Introducing Software Defined Radio to 4G Wireless: Necessity, Advantage, and Impediment

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Abstract: **This work summarizes the current state of the art in software radio for 4G systems. Specifically, this work demonstrates that classic radio structures, e.g., heterodyne reception, homodyne reception, and their improved implementations, are inadequate selections for multi-mode reception. This opens the door to software defined radio, a novel reception architecture which promises ease in multi-band, multi-protocol design. The work presents the many advantages of such an architecture, including flexibility, reduced cost via component reduction, and improved reliability via, e.g., the elimination of environmental instability. The work also explains the limitations that currently curtail the widespread use of SDR, including issues surrounding A/D converters, management of software and power, and clock generation. This provides direction for future research to enable the broad applicability of SDR in 4G cellular and beyond.**

Index Terms: **Software defined radio, receiver architecture, radio, supreheterodyne receiver, direct conversion receiver, 4G, 3G, 2.5G, wireless architecture, RF.**

I. INTRODUCTION

As the world is settling on the definition of the third generation wireless standards (3G) [1], researchers and engineers are racing to define the fourth generation (4G) [2]–[4]. The concept of 4G is best described as "wireless anytime, anywhere, in a battery powered handheld device for close to zero cost" [2]. In order to achieve this vision, 4G is shooting for very high data rates (broadband) in a very crowded (and limited) frequency spectrum. Although the applications are yet to be defined, 4G is already touting the ability to provide each user with HDTV quality video (20 Mbps compressed video and audio [5]).

In order to achieve high data rates, low power consumption and low cost, high level of integration and powerful DSP and microprocessor cores are necessary. In 1965, Gordon Moore predicted that the processing power will double every 18 months. Moore's Law [6] became a self-fulfilling prophecy for technology manufacturers of the past 35 years. Aggressive advances in technology have increased integration, reduced power consumption and lowered cost in baseband processing. However, the RF front end and the analog baseband (mixed signal) circuitry are not governed by the same "law," and remain a very challenging arena [7]–[10].

For years, radio engineers have struggled to keep pace with their baseband counterparts. Furthermore, they have been hard pressed to include a multi-band, multi-mode radio in a small form factor battery operated device. Although 4G has not been fully defined, (1) it will consist of at least one air interface for voice, video and high data rate applications, (2) it will ensure wireless connectivity (such as Bluetooth) and Wireless Local Area Network (WLAN) support and (3) it will demonstrate backward compatibility with its predecessors (2G, 2.5G, and 3G). In addition, the Federal Communications Commission (FCC) dictated that a portion of the phones sold in the US comply with the E911 ruling which requires a Global Positioning System (GPS) in the cell phone [11]. Physically, in order to address the integration of a multi-band multi-mode radio, several RF chains will have to co-exist in a single product: interference between the different radios and the added cost and complexity threaten to make this product cumbersome and expensive.

Software Defined Radio is a single radio that can be used for many modes by simply reconfiguring the radio with different software - hence the name [12]–[17]. The software may be pre-loaded in the device and may be available for Over-The-Air (OTA) download or simply downloadable from a Website. This flexible architecture will lower cost and complexity and may improve performance in terms of power consumption and reduced interference in the radio. However, SDR still demonstrates many challenges that must be resolved.

This work presents an important introduction on the current state of software defined radio (SDR) for application in 4G cellular systems. Section II opens by explaining classic radio architectures, presenting the shortcomings of these systems in multimode, multi-band operation. Separated into four subsections, Section II introduces heterodyne reception, homodyne reception, improvements on these classic techniques, and finally their failure in supporting multiple modes in a practical implementation. This sets the stage for SDR presented in Section III. Section III presents both the general form of an SDR and its ease in supporting multiple modes. Perhaps of greatest importance, Section III ends with a discussion of the various limitations of SDR to date. This sets the stage for future research and development, in both industry and academia, in the ongoing evolution of SDR.

II. CLASSICAL RADIO ISSUES

The transmit function of a radio is modulation. Modulation is a process in which one or more parameters of the carrier frequency are varied according to the baseband information. The frequency band is then shifted to a suitable region within the spectrum where the electrical signals are converted to an Elec-

Manuscript received April 25, 2002.

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1229-2370/02/$10.00

tro Magnetic (EM) waves by the antenna and then transmitted. Conversely, a receiver captures a signal "off the air" and converts it down to either an intermediate frequency (IF) or to baseband (i.e., center frequency is 0Hz). The receiver also filters out unwanted signals (blockers) that are within or around the reception band.

A. Super-Heterodyne Reception

The most widely used technique in RF design is heterodyne reception. A classical super heterodyne receiver is shown in Fig. 1.

Referring to Fig. 1, the antenna receives a broad spectrum, which is immediately filtered by the front-end filter before entering the first stage of amplification. The Low Noise Amplifier (LNA) amplifies the received signal (but will also amplify the undesired signals). Furthermore, the LNA will add noise in-band. The first mixer converts the signal to the first intermediate frequency (IF). At the IF, the signal is amplified and further filtered, where sharper filtering is applied since it is typically easier to implement at lower frequencies. A second and final stage of mixing is then used to convert the IF to a baseband signal (0 Hz) where further amplification and/or filtering might take place prior to sampling the signal. The digitized received signal is then sent to the modem for processing.

In practice, the mixer is a "stress" point in the system design [10]. The mixer is a non-linear device that limits cascaded linearity (IP3) in the system. Furthermore, the mixer will cause spurious frequency components that may be highly undesirable. The frequency components generated by a mixer are of the form $\pm N \cdot LO \pm M \cdot RF$ where RF is the RF frequency, LO is the local oscillator frequency and M, N = 0,1,2,3... There are infinite combinations of the mixer components. Because mixers generate spurious components, RF system engineers invest time to create a carefully designed frequency plan. Frequency planning takes into account the band of operation, local oscillator (LO) frequencies, channel bandwidths and other signals available from within the system (such as LO frequencies used in the transmitter and the clocks used in the baseband).

A.1 Advantages of the Super Heterodyne Receiver

The advantages of the super heterodyne receiver are:

- No LO self mixing / DC offset: LO leakage into the front end of the receiver will cause a DC offset at the output of the mixer. Since the LO and the received signal are of different frequency, the LO leakage is not significant.
- Easier Analog to Digital (A/D) converter requirements: Out of band blockers could be much higher in amplitude than the desired signal to be received. In the super-heterodyne receiver, the blockers are filtered at different stages (at least one IF). Each time the frequency is lowered, a tighter frequency filter is applied and hence the amplitude of the blockers is reduced further. Ideally one would want to remove the blockers completely. If not, the blockers must be reduced such that e.g., they do not dictate more than an additional 3 bits of requirement on the ADCs. Without filtering, blockers could require 10 or more additional bits from the ADC.

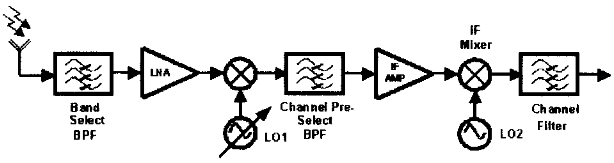

Fig. 1. Classical super heterodyne receiver.

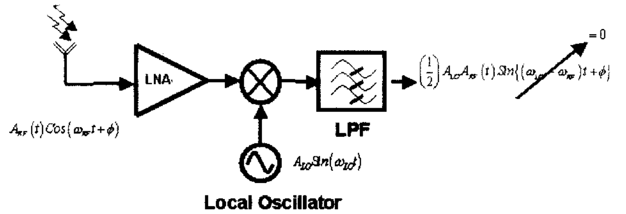

Fig. 2. Homodyne receiver (direct conversion).

- Reduced linearity requirements: Although the front-end requirement is dictated by the incoming signal and will not change significantly, the stages beyond the first mixer and filter can operate with reduced linearity.

A.2 Disadvantages of the Super Heterodyne Receiver

The disadvantages of the super heterodyne receiver are:

- Complex frequency planning: The multiple LO's mandate carefully chosen frequencies. Issues such as the image frequency must be considered [10] and [17]. For example, if $(\omega_{RF} - \omega_{LO})$ generates the desired IF, so does $(2\omega_{LO} - w_{RF})$ which is the image frequency and adds noise to the IF. The image frequency is reduced but adding additional filtering (bandpass filters are used as image reject filters) prior to the mixer. Another consideration is the half IF problem. When the interferer falls between the RF and the LO (i.e., $[\omega_{RF} + \omega_{LO}]/2$), it is down converted to $\omega_{IF}/2$ or at half IF; the second order distortions in the mixer will generate a second harmonic term at the 2 x $\omega_{IF}/2$. The new component is a blocker at the desired frequency of reception.
- Cost: Because of the many components (e.g., IF filters, amplifiers, LO's) the cost of a super heterodyne receiver is generally high.
- Size: The many components require significant board space.
- Power consumption: Additional stages consume additional power.
- Inflexible receiver: The receiver is designed to operate in a certain frequency band (set by the LO's) and a certain bandwidth (set by the filtering). Switching frequency bands is a difficult transition.

B. Direct Conversion Receiver

A direct conversion receiver is shown in Fig. 2.

This receiver operates in a manner similar to that of the super heterodyne receiver. The main difference is that the frequency is directly converted from RF to baseband (i.e., the LO is set at the same frequency as the received signal). Letting $\omega_{LO} = \omega_{RF}$ in the mixing operation, the dominant output components are:

$$\text{Mixer output} = A_{LO}A_{RF}(t)\cos(\omega_{RF}t + \phi)\sin(\omega_{LO}t). \quad (1)$$

In direct conversion

$$\omega_{RF} = \omega_{LO} = \omega. \quad (2)$$

By substituting (2) into (1), then
Mixer output

$$= A_{LO}A_{RF}(t)\cos(\omega t + \phi)\sin(\omega t). \quad (3)$$

Mixer output

$$= \frac{1}{2}A_{LO}A_{RF}(t)[\sin\{(\omega - \omega)t + \phi\} + \sin\{(\omega + \omega)t + \phi\}]. \quad (4)$$

$$\text{Mixer output} = \frac{1}{2}A_{LO}A_{RF}(t)[\sin(\phi) + \sin(2\omega t + \phi)]. \quad (5)$$

The output of the mixer consists of 2 components: a DC component (0Hz center frequency) and a 2ω term (i.e., high frequency term at 2 times the frequency). The low pass filter removes the high frequency term, and passes the DC term corresponding to ($\phi = 90°$)

$$\text{LPE output} = \frac{1}{2}A_{LO}A_{RF}(t). \quad (6)$$

B.1 Advantages of the Direct Conversion Receiver

The advantages of the DC receiver are:

- Flexibility: Since the RF is converted directly to baseband, the LO controls the frequency band of operation. In other words, the frequency band of operation can easily be changed by a simple tuning of the LO to the desired frequency band.
- Wide bandwidth: Because the configuration is not limited by frequency planning and IF selection, it is well suited to wideband operation.
- Size and Cost: This configuration requires few components, lowering size and cost.
- Power consumption: In general, this configuration consumes less power. (This is not always true as explained in the upcoming section).

B.2 Disadvantages of the Direct Conversion Receiver

The disadvantages of direct conversion receivers are:

- LO Self-Mixing and DC offsets: The LO mixes with the RF to generate a baseband signal (Fig. 3). However, the LO may leak (either conducted or radiated) into the RF input and self-mix (with the LO). This causes a DC offset at the baseband (BB). If the DC offset is static, it may be removed before the A/D converter requiring more circuitry. What DC remains forces the A/D converter to be over specified to make up for the DC shift. (Another option for removing the DC is AC coupling the output of the receiver. However, this technique is impractical since very large capacitors are required at baseband). However, in most applications the DC offset is dynamic and the amplitude of the RF signal usually dictates it. In a fading environment, the DC offset varies proportional to the power delay profile of the received signal.
- Gain and Phase Variations: In order to receive a perfect BB signal without distortions, the I and Q legs must be exactly 90° apart and the amplitude of both I and Q must be equal. In practice, there will be phase and amplitude variations between I and Q. Higher offsets cause higher distortions and DC offset. For further explanation, see [10], [18], and [19].
- Spurs or Noise at the LO: All spurs and noise at the LO and at the input of the receiver are translated to BB without filtering. This burdens the baseband with additional filtering and in some cases causes the noise to fold over into the receiver band (further degrading the received signal).
- Linearity Requirements: A major disadvantage of the direct conversion receiver is the absence of intermediate filtering. As a result, the blockers are all present at baseband and analog baseband circuitry must filter out the blockers prior to the A/D converter. Filters at baseband require very large capacitor and inductor values, which are impractical in ASIC design and discrete component implementations. If the blockers are allowed to reach the A/D converter, then higher dynamic range is required which leads to higher cost and increased power consumption.
- LO Leakage Radiated: Another phenomenon of direct conversion is that the LO may leak through the receiver front end and radiate out of the antenna, thus creating unwanted "jammers."

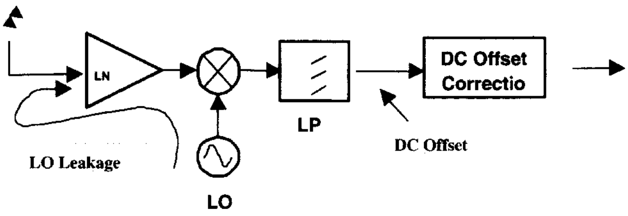

Fig. 3. DC offset generation.

C. Other Popular Receiver Implementations

Direct conversion is usually preferred because of its potential benefits. However depending on the wireless standard, direct conversion may not be practical. System and RF designers have used clever techniques to overcome the shortcomings of homodyne receivers.

C.1 Homodyne Receivers with N x LO

In order to overcome the LO leakage problem in direct conversion receivers, designers have used N times LO techniques. For example, RF designers may choose an LO operating at 2 times the RF frequency and divide the LO frequency at the mixer. Alternatively, the LO frequency may be half of the RF frequency in which case a doubler (2x) is used at the mixer. Doubler and divider circuits are not without shortcomings: for example, an ideal doubler will generate even harmonics of the LO signal with 50% duty cycle. In practice, doubler circuitry is far from ideal and generates several odd harmonics and spurious components. These harmonics degrade the performance of the mixer and hence of the receiver. A possible way around the doubler circuits is the use of sub-harmonically pumped mixers where the 2X LO is generated internal to the mixer (based on the understanding that the mixer is a non-linear element). In the case of a divider, additional power consumption, additional noise generation in the divider, and uneven duty cycle all degrade receiver performance.

C.2 Very Low IF (VLIF) / Near Zero (NZR) Receiver

To overcome the DC offset problem in homodyne receivers, designers will convert to a frequency close to DC that demonstrates all the benefits of a homodyne receiver. For example, typical intermediate frequencies chosen in a super heterodyne receiver are on the order of 100MHz ~ 400MHz. VLIF and NZR receivers would choose an IF on the order of 100KHz ~ 1MHz. By shifting the frequency slightly above DC, the signal can be AC coupled and, hence, the DC component may be removed without loss or distortion of the received signal.

C.3 Digital IF (IF Sampling) Receiver

Digital electronic design (in an ASIC) is lower cost and easier to implement than their analog counterparts. We may take advantage of this fact by digitizing the signal as early as possible. A popular technique uses the super heterodyne receiver but instead of mixing the IF to baseband and then sampling the signal, the signal is digitized directly at IF and then the filtering and downcoversion is done in the digital (discrete) domain via digital signal processing (DSP). Digital IF benefits from both the super heterodyne and the homodyne advantages. The disadvantages of an IF sampling receiver is that the ADC must run at higher sampling frequency, drawing more power.

D. Classical Implementation of a Multi-Mode Radio

Today's wireless devices are becoming more complex, and require more and more integration. For example, a cell phone may not only be required to support GSM networks worldwide (GSM / DCS / PCS) but may also have Bluetooth (BT) connectivity and a GPS receiver (all in a single handheld). The resulting cell phone, where several individual receivers will have to coexist, is bulky and expensive (because multi-mode radio would most likely use a "Velcro" approach or brute force approach). Furthermore, the handheld restricts the simultaneous use of BT, voice (GSM), and GPS for reasons of interference.

As an example, assume a dual band cellular phone with (1) a GPS receiver (to comply with the E911 FCC mandate) and (2) a Bluetooth radio. This mandates four different receivers in a single package. An implementation example is shown in Fig. 4 below.

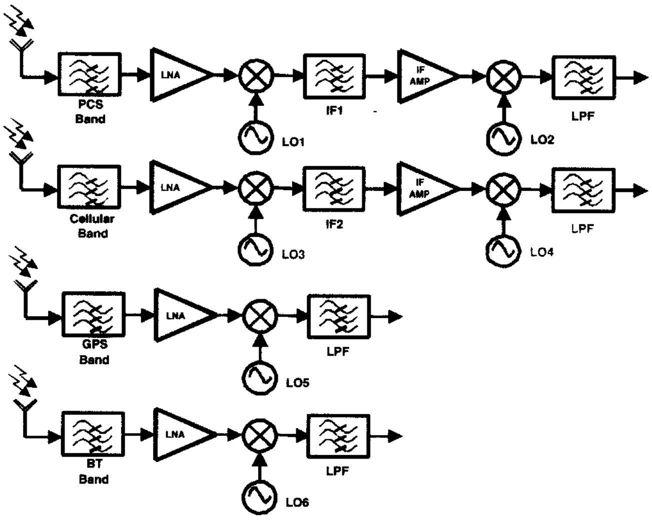

Fig. 4. Classical implementation of a multi-mode radio.

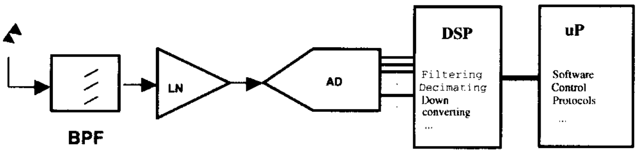

Fig. 5. Software defined radio architecture.

In Fig. 4, we present an implementation example where (1) the cellular and the PCS receivers use a super heterodyne approach (this enables them to take advantage of IF filtering to attenuate adjacent channels), and (2) the GPS and BT radios use a direct conversion receiver (since adjacent channel requirements are not as stringent in both GPS and BT). Note the high complexity (and high cost) of this radio: 6 Bandpass filters, 6 LOs, 6 mixers, and 4 Lowpass filters.

III. THE SOFTWARE DEFINED RADIO (SDR) RECEIVER

As the number of wireless standards continues to increase and as consumers continue to demand more and more wireless protocols in devices, an elegant and low cost solution for multimode radio is greatly needed. This is especially true when considering 4G, which we presuppose will be designed to also support BT, WLAN, GPS, and earlier cellular generations. With the recent advances in large-scale integrated (LSI) circuits, microprocessors and Analog to Digital converters (A/D converters), one attractive solution for a 4G multi-mode receiver is a Software Defined Radio (SDR).

An ideal SDR is shown below in Fig. 5.

The basic concept underlying Software Defined Radio (SDR) has been around for many years. As defined in the literature [13] and [20]–[22], SDR migrates the hardwired receiver to a flexible software programmable platform. A DSP may be used for tuning, signal selectivity, filtering and down conversion. As a result, a microprocessor (or ASIC) may accommodate more than one wireless standard (providing flexibility). Beyond the flexibility and economic benefits of software radios, there are also physical benefits such as environment stability and band selec-

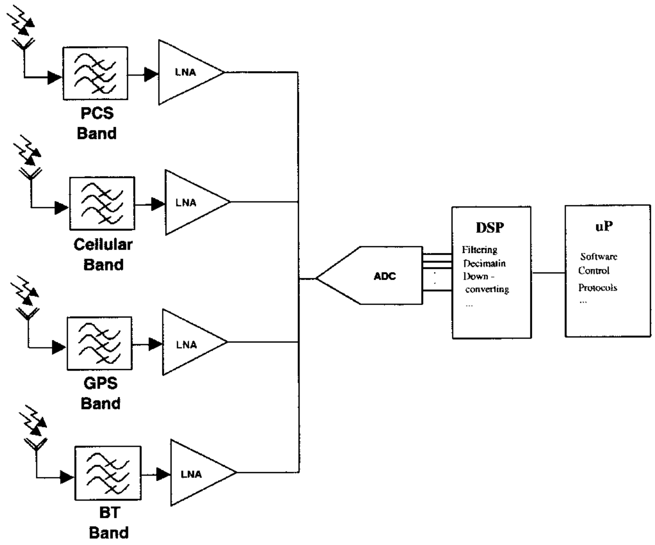

Fig. 6. Multi-mode radio implementation in SDR.

tion: Analog circuits components (e.g., filters and amplifiers) will shift with temperature, process and voltage required, e.g., temperature calibration. On the other hand, digital circuits are stable.

Overall, Software Defined Radio offers a wide range of far reaching benefits:

- Flexibility: SDR executes different software (in a microprocessor or a DSP code) for different protocols limiting the need to hardwire a receiver for each standard.
- No Mixers: There are no mixers and all "mixing" is done in the baseband. Thus there are no undesired mixing products in the radio.
- Fewer Components: Because the received signal is sampled at RF, there are very few external components. The front-end SAW filters and LNAs are all that is needed to filter out far away blockers and set the noise floor. Input levels lower than -100 dBm (10^{-10} mV!) are not uncommon. This level is well below the least significant bit (LSB) of a 20 bit A/D converter running at 3V ($3V/2^{20} = 2.86\mu V = 2.86*10^{-3}$mV per LSB), and hence will not be detected. Hence, the LNA amplifies the signal above the A/D detection threshold and the BPF filters out large out of band blockers prior to sampling.
- Lower Cost: Less components means lower material cost.
- Improved Reliability: The reliability of the product is improved because external components are reduced.
- Reduced Complexity: The complexity of the hardware is much lower on software defined radios than the classical approach.

Using the example described earlier, Fig. 6 illustrates the SDR implementation of a dual band cellular phone with a GPS receiver (to comply with the E911 FCC mandate) and a Bluetooth radio.

Comparing the complexity of the multi-mode radio in Fig. 6 versus the classical implementation shown in Fig. 4, we illustrate SDR's simplicity. Providing filters for the appropriate band of operation, the protocol for any standard can be programmed into this radio.

Software radios have started migrating from research to practical implementation and have found application in cellular base stations, satellite ground stations and other applications in which power consumption and size are not of a major concern. As of today, SDR is impractical in battery powered handheld devices such as cellular phones and PDAs. In order for SDR to become practical in time for 4G, several challenges need to be overcome:

1. A/D Converter limitations: The resolution of an A/D converter is a key criteria. In 3G, receivers are requiring an A/D with a spurious free dynamic range of greater than 105dB, which translates to a 17.5bits of resolution. (Practically speaking, 20-bit resolution is required to account for non-linearity and implementation margin.) A 20 bit resolution in SDR handhelds will lead to two problems: (1) The voltage resolution is too low. For example, consider a 20 bit A/D converter operating at 3V (typical cellular voltage 2.7 - 3.3V). The voltage per bit is $3V / 2^{20}$ = 2.86mV/bit. This resolution is unusable as voltage, temperature and DC offset cause variations in the tens of millivolts. (2) Additionally, sampling frequencies of the A/D converter must be high enough (e.g., 48 MSPS based on 8X oversampling of CDMA [23]).However, sampling rate and bits of resolution work against one another, with high resolution A/D converters (>20 bits) running at low sampling frequencies (<10 MSPS), and high sampling frequency (> 1GSPS) employing low resolution (<10 bits). Attempts to build A/D converters with higher sampling rates and higher resolution lead to the power consumption issue described next. Power consumption, assuming a sample and hold technique, was derived by Kenington [23], and is characterized by
$$P_i = \frac{kT}{t_s} 10^{(6n+1.76)/10}, \tag{7}$$
Where Pi is the power consumed in Watts, k is Boltzman's constant (=1.38x10-23 J/K), T is the device temperature in Kelvin, ts is the sampling interval and n is the number of resolution bits. From (7), an ideal 20 bit A/D converter operating at 50MHz could consume 1W of power, and from Kenington in [23], the power consumption increases an order of magnitude due to implementation in software radio, e.g., a 20-bit A/D converter operating at 50MHz may consume around 10W of power. Hence, high resolution, high sampling rate A/D converters required in battery operated software radios are not yet realized.
2. Software management: An engineering challenge will be the management of the different protocols that are required to work in the baseband software. For example, assume that a 4G SDR is attempting to support the 3 different protocols of GSM, WCDMA (3G UMTS) and BT (in addition to its own air interface). In typical operations, GSM uses 1 slot out of 8 (TS7) for control and monitor, e.g., "sniff" for neighboring cells, handoff, or to set the automatic gain control (AGC) in the receiver. Conceivably in a multi-mode implementation, the SDR would employ the same time slot (TS7) to look for WCDMA carriers or BT transmitters. The challenge in detection of a

BT transmitter is to load a different protocol stack, lock onto transmission, demodulate the BT transmission, and switch back to GSM mode all in microseconds. Short of a hard hand off (where the SDR drops the connection in one mode for another), a brute force solution requires all the protocols running simultaneously. Such a solution mandates that the processors (and DSP) run at high speeds and with large memory. A practical solution to managing the software without duplication and added complexity is required.

3. Power management: All wireless standards have a built-in standby mode or sleep mode where most of the electronic circuitry in the receiver is shut off. Minimum sections of the radio are awakened at preset time intervals to listen for a page from a base-station or sniff for local wireless devices. It is unknown how these operations will take place in SDR.
4. Clock generation: Most of the power in a radio is consumed by clock and frequency generation circuits. Additionally, the sampling clock of the ADC should be jitter free, noise free and spur free. In SDR, every wireless standard will require a different set of clocks, e.g., frame reference, chip rate, and radio channel spacing. Additionally, the distribution of the clocks throughout the radio must be carefully planned.
5. Computational efficiency: As more and more functions are moved to the software, computational efficiencies in both the DSP and the microprocessor become critical to power savings. One solution uses Java as a development environment based on an object oriented language with proper modification for real-time operations [24]. This solution allows standardization of a common hardware platform. A Java kernel downloads and executes different operating protocols. The layered structure of the software would use (or re-use) modules, e.g., coding modules can be reused between two standards. Although Java would reduce the download and run time of a protocol, it is still orders of magnitude higher than needed.
6. RF filtering: Enough filtering must be present in the front end (RF) to insure successful operation of the A/D converter. Narrow Filtering must be present at the receiver front end to filter out adjacent channels and blockers. One solution sweeps the filter characteristics (frequency) by sweeping the dielectric constant of the substrate [25]. Another solution uses MEMS (micro-electro mechanical structures) to switch filter elements in and out [26]. Both solutions are still in the research stage and are impractical for high volume deployment.

To the best of our knowledge, in both industry and academia, most of the above challenges remain unsolved. If the desired multi-band, multi-mode receivers are to support 4G receivers compatible with 2G, 3G, WLAN, and BT environments, all the above issues require careful attention.

CONCLUSION

As the wireless world moves ever closer to the fourth generation (4G), the radio implementation appears to be the weakest link. Advances in CMOS technology complement great advances in modulation and coding techniques. With the classical RF implementation lagging behind and the growing demand for greater flexibility and integration, Software Defined Radio (SDR) may be the answer. SDR provides implementation flexibility as well as size, cost and performance advantages. However, if we are to step into this future, a great deal of future research and development outlined in this article, lies ahead.

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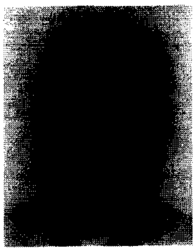

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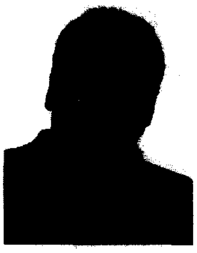

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