Circuit and System Design for Future Microwave Systems (Invited Paper)

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Abstract — **Microwave systems continue to benefit from technological and system advances that provide for new levels of performance, form factor and lowered cost. In the past, these advances were primarily associated with new materials systems or device types (e.q. GaAs, GaN, InP, MEMS, HBTs, PHEMTs, etc.). Although improvements continue in these and other new areas, system designers are increasingly looking for areas where advances in CMOS *digital IC* technology can improve the performance of *microwave* systems. The ability to realize millions of logic gates in an area the size of a bond pad provides the signal processing capability required for highly adaptive microwave systems, which monitor their environment and adapt their matching, tuning, bias, or configuration, to realize the best possible performance. These *adaptive* microwave systems will find wide application in areas as diverse as active phased-array radars, wireless local area networks and even the ubiquitous cellular telephone. This paper will summarize the device and signal processing requirements of these new adaptive systems of the future, and highlight some of the research areas required for further development of the field.**

I. INTRODUCTION

The breathtaking improvements in semiconductor material and device technology have enabled the revolution in modern microwave communications. However, these systems still largely rely on the traditional distinction between the microwave/analog front-end and the digital baseband processor. However, this distinction is slowly being eroded, as digital CMOS technology continues to advance and microwave devices reach fundamental physical and cost limits. These trends offer the opportunity for highly *adaptive* microwave systems to replace more traditional fixed system approaches.

An adaptive radio technology has the ability to "sense" its environment, and adapt its modulation, demodulation, and power dissipation in response to the resulting requirements. At the same time, it can also "monitor," and subsequently improve, its own performance. Of course, concepts like "sense" and "monitor" are inherently vague in the context of a radio, and existing modern commercial digital communications systems already perform many of these functions in a rudimentary fashion. At the same time, several recent military communications systems exhibit a high degree of adaptivity, with the ability to tune over several GHz, and modulate and demodulate a variety of waveforms [1]. However, future military and commercial communications systems will take advantage of these approaches to a much greater degree, and their costs will be driven down to the consumer level through a variety of advances in technology.

This paper will discuss the technological developments required for the future deployment of these systems.

II. TRENDS IN RADIO AND SPECTRUM USE

The last few years have witnessed an emerging consensus that traditional methods of spectrum management are both technically and economically inefficient. The FCC has responded to this through several changes in spectrum management, including the well-known ultrawide band program, and the "cognitive radio" initiative at the beginning of 2004 [2].

Spectral occupancy measurements have demonstrated that many commercially licensed frequency bands at desirable frequencies are lightly occupied. For example, measurements by the NAF showed that less than 2% of the spectrum from 700-800 MHz, and less than 20% of the spectrum from 30 MHz to 1000MHz, was regularly utilized in a typical urban area [3]. So, although this spectrum has been completely allocated, it is lightly used. Similar results have been demonstrated for frequencies above 1 GHz.

These lightly used frequency bands represent a lost economic opportunity for new wireless services and industries, but an opportunity to create a wide range of new services if acceptable solutions can be found to wider use of the spectrum. In order to take advantage of this opportunity, technologies need to developed that can utilize the spectrum "opportunistically," without interfering with existing services and devices. The term "cognitive radio" was coined to describe a range of

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technologies that detect whether a particular segment of the radio spectrum is currently in use, and to jump into and out of the temporarily-unused spectrum very rapidly, without interfering with the transmission of other authorized users. Cognitive radio approaches are being developed for a variety of applications.

One simple example of this is in the commercial digital wireless area. In this case, the proliferation of multiple commercial RF wireless standards in a common device requires some fundamental architectural innovations. For example, a future cellular telephone might be required to communicate over four possible GSM bands, as well as UMTS, 802.11a,b,g, Bluetooth, WiMax and GPS. It is conceivable that each band could require its own separate RF transceiver and digital baseband processor, leading to a "Tower of Babel" situation. Some sort of common architecture may be required to address all of these differing standards.

At the same time, military systems suffer from similar challenges of the spectrum being fully allocated and occasionally crowded, but also lightly used at most times. For example, a typical heavy division operating in a 70 km by 45km battlefield environment was estimated to experience over 10,000 individual emitters in a shared spectrum [4]. The military also has the additional burden of being required to communicate effectively in differing geographical areas throughout the world. Improved spectrum utilization techniques will minimize this interference and at the same time improve the efficiency of the use of spectrum. There are currently several major government sponsored research programs addressing platforms for cognitive radio, including the DARPA XG Program [5].

A cognitive radio is able to gather information about its environment, modify its operation in response to that information, and communicate this knowledge to other radios, with the overall goal of improving spectrum utilization and minimizing interference. In an ideal world, a cognitive radio will estimate the power levels in a number of frequency bands, and use the resulting estimates along with a spectrum-sharing protocol and communication requirements to select the coding, modulation, power, and frequency band for transmission. Some elements of cognitive radio technology exist already, such as the dynamic frequency selection used by cordless telephones and the adaptive-transmission protocols designed for FH [6] and DS [7] spread-spectrum. In a less ambitious sense, cognitive radios of the future will simply be more highly adaptive to their environment than present radios, in order to improve communication system performance and cost.

III. Radio System Architectures For Adaptive Applications

At the highest level, a general "cognitive radio" architecture senses the spectral environment by some sort of scanned spectrum monitoring along with application of a Fourier Transform analysis on a joint time frequency (JTF) basis, as shown in Fig. 1 [8]. A major challenge for these systems is the design of receivers for wideband spectral monitoring. Conceptually, this task is easily performed using the Discrete Fourier Transform (DFT) on the entire downconverted signal, but this will require a high-precision high-speed A/D converter and analog baseband section, which raises the cost and power dissipation considerably. The alternative is to use a lower-rate sampling ADC along with a tunable narrowband analog filter, with the resulting limitations of cost, accuracy and dynamic range. Methods for examining spectral activity at multiple resolutions in frequency and time need to be developed in order to ease the hardware burden of these systems. Also, if the spectrum is being monitored for a specific kind of activity – for example, the presence of an analog TV signal - then knowledge of the structure of the expected signal can be used to increase the spectrum monitor's sensitivity without an increase in ADC resolution or sampling rate.

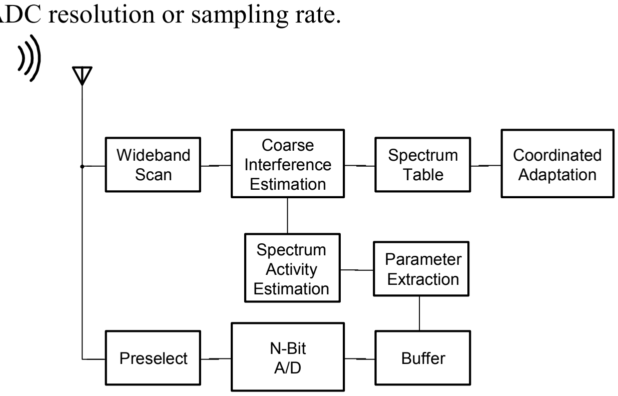

Fig. 1: General system architecture of "cognitive radio" [8].

The resulting information can be used in the receiver for interference mitigation and spectrum planning for the transmitted waveform. Conventional suppression narrowband interference again requires a costly A/D conversion, hence novel approaches beyond classical multi-user detection are required. For example, analog techniques or DSP techniques with coarse A/D could be used to estimate and subtract a strong interferer (exploiting its structure if known), with powerful error-control coding employed to handle the error floor that results from imperfect interference cancellation [9]. An enormous body of work on interference mitigation has been developed, including optimal multiuser detection [10] as well as linear interference suppression [11] and nonlinear cancellation [12].

At the next level down in the radio system design, the increasing sophistication of digital technology also means that many of the "back-end" functions currently performed in the analog-IF domain will be increasingly performed in the digital domain. This has two advantages. The first is that the sophisticated digital processing can compensate for limitations in the analog/RF domain. The second is that the power dissipation and cost of this digital processing will reduce dramatically and "scale" along with digital CMOS technology.

For example, as shown in Fig. 2, a digital low-IF receiver can perform channel selection filtering and adaptive image cancellation, compensating for I/Q mismatches in the analog-RF domain [13]. Several different algorithms have been developed for low-IF image cancellation approaches. This has significant advantages over the zero-IF solution for highly agile radio applications, since problems of second-order distortion, 1/f noise and time-varying dc offsets are less of a concern. The disadvantage is that the image cancellation is performed in the digital domain, requiring a much higher resolution ADC.

A digital IF approach can also be used in the transmitter as shown in Fig. 3 [14], where significant advantages occur because of the inherently perfect I/Q matching. As with all digital-IF approaches, the power dissipation must be carefully managed. A novel "bandpass DAC" structure was proposed in [14] for a digital-IF approach that exhibited extremely low power, excellent resolution and eliminated the need for post-conversion reconstruction filtering. Future highly integrated transceivers will exhibit these types of circuit architectures, where the RF/analog architecture is influenced by the capabilities of the digital processing.

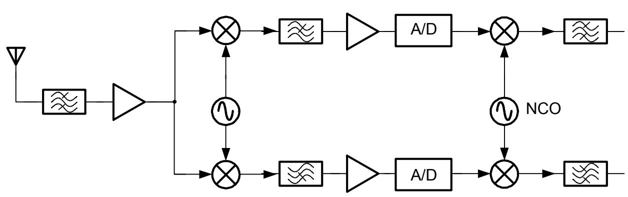

Fig. 2: Digital IF receiver architecture. In this case, the final stage of downconversion and image rejection is done in the digital domain. This places a greater burden on the ADC than more traditional approaches.

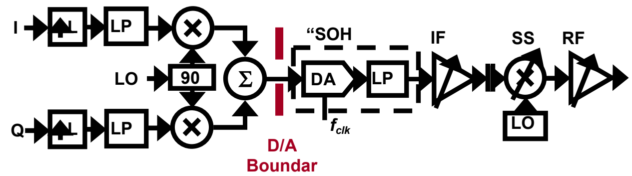

Fig. 3: Digital IF transmitter architecture from [14]. In this case, I/Q modulation of the IF is performed in the digital domain. This places a greater burden on the DAC than traditional approaches, though improved DAC architectures can minimize this limitation.

IV RF Technologies Required for Future Reconfigurable Radio Systems.

As the previous Section has demonstrated, one of the major "pressure points" in future adaptive or cognitive systems is the the A/D converter. A recent study on the possibility of a "software-defined" multi-mode GPRS/WCDMA/802.11A transceiver demonstrated that a 14-bit 150 Msps ADC, with a power consumption of less than 50 mW is required for this application [15]. This level of performance is not achievable today with low-cost ADC technology, but given the fact that the power consumption *per Msample/sec* halves roughly every two years, this level of performance will be achievable in the not-too-distant future [16]. This gap between the performance of ADCs and the requirements of the software-defined radio has historically limited the application of this approach. Clearly, a "breakthrough" in ADC performance would remove a significant barrier to the implementation of these multi-standard and reconfigurable systems.

Tunable front-end filters and impedance matching elements are another key technology required for practical dynamic reconfigurable radios of the future. In this case technological improvements are required on several fronts in order to meet stringent performance specifications. For example, a receive filter for multi-band cellular applications might have to tune its center frequency over several different receive bands, and insert notches at transmit frequencies to avoid cross-modulation distortion [17]. Furthermore, the linearity and loss of these tunable filters has to be comparable to that of fixed SAW filters. To give another example, a power amplifier in these systems will have to vary its center frequency and impedance match in response to differing requirements.

Several different alternative approaches have been developed for these filters and tuners, including MEMs-based [18,19], voltage variable dielectric [20] and varactor-based [21,22,23]. MEMS based tunable filters exhibit outstanding loss and linearity, but their reliability and manufacturability remains problematic. Varactor-diode based tunable filters and tuning networks have recently been demonstrated with excellent linearity and insertion loss in a silicon-based technology [22,23]. In this case, the linearity is improved to the point where a varactor diode based approach can be used even for large-signal applications that are sensitive to linearity, such as power amplifiers and front-end filters for wide dynamic range receivers.

The limitation of all these approaches is that they all require specialized wafer processing, so some sort of hybrid approach is required to connect the tunable filter and matching network to the transceiver. Creative work is still required here, and the lack of a low-cost, wide dynamic range, manufacturable tunable RF filter technology represents a major hurdle for the widespread deployment of cognitive radio technology.

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