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THE SOFTWARE-DEFINED RADIO IS NOW A REALITY

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ABSTRACT: The role of firmware and digital signal processing in radio transceiver design has increased to meet the global coverage requirement and to cover extra features in the mobile telephony. The Software-Defined Radio (SDR) is the practical approach for this. The paper reviews the SDR concepts, the benefits, the design steps involved in SDR, some emerging concepts, technological solutions and challenges, applications and economy.

Key words: Software-Defined Radio, Smart antenna, RF, Cognitive radio.

I. THE NEED OF TIME

The concept of integrated seamless global coverage requires that the communication devices support two distinct features: first, global roaming or seamless coverage across geographical regions; second, interfacing with different systems and standards to provide seamless services at a fixed location. Multimode phones that can switch between different cellular standards like IS-95 and Global System Mobile (GSM) fall in the first category, while the ability to interface with other services like Bluetooth or IEEE 802.11 networks falls in the second category. Further, the rate of technology innovation is accelerating, and predicting technological change and its ramifications to business is problematic. So, to keep their systems up to date, wireless systems manufacturers and service providers must respond to changes as they occur by upgrading systems to incorporate the latest innovations. Since frequent redesign is expensive, time consuming, and inconvenient to end users, interest is increasing in future-proof radios.

Existing technologies for voice, video, and data use different packet structures, data types, and signal processing techniques. Integrated services can be obtained with a radio that can communicate with devices providing complementary services. The supporting technologies and networks that the radio might have to use can vary with the physical location of the user. To successfully communicate with different systems, the radio has to communicate using different air interfaces. Furthermore, to manage changes in networking protocols, services, and environments, mobile devices supporting reconfigurable hardware also need to seamlessly support multiple protocols. Such radios can be implemented using Software-Defined Radio (SDR) architectures in which the radio reconfigures itself based on the system it will be interfacing with and the functionalities it will be supporting.

II. FEATURES OF SOFTWARE-DEFINED RADIO

The term software-defined radio was coined by Joe Mitola in 1991 to refer to the class of reconfigurable radios [1, 2]. A radio that defines in software its modulation, error correction, and encryption processes, exhibits some control over the RF hardware, and can be reprogrammed is clearly a software-defined radio. Thus, it is a radio that is substantially defined in software and whose physical layer behavior can be significantly altered through changes to its software. The functionality of conventional radio architectures is usually determined primarily by hardware with minimal configurability through software. The hardware consists of the amplifiers, filters, mixers (probably several stages), and oscillators. The software is confined to controlling the interface with the network, stripping the headers and error correction codes from the data packets, and determining where the data packets need to be routed based on the header information. Because the hardware dominates the design, upgrading a conventional radio design essentially means completely abandoning the old design and starting over again. In upgrading a software-defined radio design, the vast majority of the new content is software and the rest is improvements in hardware component design. In short, software-defined radios represent a paradigm shift from fixed, hardware-intensive radios to multiband, multimode, software-intensive radios.

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Implementation of the ideal software-defined radio would require either the digitization at the antenna, allowing complete flexibility in the digital domain, or the design of a completely flexible radio frequency (RF) front-end for handling a wide range of frequencies and modulation. A model of a practical software-defined radio is shown in Figure 1. The receiver begins with a smart antenna that provides a gain versus direction characteristic to minimize interference, multipath, and noise [4]. The smart antenna provides similar benefits for the transmitter. Most practical software-defined radios digitize the signal as early as possible in the receiver chain while keeping the signal in the digital domain and converting to the analog domain as late as possible for the transmitter using a digital to analog converter (DAC). Often the received signal is digitized in the intermediate frequency (IF) band. Conventional radio architectures employ a super heterodyne receiver, in which the RF signal is picked up by the antenna along with other spurious/unwanted signals, filtered, amplified with a low noise amplifier (LNA), and mixed with a local oscillator (LO) to an IF. Depending on the application, the number of stages of this operation may vary. Finally, the IF is then mixed exactly to baseband.

Digitizing the signal with an analog to digital converter (ADC) in the IF range eliminates the last stage in the conventional model in which problems like carrier offset and imaging are encountered. When sampled, digital IF signals give spectral replicas that can be placed accurately near the baseband frequency, allowing frequency translation and digitization to be carried out simultaneously. Digital filtering (channelization) and sample rate conversion are often needed to interface the output of the ADC to the processing hardware to implement the receiver. Likewise, digital filtering and sample rate conversion are often necessary to interface the digital hardware that creates the modulated waveforms to the digital to analog converter. Processing is performed in software using DSPs, field programmable gate arrays (FPGAs), or application specific integrated circuits (ASICs). The algorithm used to modulate and demodulate the signal may use software methodologies, such as middleware, e.g., common object request broker architecture (CORBA) [5, 6], or virtual radio machines, which are similar in function to JAVA virtual machines.

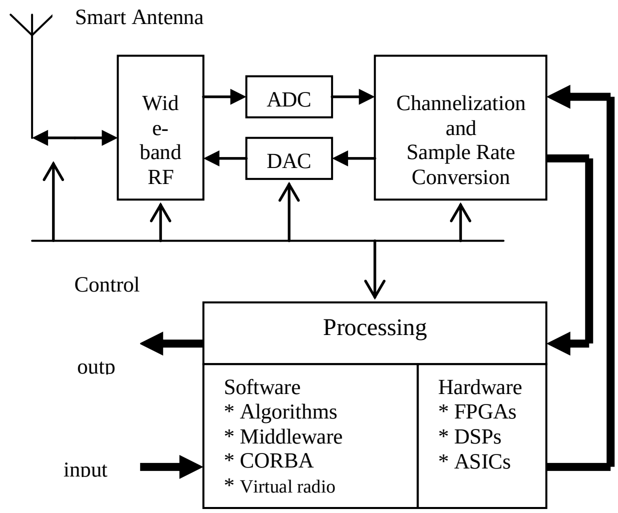

Fig. 1. Model of a Software-Defined Radio [3]

III. BENEFITS OF SOFTWARE-DEFINED RADIO

The software-defined radio provides a flexible radio architecture that allows changing the radio personality, possibly in real-time, and in the process somewhat guarantees a desired QoS. The flexibility in the architecture allows service providers to upgrade the infrastructure and market new services quickly. This flexibility in hardware architecture combined with flexibility in software architecture, through the implementation of techniques such as object oriented programming and object brokers, provides software-defined radio with the ability to seamlessly integrate itself into multiple networks with wildly different air and data interfaces. In addition, software-defined radio architecture gives the system new capabilities that are easily implemented with software. For example, typical upgrades may include interference rejection techniques, encryption, voice recognition and compression, software-enabled power minimization and control, different addressing protocols, and advanced error recovery schemes. Such capabilities are well-suited for 3G and 4G wireless requirements and advanced wireless networking approaches. In summary, following five benefits [3] are expected to push wider acceptance of software-defined radio:

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1. Multi functionality—For instance, a Bluetooth-enabled fax machine may be able to send a fax to a nearby laptop computer equipped with a software-defined radio that supports the Bluetooth interface..
2. Global mobility—The need for transparency, i.e., the ability of radios to operate with some, preferably all, of these standards in different geographical regions of the world has fostered the growth of the software-defined radio concept.
3. Compactness and power efficiency—The software-defined radio approach results in a compact and, in some cases, a power-efficient design, especially as the number of systems increases, since the same piece of hardware is reused. to implement multiple systems and interfaces.
4. Ease of manufacture—RF components are notoriously hard to standardize, however, digitization of the signal early in the receiver chain can result in a design that incorporates significantly fewer parts, meaning a reduced inventory.
5. Ease of upgrades—A flexible architecture allows for improvements and additional functionality without the expense of recalling all the units or replacing the user terminals. Furthermore, as new devices are integrated into existing infrastructures, software-defined radio allows the new devices to interface seamlessly, from the air-interface all the way to the application, with the legacy network; by dynamically downloading the software to cover the needed air-interface standard.

IV. DESIGN STEPS OF SOFTWARE-DEFINED RADIO

Radio design has always required a broad set of design skills. Although one might initially assume that software-defined radios would require simply a higher level of digital signal processing programming skill than conventional radio design, this is not the case; a higher skill level is needed for almost all aspects of the radio design because of the dependency of the radio subsystems. A generic design procedure for SDR follows and demonstrates the interaction between the various subsystems of the radio design [3].

- Step 1: Systems engineering—Understanding the constraints and requirements of the communication link and the network protocol allows the allocation of sufficient resources to establish the service given the system's constraints and requirements. For instance, constraints on the range and transmit power constrain the modulation types and data rate that can be supported. For a well-defined standard, the systems engineering aspects, such as the routing protocol, are to a great extent predetermined. However, as additional flexibility is allowed in defining the network, systems engineering and optimization becomes a complex task. In an ideal SDR with the ability to change a number of system parameters in real-time, optimizing an active communications session is a major challenge.
- Step 2: RF chain planning—The ideal RF chain for the software-defined radio should incorporate simultaneous flexibility in selection of power gain, bandwidth, center frequency, sensitivity, dynamic range, higher IP3 and 1-dB compression point, and spurious free radiation [7]. The conventional RF transceiver section is of super heterodyne type, however, in SDR various RF architectures like direct conversion [9], digital IF sampling [10], and bandpass sampling [8] architectures are suggested. Very wideband RF amplifiers, filters and oscillators circuits are required to cover the entire band of interest. Achieving strict flexibility is impractical and trade-offs must be made. If the communication system is constrained to selected commercial or military bands, this optimization problem is simplified. Nevertheless, with a software-defined radio design, it is possible to compensate for some of the inadequacies of the RF components in the digital domain. Compensations for power amplifier distortion or power management of the RF circuitry, for example, can be accomplished using pre-distortion.
- Step 3: Analog to digital conversion and digital to analog conversion selection— Analog to digital conversion and digital to analog conversion for the ideal software-defined radio is difficult to achieve, and in practice, the selection requires trading power consumption, dynamic range, and bandwidth (sample rate)[11]. Analog to digital conversion and digital to analog conversion selection is closely tied to the RF requirements for dynamic range and frequency translation. Channelization requirements also impact the selection of the analog to digital conversion and digital to analog conversion. Current conversion technology is very limited and is often the weak link in the over all system design. There are post-digitization techniques based on multirate digital signal processing that can be used to improve the flexibility of the digitization stage.
- Step 4: Software architecture selection—The architecture should allow for hardware independence through the appropriate use of middleware, which serves as an interface between applications-oriented software and the hardware layer. The software needs to be aware of the capabilities of the hardware (both DSP and RF hardware) at both ends of the communications link to ensure compatibility and to make maximum use of the hardware resources. Also, given that the software-defined radio will operate in an existing data infrastructure, it must interface quickly and efficiently with this infrastructure. This means that the software-defined radio needs to control issues such as attribute naming, error management, and addressing, regardless of the protocol used in the infrastructure. Partitioning the radio functions into objects can help with these issues as well as aid in portability and maintenance of the software. Example objects might include the blocks of the model software-defined radio shown in Figure1. Security is an important issue to ensure that

software download is legitimate. Finally, given that higher-layer protocols such as TCP have constraints inherent to the way in which they manage a session, the software architecture should consider latency and timing for the whole protocol stack.

- Step 5: Digital signal processing hardware architecture selection—The core digital signal processing hardware can be implemented through microprocessors, FPGAs, and/or ASICs. Typically microprocessors offer maximum flexibility, highest power consumption, and lowest computational rate, while ASICs provide minimal flexibility, lowest power consumption, and highest computational rate. FPGAs, on the other hand, lie somewhere between an ASIC and a DSP in these characteristics. The selection of the core computing elements depends on the algorithms and their computational and throughput requirements. In practice, a software-defined radio will use all three core computing elements, yet the dividing line between the implementation choices for a specific function depends on the particular application being supported. A very good analysis is given in [12] for SDR software and hardware architecture.
- Step 6: Radio validation—This is essential to ensure not only that the communicating units operate correctly, but also that a glitch does not cause system-level failures. Interference caused by a software-defined radio mobile unit to adjacent bands is an example of how a software-defined radio could cause a system-level failure, and this is of great concern to government regulators [13]. Given the many variable parameters for the SDR and the desire for an open and varied source of software modules, it is very difficult to ensure a fail-proof system. Testing and validation steps can be taken to help minimize risk. Structuring the software to link various modules with their limitations can help in testing compatibility of software modules.

V. SOFTWARE-DEFINED RADIO EMERGING CONCEPTS

The emerging concepts of software-defined radios are in the field of smart antennas, networking, digital preprocessing, and software. Smart antennas digitally combine antenna channels to adaptively form beams and point nulls and equalize the received signal [4]. Space Time Coding and Multiple Input Multiple Output (MIMO) Antenna System are the techniques used in SDR among many techniques to improve the performance in hostile wireless environment [14]. Software radio architectures, originally developed for military applications, are now becoming economically viable in commercial products because of the rapid advance of DSP technology. Razavilar [14] extends [4] to algorithms and traffic engineering aspects. This paper considers a wireless network with beamforming capabilities at the receiver which allows two or more transmitters to share the same channel to communicate with the base station. The concrete computational complexity and algorithm structure of a base station are considered in terms of a software radio system model, initially with an omnidirectional antenna. Hentschel and Fetweiss [15] address the critical question of providing clock references for multiple air interfaces needed for multiple SDR software personalities. Given the accuracy requirements for diverse air interfaces, the authors show that deriving multiple clocks from a single master clock has more to do with antialiasing and preserving frequency domain properties than with time domain interpolation. Papers by Munro [16] and Shepherd [17] address emerging aspects of software. Shepherd sets the software issues in a deployment context. The paper proposes a consistent software architectural framework for the dynamic implementation of these different protocols within an embedded environment. Munro critically examines the emerging needs for middleware that insulates radio applications from the rapidly evolving radio hardware platforms. The paper explores the issues of integration, the components of mobile middleware, and likely demands placed on such systems when mobile access comes to dominate personal communications. The Cognitive Radio [18] extends the SDR by enhancing the flexibilities of personal services through a Radio Knowledge Representation Language. The cognitive radio empowers SDRs to conduct expressive negotiations among peers about the use of radio spectrum across fluents of space, time and user context.

VI. TECHNOLOGICAL SOLUTIONS AND CHALLENGES

An effective solution to implement SDR consists in the combination of programmable digital baseband engines and reconfigurable analog front-end circuits. For the programmable digital baseband engine, one has to carefully trade off flexibility and energy efficiency. Flexibility should only be introduced where its impact on the total average power is sufficiently low or where it offers a broad range of control options that can be exploited effectively later in the control step. For the reconfigurable analog front end, architectures and circuits should be designed for a broad range of requirements in carrier frequency, channel bandwidth and noise performance with minimal penalty in power consumption, while also offering energy scalability. A major challenge is to enable low energy reconfigurable radio implementations, suited for handheld multimedia terminals and competitive with fixed hardware implementations. To make such terminals a reality; firstly effective energy scalability is enabled in the design of the radio baseband and front end. And secondly, the scalability is exploited to achieve low power operation by across layer controller that follows at run time the dynamics in the application requirements and propagation conditions.

Future communication systems will have to seamlessly and opportunistically integrate multiple radio technologies and heterogeneous wireless access networks to offer context dependent ubiquitous connectivity and content access. The growing demand for large data rates reveals an increasing spectrum scarcity. So, new paradigms for efficiently exploiting the spectrum are clearly needed. A continuously growing role for adaptive spectrum radios exploiting the capabilities of reconfigurable radio architectures is to be expected. Pushed to the limit, this leads to the disruptive concept of cognitive radio [18]. Cognitive radio is defined as a radio that can autonomously change its transmission parameters based on interaction with the complex environment in which it operates. The spectrum data/mining and agile air interface requirements of such cognitive radios also claim for SDR-based implementations. These CR systems can in fact be thought of as extensions of the concepts introduced above, i.e., a reconfigurable radio coupled with a now "cognitive" adaptive control that can sense, adapt and learn. The need to detect and/or generate virtually any kind of waveform in any band pushes, on the other end, the specification of the underlying reconfigurable radio to the limit.

VII. SOFTWARE-DEFINED RADIO APPLICATIONS

SDR applications and economies are inextricable. There is a need for service providers to offer differentiated services such as voice coders customized to language families, such as Asian languages [19]. The need for differentiated service, of course, is driven by market economics. Similarly, as GSM fades from cutting edge to relatively easy compare with 3G, the economics of software realizations of GSM handsets and base stations loom large. Turletti's paper characterizes processing requirements in terms of industry-standard benchmarks, substantially simplifying the cost/benefit trade-offs [20]. There is a research in consideration of GSM to hybrid multicarrier base stations. Murotake [21] similarly looks toward reconfigurable 3G base stations. Their economics driver is the opportunity to employ standard parallel processing computing platforms for the delivery of such base stations, expanding the production base of the commercial products, and potentially reducing the costs of the base stations. Cost of the entry into the base station market would also seem to be reduced using their approach. Also, there is an innovative approach to software radio technology using software-based CDMA as a proximity sensor for a virtual mouse [22]. It suggests the pervasive nature of low-cost software-based solutions to accomplishing tasks without wires. As mentioned earlier, SDR has found an application in CR. The analysis of software radio economics is also carried out [23]. The key finding is that it takes about 2 years and U.S. $25 million to transition a strong single-channel digital radio capability into a multiband, multimode SDR capability with wider bandwidth with RF and ADCs and DACs, large scale software, middleware, and pooled processing resources.

One of the commercial applications of SDR is from Alcatel-Lucent [24]. The flexibility of their radio network solutions, as demonstrated with the LTE software module that has been introduced for their 3G NodeBs, is part of a more comprehensive strategy to offer a converged RAN approach. Leveraging years of Bell Labs research in SDR and experience with software-only upgrades, Alcatel-Lucent provides unprecedented flexibility to operators in their network evolution or renovation. Beyond the ability to upgrade 3G base stations to support LTE, their solutions allow different technologies to coexist in a single base station and flexible software based spectrum refarming. Their SDR base station modules can be installed on the 500,000 Base Stations that they have already deployed, ensuring their customers investment protection and a smooth path to more advanced capabilities in the future.

VIII. CONCLUSION

With the emergence of new standards and protocols, wireless communication is developing at furious pace. The software-defined radio represent a major change in the design paradigm for radios in which a large portion of the functionality is implemented through programmable signal processing devices, giving radio the ability to change its operating parameters to accommodate new features and capabilities. A software radio approach reduces the content of RF and other analog components of conventional radio and emphasizes DSP to enhance overall receiver flexibilities. The mobile wireless communications infrastructure developers and service providers are now coming up with applications of software-defined radio in their business solutions and that is a great success of the concept of the future technology radio- the SDR.

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BIOGRAPHY

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