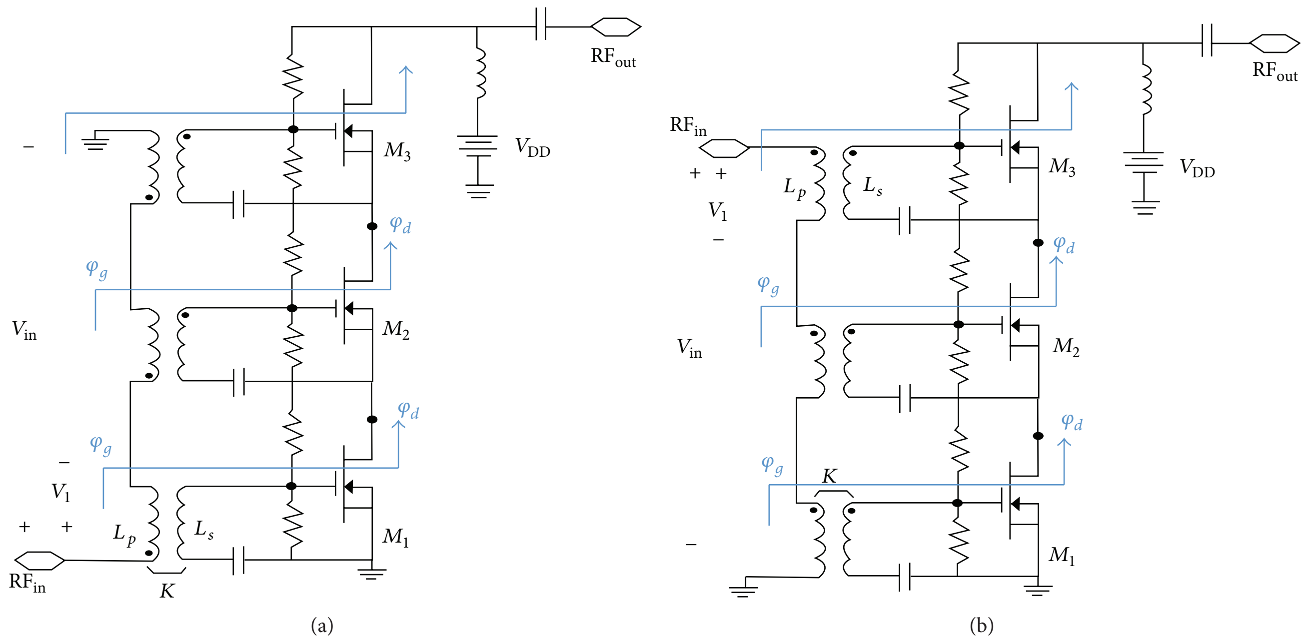

FIGURE 6: Two kinds of transformer orientations of stack PA. In (a), the transformers are opposite coupled. (b) The upside-down input fed configuration [10].

PA also demonstrates the widest bandwidth performance among CMOS PAs below 10 GHz. In [50], a high efficiency Doherty power amplifier suitable for TV band applications is proposed. It is designed following the Class AB scheme for the main amplifier and a Class C scheme for the peak one. It attained a high power-added-efficiency of 81.94%, a 42.77 dBm output power, an associated gain of 21.32 dB, and an operating frequency bandwidth between 550 and 1000 MHz (58.06% fractional bandwidth) which make it suitable for cognitive radio applications in the TV band.

In [51], the interference control in time-windowed OFDM Systems with realistic power amplifiers for cognitive radio applications is investigated. The load-tracking technique based on the frequency-varied load pull is proposed for the PA design. The interference in holes generated inside an orthogonal frequency division multiplexing (OFDM) spectrum, for applications related to cognitive radio, is discussed. Due to its simplicity, the time-windowing technique is selected in order to obtain interference reduction in the out-band region and inside the spectral hole. In this design, it is shown how to choose system parameters (number of guard subcarriers, window type, and extended guard interval duration) in the presence of a nonlinear power amplifier, whose generated interference is of dominant importance in assessing the real gain provided by the OFDM technique.

3.1.1. Tunability for Power Amplifiers. Broadband PA modules with frequency tuning capabilities have been also investigated. These modules having multiple narrowband power amplifier chips and corresponding matching circuits are joined into a platform and controlled by switches in order to obtain frequency band tuning [52, 53].

In order to lessen the number of components in PAs and corresponding matching circuits, alternative single chip solutions have been recommended. For example, while a balanced amplifier is a good applicant, it is usually not practical to use quarter wavelength size of the couplers. A distributed amplifier is another consideration, where it suffers from low efficiency and low gain and requires a relatively large chip size. On the contrary, the feedback amplifiers have a relatively small chip size, but with low gain at microwave frequencies and compromised efficiency when resistive feedback is used. As shown in [54, 55], lossy matching networks are used to attain better gain flatness, making a trade-off with the power gain. In [11], a novel reconfigurable output matching is applied in the dual mode broadband InGaP HBT PA through employing PIN diodes to adjust the LC networks as shown in Figure 7. Using the compensating matching technique, the 3-stage broadband power amplifier is achieved and the distribution of power gain among stages is optimized. The output matching circuit is realized with parallel LC tank circuits using PIN diodes in order to control the inductor value. This broadband amplifier module offers the advantage of using less components, less power insertion loss, high linearity, and small size.

3.2. Low Noise Amplifier. For the receiver side in cognitive radio, a low noise amplifier is required. In the CR applications, it is very essential to detect the presence of primary users, creating spectrum opportunities for secondary users (CR users) in order to increase the capacity of wireless communications. For realizing this function, the sensitivity of the spectral sensing in CR must be much higher than conventional radio receivers. High sensitivity integrated receivers

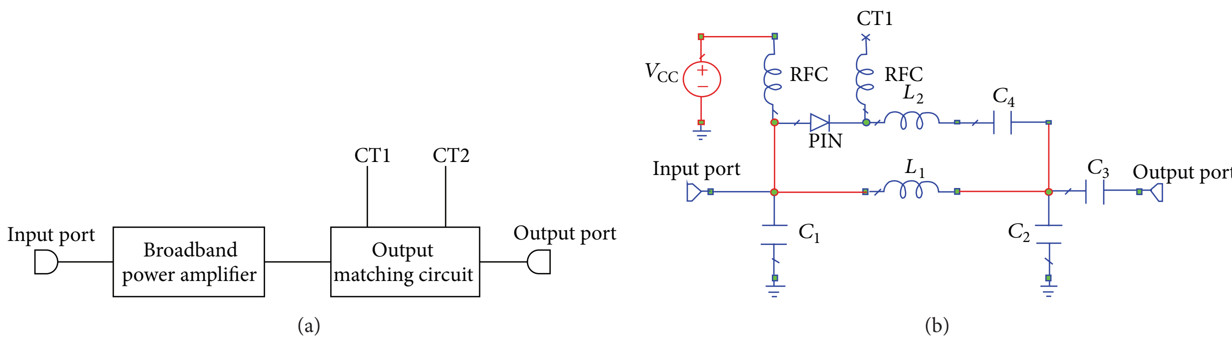

FIGURE 7: (a) Proposed broadband power amplifier module; (b) schematic of the novel reconfigurable output matching circuit [11].

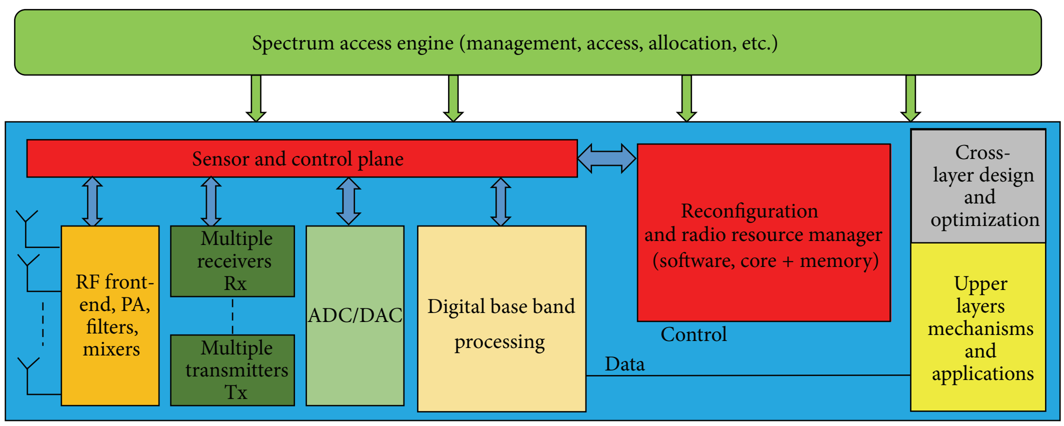

FIGURE 8: The spectrum access scheme including RF front-end.

require low noise amplifier (LNA) that can deliver sufficiently low noise figure (NF), acceptable linearity, quite high gain, and low power dissipation. These requirements must be achieved over a wide frequency range in CR. Commonly wideband LNAs consist of MOSFETs and resistors which are far from the above-mentioned requirements. Some research intends to enhance the noise performance in LNA design using noise cancellation methods. However, the gain of all those LNAs is less than 14 dB when the NF is about 4 dB, and all of them have relative large power dissipation [56–58].

Several works have been proposed in designing low noise amplifiers for cognitive radio applications. A new wideband low noise amplifier, operating in UHF band for spectral sensing in the receiver of cognitive radios, is reported in [59]. The noise canceling technique is employed in this circuit, and it yields higher gain and lower power dissipation. The method of shunt-resistive feedback is adopted for achieving a broad bandwidth. The noise figure is less than 4 dB, the gain is 18–21 dB, and the LNA consumes only 11.2 mW at 1.8 V power supply. In [60], a new full on-chip CMOS LNA topology, working in the range of 50 MHz to 10 GHz with very low power consumption, is introduced. In this LNA, the common-gate (CG) stage for wideband input matching is combined with the common-source (CS) stage for canceling the noise and distortion of CG stage. Moreover, the CS stage used both nMOS and pMOS transistors to improve the IIP2. This LNA achieves an input return loss (S11) less than −10 dB over the whole bandwidth and a noise figure of 2.3 dB to 2.8 dB while consuming only 6 mW from a 1 V power supply. The average power gain (S21) is 12 dB. The achieved IIP3 and IIP2 are about −5 dBm and 20 dBm, respectively.

4. Oscillator Design for Cognitive Radio

4.1. Introduction. Figures 8 and 9 present the main blocks of a suitable architecture for CR systems. In practice, the spectrum sensing architecture is composed of two stages. In the first stage, the target spectrum undergoes a coarse detection and analysis on relatively large subbands of interest. This allows recognizing those channels occupied by primary (strong power) signals and marking them as busy. Then, a sweep over the band of interest is applied to have a fine detection of the presence or absence of the primary signal. The second stage consists of the RF transmission block able to generate the necessary RF signals whenever a spectrum opportunity occurs.

The signal band in CRs is shared between primary and secondary transmission. In practice, there are various architectures of receivers, such as direct-conversion (homodyne), super-heterodyne, low-IF, and bandpass sampling radio architecture. However, contrarily to the conventional tuners, the spectrum sensing receivers should have similar

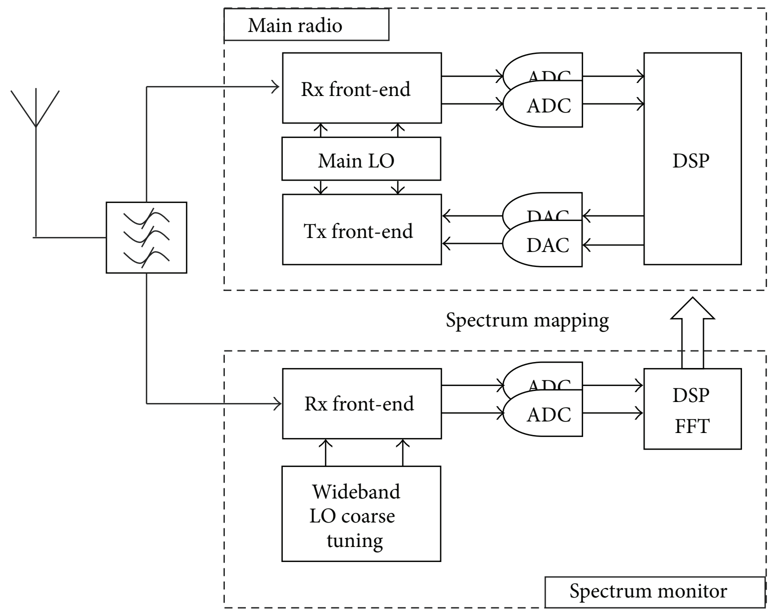

Figure 9: Spectrum monitoring and mapping scheme [12].

architectures to spectrum analyzer. The frequency of the local oscillator (LO) and its intermediate frequency should be selected outside the signal band boundary [61]. On the other hand, as the CR system should call for flexible RF architectures, with a wide frequency range, a wideband high performance controlled local oscillator with a relatively relaxed phase noise performance should be designed for the use of both spectrum monitoring and transmission functionalities.

In this section, we investigate techniques related to the design and implementation of VCOs and to the increase of their tuning range while maintaining acceptable design specifications such as phase noise, power dissipation, accuracy, and stability. In practice, two popular oscillator architectures have been proposed for spectrum sensing applications: LC tank based and ring based oscillators. The LC tank oscillators are well-known for their phase noise and low power consumption at radio frequencies and they are usually recommended in many applications. However, they suffer from low tuning range as compared to ring oscillators, a necessary step in spectrum sensing techniques. In practice, the tuning range of the LC tank based oscillator is restricted to only 10% to 20% if implemented without compensation techniques yielding then to vulnerability to process variations. The utilization of an inductor with a high quality factor however increases the chip area, the cost, and complexity of the oscillator [62]. Moreover, in a system requiring multiple output phases, additional circuits, such as I/Q generators, make the system more complex.

On the other hand, ring oscillators are considered to be suitable candidates as the core block in the required frequency synthesizer naturally with wide tuning range. Moreover, the relatively small area makes it a good choice for low cost portable devices. They are able to generate wide range frequency signals with multiple output phases without any supplementary circuits which is very practical to cognitive radio applications. However, they suffer from high level of phase noise.

4.2. The LC Tank Oscillator. In the literature, different LC resonant tanks with multiple frequencies and based on transformers or multitapped inductors have been proposed to design tunable multibands and/or wideband oscillators [63–69]. In [63–65] transformers with small turn ratio and adequate coil coupling are utilized to design differential dual-band oscillators. As the target frequency ranges from 0.4 GHz to 7 GHz, two configurations are proposed. A one-port oscillator is used for the low-band mode, while a two-port oscillator design is used for the high band.

Multitapped inductors are proposed in [66] to design an LC tank of order equal to 4, covering the two bands 0.8 GHz and 1.8 GHz with target application GSM/DCS/PCS standards. In [67], transformers with high coupling ratio and large turn ratio are used to design a dual-band oscillator (4 GHz/10 GHz). To stabilize their one-port oscillator, a notch-peak cancellation technique is proposed. Similarly, a single multitapped inductor and two-port oscillations are used in [68] to design a 3.5 GHz/10 GHz dual-band differential VCO for area-efficient wideband applications. In [69], a triple-mode wideband VCO tunable from 1.28 GHz to 6.06 GHz is proposed by utilizing loosely coupled 3-coil transformer with one-port oscillations.

All this work shows that VCOs with high order LC tanks present large prospective to design wideband or multiband applications. Nevertheless, the comparison of these VCOs with the conventional LC-VCO schemes reveals that the stability of the VCO becomes a real issue when the order of the resonator increases. This leads to an increased complexity which yields to the inclusion of many design parameters in the design of the VCO end-product. For instance, the inductor, capacitor, and the coupling between the inductors ratios should be carefully (and maybe jointly) considered in order to optimize the VCO outputs.

Fortunately, some attempts in the literature have been established [65] to derive analytical results and close-form expressions of the oscillation frequencies and of the conditions of the transformer-based one-port and two-port oscillators. This has led, from one side, to successful realizations of one-port and two-port oscillators with high order resonant tanks and to a comprehensive evaluation and comparison of different tanks topologies and designs at different bands for particular applications on the other side. Nevertheless, it is considered in [65] that the capacitors of the oscillators are lossless, a basic assumption yet invalid in real networks. To solve this problem, a complete understanding of the two-oscillator configurations (one-port and two-port) including capacitance loss, phase noise, and tank Qs is provided in [70]. It is shown that one-port oscillators consume less power but need to be stabilized if the designer is seeking oscillation at the higher peak frequency. The two-port oscillators have no stability issue and have superior phase noise performance for a given output swing but are less efficient in converting the bias current to the tank swing. Based on these observations, both configurations are combined to exploit their corresponding advantages at different frequency for spectrum sensing (and software-defined radio-SDR) applications. Accordingly, a transformer-based dual-band Q-VCO frequency synthesizer is proposed and designed [70], which supports existing wireless technologies.

In [71], a VCO with tuning range extension circuit is designed using an injection-locked frequency divider (ILFD) and flip flop dividers. The 2-stage differential ILFD can generate quadrature outputs, with a tunable divide ratio equal to 2, 3, 4, and 6 and very wide output frequency range. The proposed oscillator achieves a large frequency from 9.3 MHz to 5.7 GHz with 210 dBc/Hz of figure of merit. It is implemented using a 90 nm CMOS process. Other wideband oscillators have been also proposed in the literature using the same tuning range extension technique and QVCO. We cite, for instance, the works of [72, 73] which design VCOs for multistandard transceivers using a tuning range extension technique and QVCO. These VCOs achieve quite wide tuning range and high spurious rejection using single-sideband mixer (SSBM) with I/Q signals. However this is obtained at the detriment of large phase noise and power consumption. The work of [73] is also interesting in this regard. A tuning range extension technique is utilized using differential VCO, a mixer, and dividers. However, the VCO does not generate I/Q signals, while spurious frequencies appear at the output of the mixer.

4.3. The Ring Oscillator. Generally, a ring oscillator is composed of a cascade of different stages. Its oscillating frequency is proportional to the number of stages (N) and the transmission delay of each delay cell stage (TD). In practice, the number of stages is usually fixed for a given design while the TD reflects the charging and discharging time for the load capacitance. For instance, with a CMOS inverter based delay cell used in an oscillator, the transmission delay could be tuned by changing the bias current of the design [12]. For a differential amplifier base stage, either the tail current source or PMOS load could be varied for tuning purposes [74]. These design parameters allow to offer large VCO gain variation over the overall tuning band. In particular, very high gain is often observed in the middle of the tuning range, where the oscillator would suffer from high sensitivity to control voltage imperfections.

There is no doubt that a linear relationship between the voltage control and the oscillating frequency is required for wideband systems to ensure the locking range of the frequency synthesizer. Hence, most of the oscillators designs were based on this basic yet important approach. For CR applications using ring oscillator approach, we distinguish the work of [75] on standard 130 nm CMOS technology targeting a wide range frequency tuning range. The three-stage differential ring oscillator proposed therein is tuned by an array of MOS varactors, controlled by a staggered voltage offset system for improved tuning linearity. The proposed ring oscillator offers a measured tuning range from 4.85 GHz to 7.15 GHz, consuming 4.2 mA current from a 1.2 V supply voltage while the phase noise measurements are appropriate for such designs (−82.5 Bc/Hz at 1 MHz offset from an operating frequency of 4.88 GHz). In [13], a novel voltage-controlled ring oscillator fabricated in TSMC 0.18-m CMOS technology is designed. To maintain the linearity between frequency and voltage characteristics and phase noise specifications over a wide tuning range, a transmission gate is implemented. The proposed ring oscillator has achieved a wide operating frequency range from 20 MHz to 807 MHz covering particularly TV channel bands (or TV White Spaces TVWS). The interesting point of the proposed ring design resides in its phase noise which measures 108 dBc/Hz at 1 MHz offset from 630 MHz and its power consumption of 22 mW.

A linear current-controlled oscillator (CCO) is proposed in [76]. The output frequency of the proposed oscillator is implemented using a linear CMOS switched-capacitor frequency detector (SCFD) that operates appropriately over the frequency range of the designed oscillator. Then, a negative impedance converter (NIC) is utilized to control the supply current and complete the ring oscillator design. The interesting part of the proposed oscillator resides in the fact that it does not use operational amplifiers or resistors which makes it very easy and widely applicable in all types of oscillators. This oscillator has power consumption less than 3.6 mW in the frequency range of 140 MHz to 1.15 GHz from a supply voltage of 1.8 V with very high phase noise performance (in the order of 93.44 dBc/Hz at 1 MHz offset from the carrier frequency of 501.13 MHz). In [77], a compact and low power quadrature local oscillator is designed and implemented for the 13.3–20 GHz band using a differentially tuned LC-VCO. The same design is then converted to cover the band 5–10 GHz with continuous frequency coverage. A 4-stage differential injection-locked ring oscillator (ILRO) is used subsequently to the latch-based divider to generate quadrature output phases without restricting 50% duty cycle from input signals as those of conventional divide-by-2 approaches. When implemented in a 65 nm general purpose CMOS IC technology, the integrated quadrature-phased LO consumes 22 mA of current at a 1 V supply and offers very good phase noise performance across the entire 5–10 GHz band targeting the CR applications.

In [78, 79], an all-digital phase-locked loop using a combination of a digitally controlled ring oscillator with an LC tank is proposed to extend the tuning range of the LC tank and reduce its power dissipation. In the suggested design, an adaptive frequency calibration, based on binary search, is introduced to accelerate the frequency settling. The proposed architecture is fabricated in a 65-nm CMOS while the frequency synthesizer has an active area of 0.3 mm^2 and achieves a frequency tuning range of 2.7 to 6.1 GHz, with power consumption of less than 22 mW from a 1.2-V supply.

To improve the poor phase noise performance common in ring oscillators, a series of works have been proposed to deal with this issue [13, 80–82]. In [80], a ring based oscillator using a saturated-type differential delay cell with a positive feedback path is proposed. It is shown that the phase noise of the proposed oscillator has comparable performance as the conventional LC tank VCO. However, the frequency tuning mechanism implemented is not practical as it changes the strength of the latch in the positive feedback. Indeed, the latter could not be proportional to the control voltage which means that the oscillator could not have a linear frequency versus the input voltage. In addition, the oscillator could not operate in low frequency range such as VHF bands. To overcome this problem, a transmission gate is proposed in [81, 82] to linearize the voltage-frequency tuning relation. In [13], a monolithic ring VCO is proposed. It is based on delay cell and a 4-stage scheme taking into account the trade-off between the frequency tuning range, phase noise performance, and power consumption of the oscillator. The delay cell consists of one NMOS input pair, one PMOS positive feedback pair, and one transmission gate which connects the output of one delay cell to the input of the next one.

4.4. Other Oscillators. In [83], a Distributed Voltage-Controlled Oscillator (DVCO) suitable for CR applications is proposed and optimized. To do so, Harmonic Balance (HB) based optimization techniques have been used. The proposed DVCO aims at minimizing the output power variation along the frequency band and it consists of a distributed amplifier with a feedback loop. The oscillator tuning is achieved through biasing all the drain terminals with a fixed voltage V_{DD} and varying the gate bias voltages of the active devices in pairs. The measured DVCO frequency band, shown in Figure 10, covers from 0.75 GHz to 1.85 GHz, dissipates a power equal to 59 mW, and generates average output power of 5.2 dBm while the average measured phase noise at 1 MHz offset from the carrier across the tuning range is −111.2 dBc/Hz.

Another interesting work in this field concerns the contribution of [84], based on A CMOS spectrum sensor aiming at detecting spectral usage and spectrum holes in the 2.4 GHz industrial scientific-medical (ISM) band. The proposed design consists of a swept oscillator and frequency discriminator, both of which use the injection locking of the VCO to process the sensed signal without requiring a frequency synthesizer. The proposed sensor can detect the frequency and power of the primary signal with high accuracy at a spectrum scanning speed of 100 MHz/ms. It is worth mentioning that the sensitivity of the proposed design can be below −100 dBm when an external low noise amplifier (LNA) is used in front of the sensor Integrated Circuit.

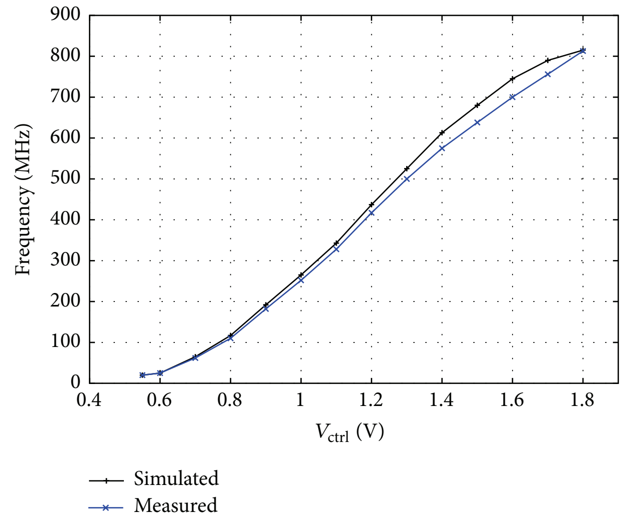

Figure 10: Frequency-voltage control characteristics [13].

5. Challenges

Although a large number of research works on CR exist, the challenges of this technology remain numerous. Besides the challenges related to intelligence distribution and implementation, decision making, sensing algorithms and learning process, delay/protocol overhead, geolocation, and flexible hardware design, major difficulties lie in the implementation and the design of antennas, amplifiers, and oscillators. The complexity found in the implementation of these RF parts is lowering the pace of its development [85]. Several works have been done in analyzing such challenges [4, 10, 14, 15, 56, 86–97].

Referring to Figure 8, for this system to operate on multiband or a broadband simultaneously, the employment of parallel processing from antennas to analog to digital interfaces is materialized. Multiantennas are necessary for MIMO operation and/or multibands operation. Passive module used for RF filtering, switching, or duplexing and impedance matching between power amplifiers and antennas are located after the antennas. After that, multireceiver (Rx) and multitransmitter (Tx) are followed before a multi-ADC/DACs module. The high performance of this system requires coding and encoding, in addition to conventional processing for modulation and demodulation, and consequently digital filtering, digital automatic gain control, dc offset cancellation, nonlinearities, and correction and calibration of analog errors. In order to improve the performance of the analog part, a feedback from baseband to RF front-end and transceiver combined with control plane and sensor is an essential step. The challenges of RF front-end and transceiver in the short-midterm are

(i) reducing the chip and passive components,

(ii) increasing their frequency-tunability,

(iii) minimizing the dissipation of power,

(iv) reducing their area.

5.1. RF Front-End: Tx and Rx. Investigating the RF front-end, the RF section needs to be particularly flexible. Flexibility requires the cognitive radio transceiver being able to adapt to multiple access methods and adaptive modulation scheme sense and use any available frequency band, establish communication with several points, switch quickly between links, and most importantly handle very large peak-to-average power ratios (PAPRs) [98]. The efficiency of the PA suffers dramatically in case of very large PAPR. Also, the large PAPR highly affects the linear upconverters leading to high power consumption.

Investigating the RF part in the transmitter, important design challenges are faced when the linearity requirement has to be encountered for high lower levels. Although the power levels in the RF part of the receiver are much lower, the presence of adjacent channel interference from different radio systems also adds to the design challenges. For linearity requirements, the expected level of blocker power above the desired channel should be also included in the design of received components. Moreover, the receiver must operate in a wide dynamic range in order to handle a large interferer and at the same time receive a much smaller wanted signal. Two challenges arise from this difficulty related to achieving acceptable noise figure performance for the overall receiver and sufficient dynamic range for the ADCs. The receiver should then have a good sensitivity required to achieve low noise factor (<3 dB) and low insertion losses (<1 dB) and high LNA and mixer linearity (IP3, IP1). It also needs to be a good blocker immunity and low local oscillator (LO) phase noise [86]. These requirements are difficult to be handled by the band limited traditional front-end technology and even by multimode/multiband and wideband transceivers. Switching the front-ends as required is usually adopted in this case [99].

Typically, these challenges and requirements are attained through the use of additional components such as surface acoustic wave (SAW) filters and crystal oscillators. However the added components are mostly costly and increase the power consumption, in addition to added lack of flexibility. On-chip filters are suggested to limit these disadvantages, but at the cost of added signal corruptions.

5.2. Low Noise Amplifiers. A CR receiver (Rx) must provide a relatively flat gain and a reasonable input return loss across BW_{CR}. Consequently, it is challenging to employ traditional RF circuit techniques. As an example, the switched-band circuits or staggered tuning formed by a cascade of stages with staggered resonance frequencies proves to be impractical for such a large bandwidth. This problem is illustrated in several papers [14, 100]; however the solutions are still inconvenient for CR systems. The design of broadband LNA

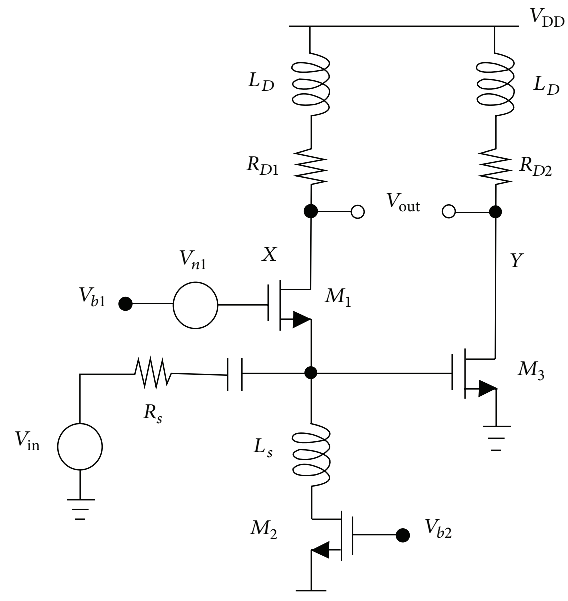

Figure 11: CG/CS stage [14].

is an interesting challenge due to the trade-offs it governs between input matching, gain, noise figure, bandwidth, and voltage headroom. The choice of the topology begins with the input matching requirement [14]. The input matching of the LNA can take on one of several forms:

(1) a common-gate (CG) stage,

(2) a common-source (CS) stage with inductive degeneration,

(3) a gain stage with resistive feedback,

(4) a combination of CS and CG stages.

However, each one of these approaches has its drawbacks. For example, the first one suffers from a relatively high noise figure in addition to severe gain-noise trade-offs. The second one does not lend itself to broadband operation.

The fourth approach could be considered as a development of the first two methods by combining the CG and GS approaches, shown in Figure 11. This provides additional voltage gain and forms a differential output along with the CG stage, with reduced noise (canceled M_1, V_{n1}) [56]. However, this topology still suffers from the drawbacks of the CG LNA, facing serious headroom issues and degraded reflection coefficient. Noise cancellation can be realized when the input signal appears with opposite polarities and the noise of a device [56]. The cancellation technique also suppresses nonlinear components produced by the input device.

5.3. Nonlinearity and LO Harmonics. In addition to third-order intermodulation, nonlinearity in cognitive radios corrupts the signal path in the presence of large interferers. As illustrated in Figure 12 two interferers at f_1 and f_2 generate a beat at $f_2 - f_1$ as they face even-order distortion in the LNA and the input stage of the mixer. Due to random asymmetries

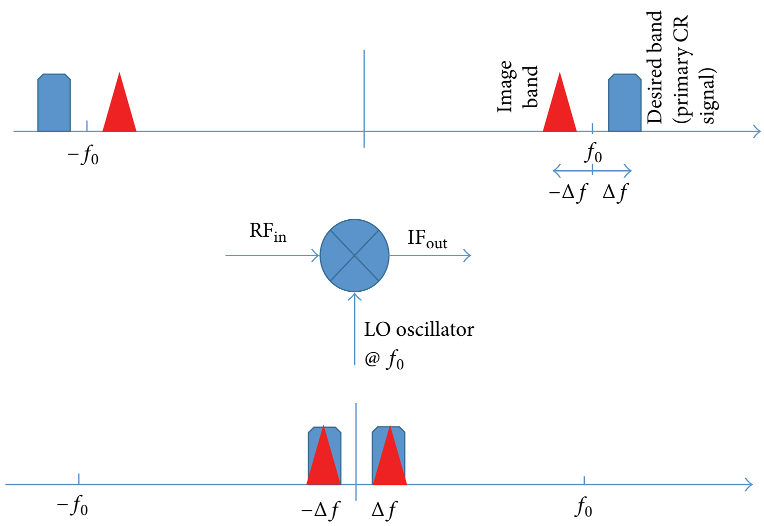

Figure 12: Example of even-order distortion in spectrum sensing receivers due to image bands.

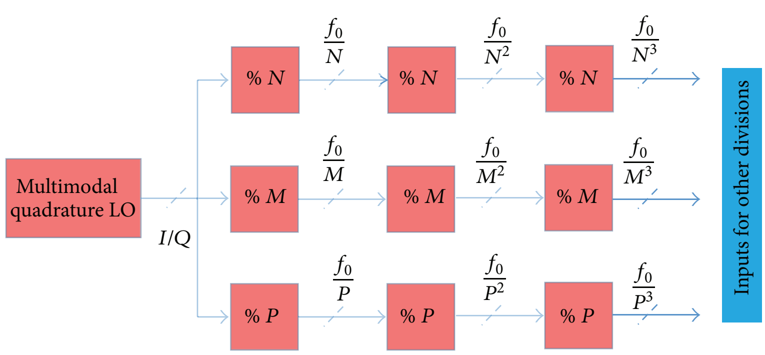

Figure 13: Multidecade carrier generation using a single multimodal LO.

within the mixer, a fraction of this random beat leaks to the baseband without frequency translation, thus destroying the downconverted signal. The LNA itself also produces components at f_2+f_1 and f_2-f_1, both of which may lie within $\mathrm{BW}_{\mathrm{CR}}$. That is, the LNA becomes the bottleneck. Another effect arising from even-order distortion is the demodulation of AM interferers.

5.4. LO Path Design. Another challenge in CR arises from the design of Local Oscillators. The carrier synthesis for cognitive radios must follow three principles [14]:

(1) Each frequency component must be produced in quadrature form.

(2) Single-sideband (SSB) mixing must be avoided because of its large spurious content.

(3) For a frequency divided by an odd number, it must be divided by 4 so as to generate quadrature phases.

Using one decade of carrier frequencies, some of the issues related to the LO path design shoot from the supply coupling within divider chains. An alternative approach to multidecade carrier synthesis is illustrated in Figure 13. The circuit consists of a quadrature LC oscillator operating at one of two frequencies (e.g., 17.5 GHz and 14 GHz) and three divider chains providing divide ratios of 2, 3, 4, 5, 6, 8, and 10. The worst-case oscillator tuning range in this case is 14% compared to 12.5% in the first case.

The circuit produces quadrature phases at all outputs. An exception to the third principle prescribed above is given through the use of quadrature Miller dividers [91], in which an SSB mixer is used to form a Miller loop, and all of the unwanted frequencies generated by the SSB mixer are translated to zero, or to its harmonics as they travel to the output. However, the principal disadvantage of quadrature Miller dividers is the need for quadrature LO inputs, which suffer from higher phase noise [92] and exhibit two possible but poorly controlled oscillation frequencies [101].

5.5. Antenna Cancellation for Simultaneous Cognitive Radio Communication and Sensing. For real time and accurate monitoring of the radio spectrum, concurrent communication and sensing is a vital CR functionality. This depends on the ability of isolating the communication path from

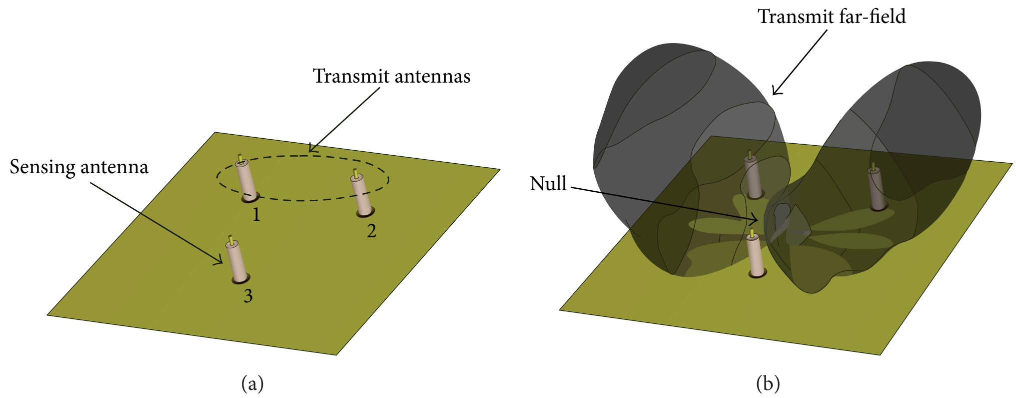

Figure 14: (a) The numerical model of the array prototype comprised of three short monopoles and (b) the far-field beam pattern when out-phasing the transmit antennas [15].

the sensing path to a level which ensures that the local transmissions do not overload the sensing unit when the transmitting and sensing antennas are collocated in the same CR device. This can be achieved by equipping the CR with redundant transmit antennas to form a spatial filter that selectively cancels the transmit signal in the sensing direction [15]. Such antenna cancellation could result in an isolation level of 60 dB as depicted in [15] that can be further increased when combined with active power cancellation in the RF or baseband stage.

The concept of using multiple antennas has also been used to cancel the interference via zero forcing or far-field null steering [93, 102]. The transimpedance between the transmit and sensing ports is hence diminished and the transmit power is spatially canceled in the sensing direction before arriving at the sensing antenna. This is different from active filtering where the leaked power is canceled after the sensing port in the RF front-end and also different from the passive antenna cancellation [89] in the sense that the destructive interference is designed by properly weighting the transmit antennas rather than by physically locating the transmit antennas at proper distances from the sensing antenna. Consequently, as long as the frequency response of the phase-shifting components and the antennas is wideband, this results in a wideband performance. Part of the antenna isolation is owed to the mutual coupling loss between the antennas; in addition, an adaptive spatial filter that selectively nulls the transmit signal in the sensing direction can be formed, as shown in the example in Figure 14(a) for which two antennas are dedicated for data transmission and the third antenna is dedicated for sensing. The null steering should be performed in an adaptive manner according to the scattering channel environment; thus adaptive antenna cancellation should be implemented in a real-life scenario. The two transmit signals should be equal and out-phased by π radians. Inspecting Figure 14(b) showing the power beampattern of the transmit antennas under such excitation, it is clearly shown that an artificial null is formed toward the sensing antenna via the spatial filter thus enhancing the antenna isolation.

6. Conclusions

In this paper, a literature review of the RF front-end of CR systems has been investigated. Starting with a brief description of CR systems, an extensive review of the antennas, amplifiers, and mixers design schemes used in CR systems has been presented. Moreover, an investigation of some of the challenges facing the design of RF front-end for CR systems in the near future has been illustrated. It is very clear that the design issues include but are not limited to power efficiency, chip dimension, phase noise, and the reconfigurability, yet the power amplifier remains one of the main bottlenecks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] M. Kitsunezuka, K. Kunihiro, and M. Fukaishi, "Efficient use of the spectrum," *IEEE Microwave Magazine*, vol. 13, no. 1, pp. 55–63, 2012.

[2] N. Abbas, Y. Nasser, and K. E. Ahmad, "Recent advances on artificial intelligence and learning techniques in cognitive radio networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, article 174, 2015.

[3] E2R-II Project White Paper, "RF transceiver architecture for cognitive radio user equipment," June 2007.

[4] B. Razavi, "Cognitive radio design challenges and techniques," *IEEE Journal of Solid-State Circuits*, vol. 45, no. 8, pp. 1542–1553, 2010.

[5] E. T. Rahardjo, F. Y. Zulkifli, and A. Widiastri, "Printed antenna design for cognitive radio application at 1.8 GHz and 2.35 GHz spectrum allocation," in *Proceedings of the Asia-Pacific Microwave Conference (APMC '11)*, pp. 1881–1884, Melbourne, Australia, December 2011.

[6] D. T. Le and Y. Karasawa, "Design of a broadband reconfigurable antenna for cognitive radio," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI '12)*, pp. 1–2, Chicago, Ill, USA, July 2012.

[7] H. F. Abutarboush, S. Khan, R. Nilavalan, H. S. Al-Raweshidy, and D. Budimir, "Reconfigurable wideband patch antenna for radio congnitive," in *Proceedings of the Loughborough Antennas and Propagation Conference (LAPC '09)*, pp. 141–144, Loughborough, UK, November 2009.

[8] Y. Tawk, J. Costantine, K. Avery, and C. G. Christodoulou, "Implementation of a cognitive radio front-end using rotatable controlled reconfigurable antennas," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 5, pp. 1773–1778, 2011.

[9] Y. Tawk, J. Costantine, S. Hemmady, G. Balakrishnan, K. Avery, and C. G. Christodoulou, "Demonstration of a cognitive radio front end using an optically pumped reconfigurable antenna system (OPRAS)," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1075–1083, 2012.

[10] P.-C. Huang, Z.-M. Tsai, K.-Y. Lin, and H. Wang, "A high-efficiency, broadband CMOS power amplifier for cognitive radio applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 12, pp. 3556–3565, 2010.

[11] H. Zhang, H. Gao, and G.-P. Li, "A novel tunable broadband power amplifier module operating from 0.8 GHz to 2.0 GHz," in *Proceedings of the IEEE MTT-S International Microwave Symposium Digest*, pp. 661–664, Long Beach, Calif, USA, June 2005.

[12] I. S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in *Magnetism, Volume III*, G. T. Rado and H. Suhl, Eds., pp. 271–350, Academic Press, New York, NY, USA, 1963.

[13] J. Choi, K. Lim, and J. Laskar, "A ring VCO with wide and linear tuning characteristics for a cognitive radio system," in *Proceedings of the IEEE Radio Frequency Integrated Circuits Symposium (RFIC '08)*, pp. 395–398, Atlanta, Ga, USA, June 2008.

[14] B. Razavi, "Challenges in the design of cognitive radios," in *Proceedings of the IEEE Custom Integrated Circuits Conference (CICC '09)*, pp. 391–398, San Jose, Calif, USA, September 2009.

[15] E. P. Tsakalaki, O. N. Alrabadi, A. Tatomirescu, E. de Carvalho, and G. F. Pedersen, "Antenna cancellation for simultaneous cognitive radio communication and sensing," in *Proceedings of the International Workshop on Antenna Technology (iWAT '13)*, pp. 215–218, Karlsruhe, Germany, March 2013.

[16] J. R. Kelly, E. Ebrahimi, P. S. Hall, P. Gardner, and F. Ghanem, "Combined wideband and narrowband antennas for cognitive radio applications," in *Proceedings of the IET Seminar on Cognitive Radio and Software Defined Radio: Technologies and Techniques*, pp. 1–4, London, UK, September 2008.

[17] P. S. Hall, P. Gardner, J. Kelly, E. Ebrahimi, M. R. Hamid, and F. Ghanem, "Antenna challenges in cognitive radio," in *Proceedings of the International Symposium on Antenna and Propagation (ISAP '08)*, October 2008.

[18] M. Komulainen, M. Berg, H. Jantunen, E. T. Salonen, and C. Free, "A frequency tuning method for a planar inverted-F antenna," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 4, pp. 944–950, 2008.

[19] N. Behdad and K. Sarabandi, "Dual-band reconfigurable antenna with a very wide tunability range," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 409–416, 2006.

[20] M. Ali, A. T. M. Sayem, and V. K. Kunda, "A reconfigurable stacked microstrip patch antenna for satellite and terrestrial links," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 426–435, 2007.

[21] S. Nikolaou, R. Bairavasubramanian, C. Lugo Jr. et al., "Pattern and frequency reconfigurable annular slot antenna using pin diodes," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 439–448, 2006.

[22] C.-J. Wang and W.-T. Tsai, "A slot antenna module for switchable radiation patterns," *IEEE Antennas and Wireless Propagation Letters*, vol. 4, no. 1, pp. 202–204, 2005.

[23] S.-H. Chen, J.-S. Row, and K.-L. Wong, "Reconfigurable square-ring patch antenna with pattern diversity," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 2, pp. 472–475, 2007.

[24] S.-H. Hsu and K. Chang, "A novel reconfigurable microstrip antenna with switchable circular polarization," *IEEE Antennas and Wireless Propagation Letters*, vol. 6, pp. 160–162, 2007.

[25] E. Ebrahimi and P. S. Hall, "A dual port wide-narrowband antenna for cognitive radio," in *Proceedings of the 3rd European Conference on Antennas and Propagation (EuCAP '09)*, pp. 809–812, March 2009.

[26] H. F. Abu Tarboush, S. Khan, R. Nilavalan, H. S. Al-Raweshidy, and D. Budimir, "Reconfigurable wideband patch antenna for cognitive radio," in *Proceedings of the Loughborough Antennas & Propagation Conference (LAPC '09)*, pp. 141–144, Loughborough, UK, November 2009.

[27] G. T. Wu, R. L. Li, S. Y. Eom et al., "Switchable quad-band antennas for cognitive radio base station applications," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 5, pp. 1468–1476, 2010.

[28] M. Al-Husseini, A. Ramadan, K. Y. Kabalan, A. El-Hajj, Y. Tawk, and C. G. Christodoulou, "A simple dual-port antenna system for cognitive radio applications," in *Proceedings of the International Conference on High Performance Computing and Simulation (HPCS '11)*, pp. 549–552, IEEE, Caen, France, July 2010.

[29] A. H. Ramadan, M. Al-Husseini, K. Y. Kabalan et al., "A narrowband frequency-tunable antenna for cognitive radio applications," in *Proceedings of the 6th European Conference on Antennas and Propagation (EuCAP '12)*, pp. 3273–3277, Prague, Czech Republic, March 2012.

[30] T. Aboufoul, A. Alomainy, and C. Parini, "Reconfiguring UWB monopole antenna for cognitive radio applications using GaAs FET switches," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 392–394, 2012.

[31] M. Y. Abou Shahine, M. Al-Husseini, Y. Nasser, K. Y. Kabalan, and A. El-Hajj, "A reconfigurable miniaturized spiral monopole antenna for tv white spaces," in *Proceedings of the Progress in Electromagnetics Research Symposium (PIERS '13)*, pp. 1026–1029, Stockholm, Sweden, August 2013.

[32] Y. Tawk and C. G. Christodoulou, "A new reconfigurable antenna design for cognitive radio," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, no. 1, pp. 1378–1381, 2009.

[33] Y. Tawk, J. Costantine, and C. G. Christodoulou, "A frequency reconfigurable rotatable microstrip antenna design," in *Proceedings of the IEEE International Symposium on Antennas and Propagation*, p. 14, July 2010.

[34] Y. Tawk and C. G. Christodoulou, "A cellular automata reconfigurable microstrip antenna design," in *Proceedings of the IEEE International Symposium on Antennas and Propagation*, pp. 1–4, IEEE, Charleston, SC, USA, June 2009.

[35] C. J. Panagamuwa, A. Chauraya, and J. C. Vardaxoglou, "Frequency and beam reconfigurable antenna using photoconducting switches," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 449–454, 2006.

[36] R. N. Lavallee and B. A. Lail, "Optically-controlled reconfigurable microstrip patch antenna," in *Proceedings of the IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting (APSURSI '08)*, pp. 1–4, San Diego, Calif, USA, July 2008.

[37] L. N. Pringle, P. H. Harms, S. P. Blalock et al., "A reconfigurable aperture antenna based on switched links between electrically small metallic patches," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 6, pp. 1434–1445, 2004.

[38] R. L. Haupt and J. R. Flemish, "Reconfigurable and adaptive antennas using materials with variable conductivity," in *Proceedings of the 2nd NASA/ESA Conference on Adaptive Hardware and Systems*, pp. 20–26, IEEE, Edinburgh, UK, August 2007.

[39] Y. Tawk, A. R. Albrecht, S. Hemmady, G. Balakrishnan, and C. G. Christodoulou, "Optically pumped reconfigurable antenna systems (OPRAS)," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI '10)*, pp. 1–4, IEEE, Toronto, Canada, July 2010.

[40] D. E. Anagnostou, G. Zheng, M. T. Chryssomallis et al., "Design, fabrication, and measurements of an RF-MEMS-based self-similar reconfigurable antenna," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 422–432, 2006.

[41] M.-I. Lai, T.-Y. Wu, J.-C. Hsieh, C.-H. Wang, and S.-K. Jeng, "Design of reconfigurable antennas based on an L-shaped slot and PIN diodes for compact wireless devices," *IET Microwaves, Antennas & Propagation*, vol. 3, no. 1, article 47, 2009.

[42] J. J. Xu, Y.-F. Wu, S. Keller et al., "1-8-GHz GaN-based power amplifier using flip-chip bonding," *IEEE Microwave and Wireless Components Letters*, vol. 9, no. 7, pp. 277–279, 1999.

[43] M. J. Schindler, J. P. Wendler, M. P. Zaitlin, M. E. Miller, and J. R. Dormail, "A K/KA-band distributed power amplifier with capacitive drain coupling," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, no. 12, pp. 1902–1907, 1988.

[44] M. Hirata, T. Oka, M. Hasegawa et al., "Fully-integrated GaAs HBT power amplifier MMIC with high linear output power for 3 GHz-band broadband wireless applications," *Electronics Letters*, vol. 42, no. 22, pp. 1286–1287, 2006.

[45] A. Vasylyev, P. Weger, and W. Simbürger, "Ultra-broadband 20.5-31 GHz monolithically-integrated CMOS power amplifier," *Electronics Letters*, vol. 41, no. 23, pp. 1281–1282, 2005.

[46] J.-W. Lee, L. F. Eastman, and K. J. Webb, "A gallium-nitride push-pull microwave power amplifier," *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 11, pp. 2243–2249, 2003.

[47] J.-W. Lee and K. J. Webb, "Broadband GaN HEMT push-pull microwave power amplifier," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 9, pp. 367–369, 2001.

[48] A. Sayed and G. Boeck, "Two-stage ultrawide-band 5-W power amplifier using SiC MESFET," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 7, pp. 2441–2449, 2005.

[49] Y.-J. E. Chen, L.-Y. Yang, and W.-C. Yeh, "An integrated wide-band power amplifier for cognitive radio," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 10, pp. 2053–2058, 2007.

[50] M. Y. Abou-Shahine, Y. Nasser, and K. Y. Kabalan, "A high efficiency doherty power amplifier for tv band applications," *Journal of Electromagnetic Analysis and Applications*, vol. 7, no. 12, pp. 291–301, 2015.

[51] A. Cipriano, J. Gasnier, and T. Erseghe, "Interference control in time windowed OFDM systems with realistic power amplifiers for cognitive radio applications," in *Proceedings of the 17th International Conference on Software, Telecommunications and Computer Networks (SoftCOM '09)*, pp. 181–185, September 2009.

[52] K. Yamamoto, T. Shimura, T. Asada et al., "A 3.2-V operation single-chip AlGaAs/GaAs HBT MMIC power amplifier for GSM900/1800 dual-band applications," in *Proceedings of the IEEE MTT-S International Microwave Symposium Digest*, vol. 4, pp. 1397–1400, Anaheim, Calif, USA, June 1999.

[53] Z. Shuyun, P. Bretchko, J. Mokoro, and R. McMorrow, "A novel power amplifier module for quad-band wireless handset applications," in *Proceedings of the IEEE Radio Frequency Integrated Circuits Symposium (RFIC '03)*, vol. 59, pp. 129–132, IEEE, June 2003.

[54] T. Arell and T. Hongsmatip, "A unique MMIC broadband power amplifier approach," *IEEE Journal of Solid-State Circuits*, vol. 28, no. 10, pp. 1005–1010, 1993.

[55] X. Zhu, X. Chen, and J. Ling, "2–6 GHz GaAs MMIC power amplifier," in *Proceedings of the 2nd International Conference on Microwave and Millimeter Wave Technology (ICMMT '00)*, pp. 134–137, Beijing, China, 2000.

[56] F. Bruccoleri, E. A. M. Klumperink, and B. Nauta, "Wide-band CMOS low-noise amplifier exploiting thermal noise canceling," *IEEE Journal of Solid-State Circuits*, vol. 39, no. 2, pp. 275–282, 2004.

[57] Y. Liao, Z. Tang, and H. Min, "A wide-band CMOS low-noise amplifier for TV tuner applications," in *Proceedings of the IEEE Asian Solid-State Circuits Conference (ASSCC '06)*, pp. 259–262, Hangzhou, China, November 2006.

[58] K. Wang and Z. Wang, "148 kHz-1.5 GHz broadband CMOS differential LNA for DRM/DAB tuner," in *Proceedings of the 4th IEEE International Conference on Circuits and Systems for Communications (ICCSC '08)*, pp. 816–819, Shanghai, China, May 2008.

[59] Y.-J. E. Chen, L.-Y. Yang, and W.-C. Yeh, "A CMOS low-noise amplifier for spectral sensing in cognitive radios," in *Proceedings of the Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics*, pp. 37–40, Shanghai, China, November 2009.

[60] A. Ansari and M. Yavari, "A very wideband low noise amplifier for cognitive radios," in *Proceedings of the 18th IEEE International Conference on Electronics, Circuits and Systems (ICECS '11)*, pp. 623–626, IEEE, Beirut, Lebanon, December 2011.

[61] A. Sahai and D. Cabric, "Spectrum sensing-fundamental limits and practical challenges," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN '05)*, Baltimore, Md, USA, November 2005.

[62] J. Craninckx and M. S. J. Steyaert, "A 1.8-GHz low-phase-noise CMOS VCO using optimized hollow spiral inductors," *IEEE Journal of Solid-State Circuits*, vol. 32, no. 5, pp. 736–744, 1997.

[63] A. Bevilacqua, F. P. Pavan, C. Sandner, A. Gerosa, and A. Neviani, "A 3.4–7 GHz transformer-based dual-mode wideband VCO," in *Proceedings of the 32nd IEEE European Solid-State Circuits Conference (ESSCIRC '06)*, pp. 440–443, IEEE, September 2006.

[64] F. Tzeng, D. Pi, A. Safarian, and P. Heydari, "Theoretical analysis of novel multi-order LC oscillators," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 54, no. 3, pp. 287–291, 2007.

[65] A. Bevilacqua, F. P. Pavan, C. Sandner, A. Gerosa, and A. Neviani, "Transformer-based dual-mode voltage-controlled oscillators," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 54, no. 4, pp. 293–297, 2007.

[66] N. T. Tchamov, S. S. Broussev, I. S. Uzunov, and K. K. Rantala, "Dual-band LC VCO architecture with a fourth-order resonator," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 54, no. 3, pp. 277–281, 2007.

[67] S. Rong and H. C. Luong, "A 1V 4GHz-and-10GHz transformer-based dual-band quadrature VCO in 0.18 μm CMOS," in *Proceedings of the IEEE Custom Integrated Circuits Conference (CICC '07)*, pp. 817–820, IEEE, San Jose, Calif, USA, September 2007.

[68] J. Borremans, A. Bevilacqua, S. Bronckers et al., "A compact wideband front-end using a single-inductor dual-band VCO in 90 nm digital CMOS," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 12, pp. 2693–2705, 2008.

[69] Z. Safarian and H. Hashemi, "Wideband multi-mode CMOS VCO design using coupled inductors," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 56, no. 8, pp. 1830–1843, 2009.

[70] S. Rong and H. C. Luong, "Analysis and design of transformer-based dual-band VCO for software-defined radios," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 3, pp. 449–462, 2012.

[71] K. Okada and A. Matsuzawa, "Reconfigurable RF CMOS circuit design for cognitive radios," in *Proceedings of the International SoC Design Conference (ISOCC '09)*, pp. 96–99, IEEE, Busan, South Korea, November 2009.

[72] D. Guermandi, P. Tortori, E. Franchi, and A. Gnudi, "A 0.83-2.5-GHz continuously tunable quadrature VCO," *IEEE Journal of Solid-State Circuits*, vol. 40, no. 12, pp. 2620–2626, 2005.

[73] Y. Ito, H. Sugawara, K. Okada, and K. Masu, "A 0.98 to 6.6 GHz tunable wideband VCO in a 180 nm CMOS technology for reconfigurable radio transceiver," in *Proceedings of the IEEE Asian Solid-State Circuits Conference Digest of Technical Papers (ASSCC '06)*, pp. 359–362, IEEE, Hangzhou, China, November 2006.

[74] H. Q. Liu, W. L. Goh, L. Siek, W. M. Lim, and Y. P. Zhang, "A lownoise multi-GHz CMOS multiloop ring oscillator with coarse and fine frequency tuning," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 17, no. 4, pp. 571–577, 2009.

[75] S. Liang and W. Redman-White, "A linear tuning ring VCO for spectrum monitor receiver in cognitive radio applications," in *Proceedings of the 20th European Conference on Circuit Theory and Design (ECCTD '11)*, pp. 65–68, IEEE, August 2011.

[76] S. Cui, B. Banerjee, and V. Acharya, "A linearized current-controlled oscillator for ultra-low power wideband and cognitive radios," in *Proceedings of the 55th International Midwest Symposium on Circuits and Systems (MWSCAS '12)*, pp. 146–149, IEEE, August 2012.

[77] J. Lu, N.-Y. Wang, and M.-C. F. Chang, "A compact and low power 5–10 GHz quadrature local oscillator for cognitive radio applications," *IEEE Journal of Solid-State Circuits*, vol. 47, no. 5, pp. 1131–1140, 2012.

[78] L. Xu, K. Stadius, T. Rapinoja, and J. Ryynänen, "Agile frequency synthesizer for cognitive radios," in *Proceedings of the European Conference on Circuit Theory and Design Conference Program (ECCTD '09)*, pp. 275–278, Antalya, Turkey, August 2009.

[79] L. Xu, K. Stadius, and J. Ryynänen, "A low-power wide-band digital frequency synthesizer for cognitive radio sensor units," in *Proceedings of the 35th European Solid-State Circuits Conference (ESSCIRC '09)*, pp. 184–187, IEEE, September 2009.

[80] C.-H. Park and B. Kim, "A low-noise, 900-MHz VCO in 0.6-μm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 34, no. 5, pp. 586–591, 1999.

[81] I.-C. Hwang, C. Kim, and S.-M. S. Kang, "A CMOS self-regulating VCO with low supply sensitivity," *IEEE Journal of Solid-State Circuits*, vol. 39, no. 1, pp. 42–48, 2004.

[82] M.-L. Sheu, T.-W. Lin, and W.-H. Hsu, "Wide frequency range voltage controlled ring oscillators based on transmission gates," in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS '05)*, pp. 2731–2734, Kobe, Japan, May 2005.

[83] A. Acampora, A. Collado, and A. Georgiadis, "Nonlinear analysis and optimization of a distributed voltage controlled oscillator for cognitive radio," in *Proceedings of the IEEE International Microwave Workshop Series on RF Front-ends for Software Defined and Cognitive Radio Solutions (IMWS '10)*, pp. 1–4, Aveiro, Portugal, February 2010.

[84] F.-K. Wang, C.-T. Chen, J.-R. Tsai et al., "A CMOS spectrum sensor using injection locking of two voltage-controlled oscillators for cognitive radio system," in *Proceedings of the IEEE Radio Frequency Integrated Circuits Symposium (RFIC '11)*, pp. 1–4, IEEE, Baltimore, Md, USA, June 2011.

[85] P. Pawelczak, K. Nolan, L. Doyle, S. Oh, and D. Cabric, "Cognitive radio: ten years of experimentation and development," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 90–100, 2011.

[86] V. T. Nguyen, F. Villain, and Y. L. Guillou, "Cognitive radio RF: overview and challenges," *VLSI Design*, vol. 2012, Article ID 716476, 13 pages, 2012.

[87] E. Tsakalaki, O. N. Alrabadi, A. Tatomirescu, E. de Carvalho, and G. F. Pedersen, "Concurrent communication and sensing in cognitive radio devices: challenges and an enabling solution," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 3, pp. 1125–1137, 2014.

[88] A. Ali, O. Hammi, and T. Y. Al-Naffouri, "Compressed sensing based joint-compensation of power amplifier's distortions in OFDMA cognitive radio systems," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 3, no. 4, pp. 508–520, 2013.

[89] L. Zhang, Y.-C. Liang, and Y. Xin, "Joint beamforming and power allocation for multiple access channels in cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 38–51, 2008.

[90] B. Razavi, "Multi-decade carrier generation for cognitive radios," in *Proceedings of the Symposium on VLSI Circuits*, pp. 120–121, Kyoto, Japan, June 2009.

[91] C.-C. Lin and C.-K. Wang, "A regenerative semi-dynamic frequency divider for mode-1 MB-OFDM UWB hopping carrier generation," in *Proceedings of the IEEE International Solid-State Circuits Conference, 2005. Digest of Technical Papers (ISSCC '05)*, pp. 206–207, San Francisco, Calif, USA, February 2005.

[92] B. Razavi, "Design of millimeter-wave CMOS radios: a tutorial," *IEEE Transactions on Circuits and Systems. I. Regular Papers*, vol. 56, no. 1, pp. 4–16, 2009.

[93] W. Lee and D.-H. Cho, "Enhanced spectrum sensing scheme in cognitive radio systems with MIMO antennae," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 3, pp. 1072–1085, 2011.

[94] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the 16th Annual International Conference on Mobile Computing and Networking (MobiCom '10)*, pp. 1–12, September 2010.

[95] M. Y. Abou-Shahine, M. Al-Husseini, A. H. Ramadan, K. Y. Kabalan, and Y. Nasser, "Antenna designs for cognitive radio application in the TV band," *International Journal of Scientific & Engineering Research*, vol. 6, no. 2, pp. 975–980, 2015.

[96] M. Haroun, H. Kobeissi, O. Bazzi et al., "Effect of RF impairments on spectrum sensing techniques," in *Proceedings of the Wireless Telecommunications Symposium (WTS '14)*, pp. 1–6, IEEE, Washington, DC, USA, April 2014.

[97] L. Safatly, B. Aziz, A. Nafkha et al., "Blind spectrum sensing using symmetry property of cyclic autocorrelation function: from theory to practice," *EURASIP Journal on Wireless Communications and Networking*, vol. 2014, no. 1, article 26, 2014.

[98] S. Zabre, J. Palicot, Y. Louet, C. Moy, and C. Lereau, "Carrier per carrier analysis of SDR signals power ratio," in *Proceedings of the SDR Forum Technical Conference*, Orlando, Fla, USA, 2006.

[99] T. Sowlati, B. Agarwal, J. Cho et al., "Single-chip multiband WCDMA/HSDPA/HSUPA/EGPRS transceiver with diversity receiver and 3G digRF interface without SAW filters in transmitter/3G receiver paths," in *Proceedings of the IEEE International Solid-State Circuits Conference (ISSCC '09)*, pp. 116–117, San Francisco, Calif, USA, February 2009.

[100] S. Shekhar, X. Li, and D. J. Allstot, "A fully-integrated uhf receiver with multi-resolution spectrum-sensing (MRSS) functionality for IEEE 802.22 cognitive-radio applications," in *Proceedings of the IEEE Radio Frequency Integrated Circuits Symposium, Digest of Technical Papers (RFIC '08)*, pp. 526–633, April 2008.

[101] S. Li, I. Kipnis, and M. Ismail, "A 10-GHz CMOS quadrature LC-VCO for multirate optical applications," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 10, pp. 1626–1634, 2003.

[102] N. Jindal, "MIMO broadcast channels with finite-rate feedback," *IEEE Transactions on Information Theory*, vol. 52, no. 11, pp. 5045–5060, 2006.