

# RF Technology Enablers for Software-Defined Radios

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**SUMMARY** RF system and circuit approaches for cognitive radios, based on software defined radio technology, are discussed. The increasing use of digital techniques, combined with wideband data converters and tunable front-end technologies, will enable these systems to become cost effective in the coming years.

**key words:** *cognitive radio, RF MEMS, radio transceiver, varactor*

## 1. Introduction

The last few years have witnessed an emerging consensus that traditional methods of spectrum management are both technically and economically inefficient. In the United States, 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. The background behind this initiative, and cognitive radio technology in general is given in [1]. 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 1000 MHz, was regularly utilized in a typical urban area [2]. 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 widen the use of the spectrum. In order to take advantage of this opportunity, technologies need to be 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 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, digital TV, 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.

The use of cognitive radio technology — based on software defined radios — represents a departure from the traditional model of spectrum use and allocation. In the United States, the traditional use of spectrum is based on the Radio Act of 1912 and its successors, which allocated particular frequencies to specific users to prevent interference. The economic and social consequences of this allocation of the spectrum were low-cost consumer devices and assured quality of service for public safety. At the same time, the result was an inefficient use of spectrum, which quickly became a precious resource. The mobile terminals that operate in this environment can be “dumb” — little network awareness is required and frequency, modulation, and receiver standards can be set at the time of manufacture.

By contrast, a cognitive radio technology will be able to fill in the underutilized “white spaces” in the licensed spectrum with unlicensed nodes. This will provide economic incentives for delivery of new services and technology. Technically, the mobile terminals must be “smart” — network awareness will be required and cooperation, negotiation, and reconfigurability are necessary. Frequency, modulation, and receiver standards will be context dependent.

A cognitive radio could negotiate cooperatively with other spectrum users to enable more efficient sharing of spectrum. It could also identify portions of the spectrum that are unused at a specific time or location and transmit in such unused “white spaces,” resulting in more intense, more efficient use of the spectrum while avoiding interference to other users. Cognitive radio technology could also be used to facilitate interoperability between or among communication systems in which frequency bands and/or transmission formats differ. For example, a cognitive radio could select the appropriate operating frequency and transmission format, or it could act as a “bridge” between two systems by receiving signals at one frequency and format and retransmitting them at a different frequency and format. Finally, cognitive radio technology can facilitate the use of

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secondary markets in spectrum and improve access to spectrum in rural areas. A block diagram of a typical cognitive radio system is shown in Fig. 1 [3].

What are the analog and RF hardware consequences of this new radio technology? Very wide baseband bandwidths (> 100 MHz) will be required to accommodate the wide tuning range. Tuning bandwidths of several GHz will be required with high performance, low-cost and low dc power consumption. Multiple antennas, and perhaps MIMO, will be required at the handset. The critical performance drivers will move into tunable passives for RF re-configuration and wideband data converters, rather than the active modulation and demodulation functions. A typical SDR might be required to tune in a continuous range from 500 MHz to well over 5 GHz, and adapt its bandwidth, power, and modulation standard on an “as-needed” basis.

These software defined radios will require circuit techniques that facilitate RF adaptivity. Examples of adaptive circuits that might be suitable for SDR applications include wide bandwidth data converters, tunable filters, tunable passive matching networks for low-noise and power amplifiers, and multi-band VCO’s. An ideal tuning element for these applications will exhibit extremely low loss, nearly zero dc power consumption, a very high linearity to accommodate the incredibly wide dynamic range of the signal, ruggedness to high voltage and high current carrying capabilities, wide tuning range (consistent with a frequency range of over a decade), high reliability, very low cost, low area usage, and have a tuning speed that is consistent with adaptive applications.

This paper will summarize the RF technological opportunities and challenges presented by software defined radios. Section 2 will summarize radio architectures for software defined radio applications. Section 3 summarizes recent results on RF MEMS technologies, with particular emphasis on their application to reconfigurable radios. Section 4 summarizes the use of high dynamic range tunable varactor diodes for RF reconfigurability. Some combination of these technologies is required for the performance and cost-sensitive software defined radio of the future.

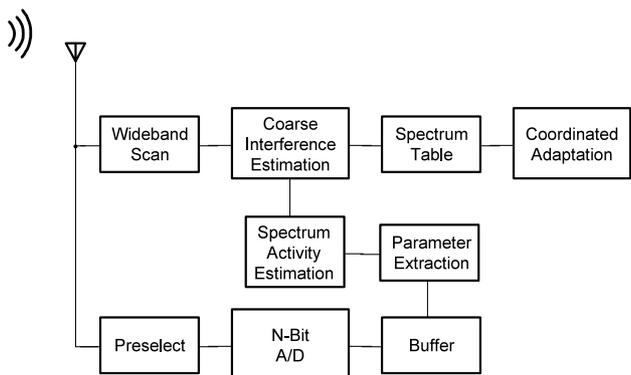


Fig. 1 General system architecture of “cognitive radio” [3].

## 2. Radio System Architectures for Software Defined Radio Applications

At the level of the radio system design, the increasing sophistication of digital technology 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 [4]. 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 [5], 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 [5] 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.

Clearly, one of the major “pressure points” in future

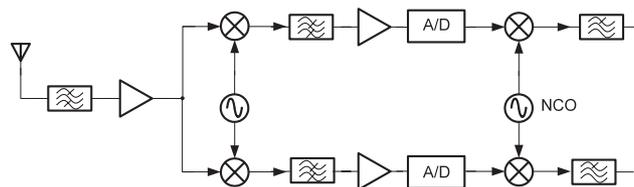


Fig. 2 Digital IF receiver architecture. In this case, the final stage of downconversion and image rejection is done in the digital domain. This places a greater burden on the ADC than more traditional approaches.

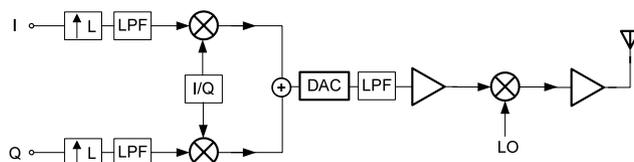
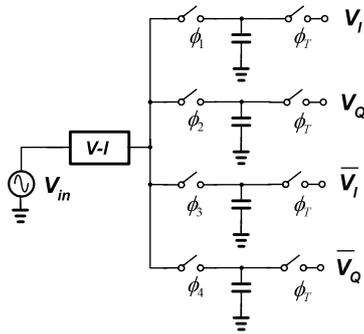


Fig. 3 Digital IF transmitter architecture from [5]. In this case, I/Q modulation of the IF is performed in the digital domain. This places a greater burden on the DAC than traditional approaches, though improved DAC architectures can minimize this limitation.



**Fig. 4** Sub-sampled quadrature downconverting mixer [8],[9]. The transfer function can be altered by changing the timing of the switches and the sub-sampling ratio.

adaptive or cognitive systems is 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 [6]. 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 [7]. 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 “break-through” in ADC performance would remove a significant barrier to the implementation of these multi-standard and reconfigurable systems.

One final monolithic receiver approach that has recently been proposed utilizes sub-sampling, combined with a passive switched-capacitor FIR filter for downconversion [8],[9], one example of which is shown in Fig. 4. Sub-sampling receivers have been proposed for many years, but the historical problem of noise accumulation limited their usefulness. These more recent approaches employ a relatively high sub-sample rate and a low-pass filter/integrator before the sampler to minimize the noise problems. In fact, if the pole frequency of the filter is set to the channel center frequency, the Noise Figure penalty of this approach is a modest 3.9 dB [8]. One advantage of this approach is that the transfer function of the downconverting mixer can be adjusted by changing the timing of the sampling gates. Another potential advantage is that the FIR filter consists completely of switches and capacitors, so it is passive and will scale easily with subsequent technology generations in silicon.

### 3. RF MEMS for Software Defined Radios

PIN Diodes or GaAs PHEMT switches are widely used today for adaptive RF circuit applications, most commonly in the T/R switch of Time-Division Duplex (TDD) systems like GSM and 802.11 wireless local area networks. These technologies have been developed over many decades, and have attained a high degree of sophistication and maturity.

However, these solutions are considered to be too expensive, or to consume too much dc power, to be an acceptable long term solution for cost and performance sensitive SDR applications. This limitation has triggered a search for adaptive tuning alternatives that do not suffer from the drawbacks of traditional tuning or switching approaches.

The widespread development of MEMS technologies promises one route for the development of new classes of SDR transceivers. This potential has been realized in a dramatic fashion in recent years, with research on MEMS for RF applications increasing very substantially [10].

One example is the MEMS switch, which in its most popular implementation is able to switch between two fixed capacitance or impedance values. RF MEMS capacitors provide a very high Quality Factors (Q) of between 300 and 600 and extraordinarily high linearity [11],[12], but they require non-standard processing and packaging techniques—hermetic packaging ideally—high control voltages, and their reliability and switching speed are still limited compared to semiconductor-based solutions. The substrate for fabrication of these devices can be GaAs, Silicon or Glass.

RF MEMS devices for tuning applications include switches, impedance tuners, and variable capacitors. The motive force used to move the structures on the wafer surface is typically electrostatic attraction, although magnetic, thermal, and even gas-based micro-actuator structures have been developed. However, the preferred approach today seems to be electrostatic actuation, with switching voltages typically in the range of 15–50 V although the dc power dissipation is essentially zero since the required switching current is entirely displacement current.

Several different RF MEMS switch architectures have been developed, including the air-bridge structure [13],[14] and the classic bending beam switch structure [15],[16]. The air-bridge structure utilizes a very high capacitance variation of approximately 150 : 1 to achieve the switching action.

RF MEMS technology promises to provide dramatically improved switching and filtering capabilities at the front end of radio receivers, as shown in Fig. 5. At typical cellular telephone or WLAN frequencies, the isolation of a MEMS switch can exceed 60 dB, and its insertion loss when “closed” is less than 0.3 dB. In addition, the intermodulation and distortion of these devices is virtually nonexistent, rendering their dynamic range more than adequate for the most demanding SDR receiver applications. A MEMS tunable bandpass filter could serve partial channel selection as well as “roofing” functions for an SDR receiver. A second benefit of the highly integrated MEMS filters is that many of them can be integrated on a single integrated circuit die, making the possibility of broadband RF channel or band selection a practical reality for the first time. Under normal circumstances, the use of this proposed architecture would appear to be absurdly impractical; all of the filters would be prohibitively expensive and require an enormous amount of board space.

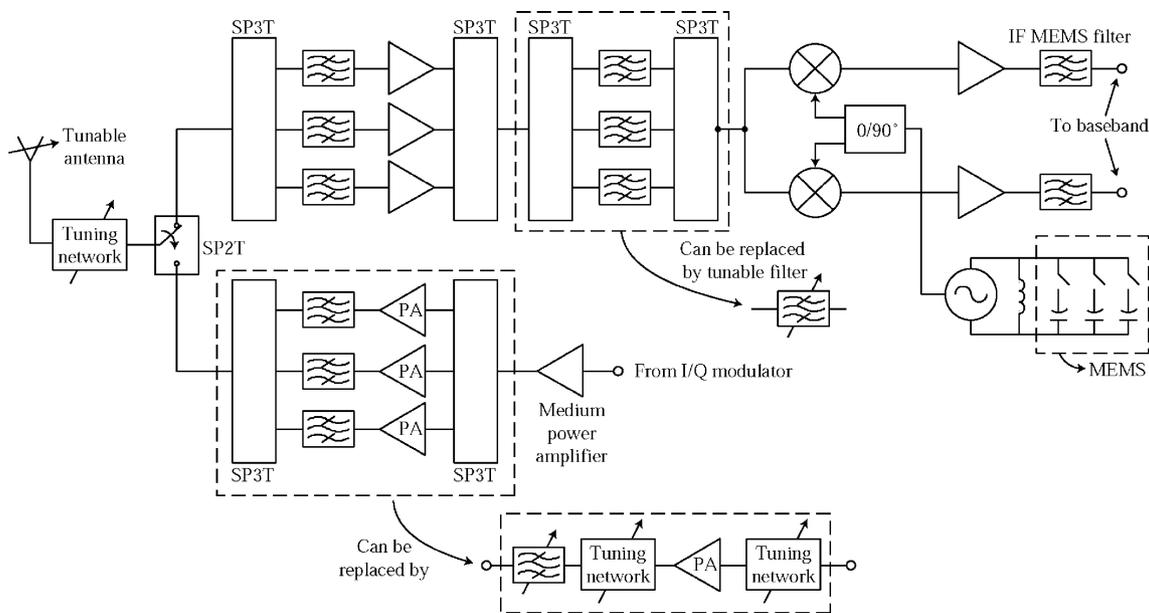


Fig. 5 Proposed MEMS-based receiver employing tunable front-end filter [10].

However, in this case, the use of MEMS technology allows the filters and switches to be implemented monolithically almost “for free,” and the dynamic range burden on the active mixer and channel filter is greatly reduced by the filtering action of the monolithic elements. In essence, the dynamic range requirements on the active devices are moved onto the passive devices — a very beneficial tradeoff!

On the transmitter side, the use of MEMS technology may allow for the realization of high-quality on-chip matching networks at the output of power amplifiers. It is this critical area that often limits the performance of power amplifiers, which is why power amplifiers have historically been implemented with off-chip power matching networks. The reliability of RF MEMS switches under high power switching action remains a challenging research problem.

Furthermore, the use of MEMS devices for mmW filtering and coupling can completely eliminate the need for expensive and bulky waveguide components, easing the realization of low-cost mmW systems.

#### 4. High-Quality Tunable RF Varactor Diodes for Software Defined Radios

In view of the need for high-quality adaptive RF circuits, varactor diodes would seem to be an attractive alternative to pin diodes, PHEMTs and even MEMS switches. However, their inherently nonlinearity behavior disqualifies them for use with modern communication standards, which are characterized by high peak-to-average power ratios. In addition, their Q factors are usually too low at RF (30–70 typically) for the most demanding applications. These factors have historically limited the application of varactor diodes to low performance system applications.

However, improved varactor diode-based circuit topologies, along with a high performance varactor diode

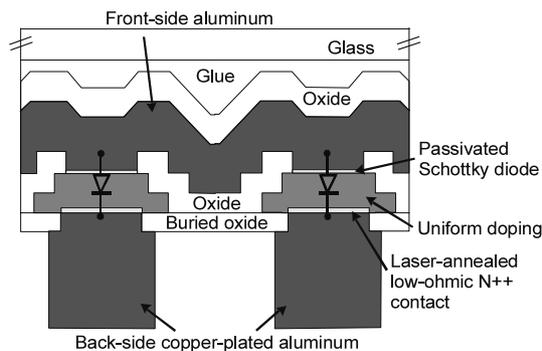


Fig. 6 Cross-section of high linearity silicon-on-glass varactor stack [18].

process technology, have recently been demonstrated with very low distortion [17]. In addition, a silicon-based process technology was demonstrated with diodes Q’s ranging from 100 to over 500 at 2 GHz, with capacitance values up to 50 pF, and with extremely low parasitic capacitances [18]. These developments revive interest in varactor diodes as a viable tuning approach for high-performance SDR front-ends.

This technology provides a low loss substrate and patterning of both the front and back sides of the wafer so the intrinsic varactor can be directly contacted by thick metal on both sides [19]. This eliminates the need for a buried layer or finger structures. The cross section is given in Fig. 6. The measured Q of varactor structures realized in this technology (using a uniform doping of  $1 \times 10^{17} \text{ cm}^{-3}$ ) varied from 100 to 600 as the bias voltage changed, due the decreasing length of the undepleted region at larger reverse bias voltages [19]. RF tuners have been implemented in this technology, where the impedance points cover the range from 0.2 to 82 ohm, yielding a VSWR > 250 : 1. The measured loss varies from 0.4 dB at 3 Ω to 2 dB for  $Z_{in} = 50 \Omega$ . This

structure is ideal for tuning a power amplifier across a road range of frequencies and output powers.

The limitation of all these approaches — both MEMS and varactor-based — is that they 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.

## 5. Conclusions

This paper has summarized some of the key enabling RF technologies for future cognitive/software defined radio systems. The key feature of these systems is the necessity to accommodate an extraordinarily wide dynamic range at the receiver input, without dissipating excessive power or becoming cost prohibitive. These challenges can be addressed in two different ways: from a system design perspective or from a technology perspective. Innovations in system design will involve increasing use of digital signal processing to accomplish traditional analog functions, and the remaining analog functions will exhibit a high degree of reconfigurability. Innovations in semiconductor technology will focus on improved passive device performance, with particular emphasis on reconfigurable filters and matching networks, using MEMS and possibly high-quality varactor diodes.

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