Team Paper Assignment

Software Defined Radio

The Revolution of Wireless Communication

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It is no secret that anticipated technologies are often hyped as being “hot”, especially in the rapidly evolving and highly dynamic field of wireless communication. These very same technologies about which everybody has talked so enthusiastically then disappear silently, without leaving any impact on the industry, and remaining merely as just another vocabulary in the glossary of Newton’s Telecom Dictionary. However, this time it seems really different…

The emergence of a promising, versatile technology into the commercial world seems to set the entire communication industry into pure excitement. Not only has it definitely become a major focus of attention, but it is also catalyzing enhancement of new standards as the industry is taking its big steps towards the age of “third generation,” 3G communication. **Software defined radio** (SDR) is receiving enormous recognition as the next evolutionary stage of wireless technology, getting support from governmental agencies as well as civil and commercial entities. The numerous benefits provided by SDR have created widespread interest, and the triumphal procession of software-based radio systems now only remains a question of time.

In a comprehensive approach, this report is going to give a broad overview about software defined radio in three parts: Part 1 is going to cover the history of SDR in militaristic development projects, identify problems of current digital hardware based radio systems, and define the concept as well as describe the potentials associated with SDR. Part 2 is going to give an explanation about the architecture and functionality of the SDR technology. Finally, part 3 will focus on regulatory issues, as well as explore current applications and future potentials of SDR.

I. General Overview

1. Militaristic Development of Software Based Radio Systems

1.1 SPEAKeasy

As with many new technologies, software defined radio has been initiated by the military in an attempt to alleviate numerous problems associated with traditional radio systems. Although there had been multimode and programmable radio prototypes since the 1970s, the project SPEAKeasy is said to have brought out the real first software based radio systems in existence.[1] Numerous military instances such as the Defense Advanced Research Projects Agency (DARPA), Army, Navy, Air Force and National Security Agency (NSA) participated in this joint effort.[2]

In general, the project served two critical goals. First, there was an interest in the development of a radio system based on utilization of programmable processing to enable the emulation of different military radio signals operating within a wide frequency range. The other goal was targeted at creating the possibility of allowing future incorporation of new coding and modulation standards in radio systems with advancement of new technologies.[3] The militaristic developers hoped for the accomplishment of several benefits that a software based system could provide. These benefits included:

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[1] http://www.mitre.org/work/tech_papers/tech_papers_03/nguyen_radio/nguyen.pdf
[2] http://www.its.bldrdoc.gov/meetings/art/art98/slides98/bons/bons_s.pdf
[3] http://en.wikipedia.org/wiki/Software_defined_radio#History

- **Interoperability** through emulation of different radio signals
- **Flexibility** to allow scalable reconfiguration in regard to platform requirements
- **Responsiveness** to allow quick and easy incorporation of future developments
- **Cost reduction** potentials for deployment of radio systems[4]

1.1.1 SPEAKeasy Phase 1

SPEAKeasy was implemented in two phases. Phase 1 was initiated in 1992, with the specific goal to develop technologies that support the implementation of multiband, multimode radios, and demonstrate a specific radio system which could operate with ground force, naval, air force radios and satellites in the range of 2MHz to 2 GHz.[5]

The project developed a radio system, which achieved most of the predefined goals. Some of the relevant insights that could be gained included that the division of a wide frequency range into smaller sub-bands was required, which were to be processed by different integrated analog radio technologies feeding the same analog-to-digital converters. This has become the basic concept for wide band software radios.[6] The proposed architecture for transmitters and receivers has laid the framework for further research and development efforts. Also, developers realized that an open architecture was a fundamental requirement for the development of such a radio system.[7] However, one drawback was presented in the problem that the utilized processor was not able to keep several radio conversations on the air at once.

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[4] http://www.its.bldrdoc.gov/meetings/art/art98/slides98/bons/bons_s.pdf
[5] http://en.wikipedia.org/wiki/Software_defined_radio#History
[6] http://en.wikipedia.org/wiki/Software_defined_radio#History
[7] http://www.its.bldrdoc.gov/meetings/art/art98/slides98/bons/bons_s.pdf

1.1.2 SPEAKeasy Phase II

After the successful development of a radio system which could support a wide frequency range, the second phase of SPEAKeasy was targeted at the creation of an open architecture, reconfigurable system, allowing the bridging of different radio protocols through cross-channel connectivity enabling several conversations at once.[8]

Only fifteen months later, the developers introduced a demonstration radio which could operate within a frequency range of 4 MHz to 400 MHz. Although Phase 2 was scheduled as a three year development project, it was shortly halted after this successful demonstration, and the demonstration version went into production.[9]

The architecture was based on standard interfaces open to different modules for the management of different radio functions, resulting in a much smaller and lighter radio system than in Phase 1 (see table 1)[10]

[8] http://en.wikipedia.org/wiki/Software_defined_radio#History
[9] http://en.wikipedia.org/wiki/Software_defined_radio#History
[10] http://en.wikipedia.org/wiki/Software_defined_radio#History

Radio Frequency Control:	Management of analog radio components
Modem Control:	Resource management for support of different modulation and demodulation schemes
Waveform Processing:	Processing of modem functions and modulation schemes
Cryptographic Processing:	Management of security functions
Multimedia Module:	Voice processing
Human Interface:	Local and remote control function
Routing Module:	Provision of network services
Control Module:	Overall control function

Table 1: Integrative components of the SPEAKeasy architecture (adapted from Wikepedia.org)

Instead of utilizing a central operating system, the different modules communicated over a shared PCI computer bus through a layered protocol. The project also introduced the utilization of the field programmable gate arrays (FPGA), a microprocessor used for digital processing.[11]

[11] http://en.wikipedia.org/wiki/Software_defined_radio#History

1.2 Joint Tactical Radio System (JTRS)

As the descendant of the SPEAKeasy project, the Joint Tactical Radio System was established as a program by the U.S. Department of Defense in 1999 in order to achieve software programmability in radio technology enabling the support of multiple protocols and frequency bands for military communications. [12] The DoD recognized the need for direct radio-to-radio communication to support different warfighters of any military domain in critical situations.[13]

Based on CORBA and POSIX (explained later in greater detail) as operating systems for the coordination of different modules, JTRS developed an open architecture development framework for software based radio systems.[14] The framework has been provided by the Software Communications Architecture (SCA), which was developed by JTRSA and provides a set of specifications that describe the communication and interaction between different radio modules.[15]

JTRS is working closely with numerous other entities, such as the SDR Forum, a non-profit organization which consists of vendors and other stakeholders, and the Object Management Group (OMG), to push the further development of software based radio systems.[16] Current plans of the DoD include the replacement of all traditional radio equipment with software based radio devices, with an estimated budget of 4.7 million USD for the next four years.[17]

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[12] http://en.wikipedia.org/wiki/Software_defined_radio#History
[13] http://jtrs.army.mil
[14] http://en.wikipedia.org/wiki/Software_defined_radio#History
[15] http://www.crc.ca./en/html/rmsc/home/sdr/sdr?pfon=yes
[16] http://www.mitre.org/work/tech_papers/tech_papers_03/nguyen_radio/nguyen.pdf
[17] http://www.embeddedstar.com/press/content/2004/7/embedded15637.html

2. Fixed Digital Hardware Based Radio Systems

2.1 Disadvantages of Traditional Hardware Based Systems

For the past two decades, digital hardware based radio systems have been dominantly prevailing the radio technology in the commercial world.[18] Although these systems have provided the industry with reliable services, there are numerous problems and disadvantages associated with hardware intensive architectures which have eventually led to the gradual shift to software based solutions. In the following, we explore some of these negative attributes.

First of all, radio functions have traditionally been in the realm of a complex composition of various hardware components. For as in base stations as one example, these structures include a mixture of radios, control architecture, and communication and control infrastructure.[19] Numerous fixed components operating in concert are required for the processing and transmission of different radio signals in such systems. The resulting problem is inflexibility, prohibiting interoperability of different standards and limiting support and processing capacities to only one set air-interface protocol with hardware based systems. [20]

The rapid sophistication of wireless standards presents yet another major problem. Several wireless transmission standards such as the General Packet Radio Service (GPRS), Enhanced Data Rates for GSM Evolution (EDGE) and 3G standards are evolving and have become a reality. However, since hardware systems are only capable of processing one protocol through one system, service providers would require to deploy

[18] http://ourworld.compuserve.com/homepages/jmitola
[19] http://www.aircom.com/cti-reprint.pdf
[20] http://www.eetimes.com/article/showArticle.jhtml?articleId=12801539

several towers at all sites to accommodate multiple standards since legasets (legacy handsets) do not disappear instantaneously as desired by the providers.[21] This results in unfavorable long time-to-market duration and decelerates the innovation circle for the industry. Another possibility would be to upgrade the hardware infrastructure as new technologies and standards emerge. However, this proves to be inefficient and only possible through cost intensive hardware modifications or replacements.[22]

For service providers of wireless communication, backhaul costs can be identified as another major disadvantage. The traditional scenario requires either the lease of T1 lines from local exchange carriers (LEC) or competitive providers (CLEC) for each remote base station in order to backhaul traffic, or fixed microwave facilities. Taking into consideration that numerous base stations usually are deployed to achieve greater coverage, the monthly recurring backhaul costs are significant.[23]

3. The Emergence of Software Defined Radios

Although the militaristic endeavors as described earlier had demonstrated the advantages provided by software based radio systems, it was not until few years ago when SDR finally started unfolding its viability for commercial applications.[24] As wireless technology has made its step into the new century, the commercial implementation of SDR has proved to be more cost effective and feasible, leading toward the gradual transition of traditional hardware intensive digital architectures being replaced by software based radio solutions. The continuous progression in the

[21] http://www.intel.com/update/contents/wi07031.htm
[22] http://www.aircom.com/cti-reprint.pdf
[23] http://www.aircom.com/cti-reprint.pdf
[24] http://www.arrl.org/tis/info/sdr.html

technological areas of embedded microprocessing, A/D conversion, object-oriented programming and RF digitization has enabled the development toward such software based radio systems.[25]

3.1 SDR Concept Definitions

There are numerous definitions of Software Defined Radio in existence, all of which are not totally consistent with each other. The Federal Communications Commission (FCC) defines SDR as a "generation of radio equipment that can be reprogrammed quickly to transmit and receive on any frequency within a wide range of frequencies, using virtually any transmission format and any set of standards".[26] The International Telecommunication Union (ITU) has proposed a definition of SDR as a "radio in which the operating parameters including inter alia frequency range, modulation type, and/or output power limitations can be set or altered by software".[27] In contrary, the SDR Forum, as an international, non-profit organization promoting the development of SDR, offers a broader definition: "Software defined radio is a collection of hardware and software technologies that enable reconfigurable systems architectures for wireless networks and user terminals".[28] One reason for the advent of several inconsistent definitions is probably due to the broad and complex nature of technology itself, and the variety of possible means for implementation of SDR systems.

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[25] http://jtrs.army.mil/sections/technicalinformation/fset_technical.html
[26] http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2000/nret0004.html
[27] http://www.sdrforum.org/MTGS/mtg_38_apr04/04_i_0036_v0_00_cognitive_radio_04_26_04.pdf
[28] http://www.sdrforum.org/sdr_brochure_10_24_02.pdf

3.2 Five Tiers of Software Defined Radio

The complexity of the SDR construct has led to the existence of many, inconsistent definitions. With the goal to promote a more common understanding of the technology, the SDR Forum has established the five tiers encompassing different categories of software radio systems. [29]

Tier 0 describes hardware based radios, and is actually not considered to fall into the realm of SDR. The simplest SDR technology begins with Tier 1, which describes software controlled radios (SCR) with only the control functions being processed by software.[30] The simplest example to this is a dual mode cell phone, which consists of two hardware radios for two different standards. The software simply controls which radio should be utilized. Later upgrades to new evolving standards are not possible.[31]

Reconfigurable software defined radios present Tier 2. As implied by their name, these SDR systems include reconfiguration by allowing control over modulation techniques, security functions (such as frequency hopping) and waveform requirements over a broad frequency range provided by software. Tier 2 SDRs include processing applications such as application-specific integrated circuits (ASIC), field-programmable gate arrays (FPGA) and digital signal processors (DSP).[32] Although reconfigurable SDRs are the most commonly used systems today, especially for military applications, due to the rapid sophistication of the general SDR technology these systems become

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[29] http://www.wsdmag.com/Articles/ArticleID/6509/6509.html
[30] http://www.wsdmag.com/Articles/ArticleID/6509/6509.html
[31] http://www.findarticles.com/p/articles/mi_m0HEP/is_2_21/ai_98010339
[32] http://www.wsdmag.com/Articles/ArticleID/6509/6509.html

increasingly obsolete.[33] One example for a Tier 2 system is the earlier discussed SpeakEasy system.

Tier 3 software defined radios, also called ideal software radios (ISR), will eventually become the mostly implemented systems within the near future. Based on the extended possibilities of programmability to the entire system, analog conversion will be completely realized only by the antenna, microphones and speakers. Heterodyne mixing components, which serve the function to convert incoming radio frequency to a constant frequency, are eliminated in ideal software radios, as well as components for analog amplification.

In contrary, Tier 4 systems are currently not more than merely a vision of SDRs. The SDR Forum declares that ultimate software radios (USR) as Tier 4 technologies “are defined for comparison purposes only”.[34] In theory, these USRs are supposed to be capable of supporting a broad frequency range, air-interfaces and applications, allowing switching between air-interface formats and different applications within only milliseconds.[35]

[33] http://www.findarticles.com/p/articles/mi_m0HEP/is_2_21/ai_98010339
[34] http://www.sdrforum.org/faq.html
[35] http://www.sdrforum.org/faq.html

4. Advantages of Software Defined Radios

The term software defined radio was first coined in the year 1991.[36] With radio functionality embedded and processed within software modules, there are numerous advantages associated with the SDR technology.[37] The following passages will provide an overview about these potentials.

The greatest advantage of the implementation of SDR systems is the introduction of new means of inherent dynamic flexibility and upgradeability. [38]

SDR is based on open architecture and consists of a common, generic hardware platform, which allows for flexible installment of different software applications as required for signal transmission.[39] These generic hardware platforms might be used for support of different protocols, services and products. The results are multiband, multimode radio systems able to conform to various protocols such as AMPS, TDMA, CDMA or GSM, which are the most used air-interface standards currently. It is widely believed that TDMA and GSM will eventually merge to one standard in the near future.[40] Taking into consideration that millions of subscriber handsets are currently in use that would not conform to this standard, the instant mergence of both standards would be nearly impossible. Through the coexistence of several software modules within one system and their programmability, accommodation and dynamic support of different standards becomes possible.[41]

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[36] http://www.findarticles.com/p/articles/mi_m0HEP/is_2_21/ai_98010339
[37] http://www.wipro.com/insights/softwareradio.htm
[38] http://ourworld.compuserve.com/homepages/jmitola
[39] http://jtrs.army.mil/sections/technicalinformation/fset_technical.html
[40] http://www.aircom.com/cti-reprint.pdf
[41] http://www.aircom.com/cti-reprint.pdf

Interoperable systems facilitate reduction of the time-to-market duration, since during transition phases to new technologies, legacy and new standards can coexist until the market's final acceptance of the new standard, enabling faster integration of new technologies and resolving the tyranny of legasets.[42]

Especially toward the evolution of future standards supporting high-speed data services, such as the previously mentioned GPRS, EDGE and 3G, software defined base stations will be of advantage enabling integration of multiple protocols and dynamic capacity shifting between services as required.[43] The positive impact on future capital costs for service providers through less required infrastructure deployment could eventually cause lower service charges for subscribers.[44]

Along with the flexibility comes the leverage of efficiency and sustainability of radio systems through functionality processed within software modules. Since the need for hardware modifications and replacements is being eliminated through SDR, provider equipment can be used for an extended period of time as insertion and reconfiguration of new standards becomes much easier, either through over-the-air uploads or directly on-site.[45] Less fixed hardware components also means less maintenance, as well as the utilization of a generic hardware platform results in cheaper equipment costs.[46]

SDR also provides the advantage of promoting a more efficient use of the spectrum, as described as an example in the following scenario. The requirement to provide backhaul through leased lines or fixed microwave facilities in traditional

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[42] http://www.eetimes.com/article/showArticle.jhtml?articleId=12801539
[43] http://www.aircom.com/cti-reprint.pdf
[44] http://www.aircom.com/cti-reprint.pdf
[45] http:jtrs.army.mil/sections/technicalinformation/fset_technical.html
[46] http://www.eetimes.com/article/showArticle.jhtml?articleId=12801539

architectures presents a huge cost factor for wireless service providers, as described earlier.

Through SDR, providers are not limited to physical backhaul links since parts of the radio spectrum could be utilized for wireless backhaul to software based central base station controllers. Single base stations are wirelessly connected to the controller, with only one central physical link remaining which connects the wireless infrastructure to the mobile telecommunications switching office. This presents a much more cost effective solution, eliminating a huge part of recurring operating costs and promoting an efficient way of allocating resources to meet subscriber needs.[47]

Furthermore, base stations can be adjusted and relocated easier as coverage and capacity demands change since a physical link is not required. Software base stations will also allow for easier deployment because of less hardware components that result in smaller system size.[48] SDR integrated base stations present great opportunities to providers of mobile and cellular services.

As for subscribers, the same advantages will be available in mobile handsets, such as in cellular phones, PDAs, laptops or other handheld devices. This includes accommodation to multiple communication standards and air-interface protocols, migration capabilities to new emerging standards through software downloads and programmability through software modules.[49]

However, even more important than for provider equipment, the integration of SDR in subscriber sets will require consideration of two important technical factors. As

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[47] http://www.aircom.com/cti-reprint.pdf
[48] http://www.eetimes.com/article/showArticle.jhtml?articleId=12801539
[49] http://www.privateline.com/Switching/sdr.html

for one, integrated chips will need to be designed in a reasonable size for handheld devices, as well as power consumption issues have to be considered.[50] Of greater importance is how service providers will solve the dilemma on “issues such as fraud, billing of calls and levels of service”.[51] Economical aspects and the willingness of providers to cooperate will dictate the further integration of SDR in subscriber devices.

The ultimate goal is the development of handsets which enable access to a variety of different wireless services. Software defined radio has the ability to support handhelds that could finally help this ever existent dream of convergence to become reality. Numerous applications such as cellular phone services, web browsing, email, global positioning or video conferencing could be integrated into one system.[52] Although these kinds of highly convergent systems are not even close to being realistic at the moment, the fact that SDR carries these great potentials makes it even more exiting to follow its future path.[53]

Overall, the FCC hopes that the implementation of SDR will promote a more efficient use of the spectrum, expand access to wireless services and encourage more competition among service providers.[54] Table 2 concludes this section with a comprehensive overview of the advantages as described.

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[50] http://www.uni-duisburg.de/FB9/KT/veroeftl/itg_01_03_29.PDF
[51] http://www.privateline.com/Switching/sdr.html
[52] http:www.intel.com/update/contents/wi07031.htm
[53] http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci333184,00.html
[54] http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2000/nret0004.html

Interoperability:	Support of multiple standards through multimode, multiband radio capabilities
Flexibility:	Efficient shift of technology and resources
Adaptability:	Faster migration towards new standards and technologies through programmability and reconfiguration
Sustainability:	Increased utilization through generic hardware platforms
Reduced Ownership Costs:	Less infrastructure, less maintenance, easier deployment

Table 2: Advantages of software defined radio

II. Technological Overview

Software defined radio architectures have continuously evolved since the inception of the flexible-radio concept. New advances in digital components proceed to modify even the latest designs, thwarting attempts to define specifications. The SDR Forum is working in conjunction with a variety of vendors and industry partners to develop a process of standardization to achieve general compatibility between devices. The Forum has submitted a proposal to JTRS for high-speed signal processing standardization in order to avoid the danger of limiting the potential for SDR if vendors create non-interoperable proprietary designs.

In the technological overview, a conventional receiver will be examined, the overall architecture of SDR will be discussed, and various component implementations and design possibilities will be addressed. Finally, this section will review the risks and concerns associated with the development of this revolutionary technology.

1. Conventional Radio

In an effort to best understand the processes behind software defined radio, an overview of a conventional radio component strand can provide clarification. For a conventional radio super-heterodyne radio system, the radio frequency (RF) enters through the system antenna and travels through a band-pass filter, eliminating unwanted frequencies. The permitted signal is then taken through a heterodyne procedure, passing through a localized oscillator (OC) where a new signal is introduced and mixed with the RF; the result of this analog down-conversion is known as the intermediate frequency (IF). The IF may pass through additional OC stages depending on the frequency required by the analog-to-digital converter (A/D), a component which converts the signal to its digital equivalent. The signal is then carried to the digital signal processor (DSP) or generic processor (GPP), decoding and relaying data to the user interface (see figure 1).

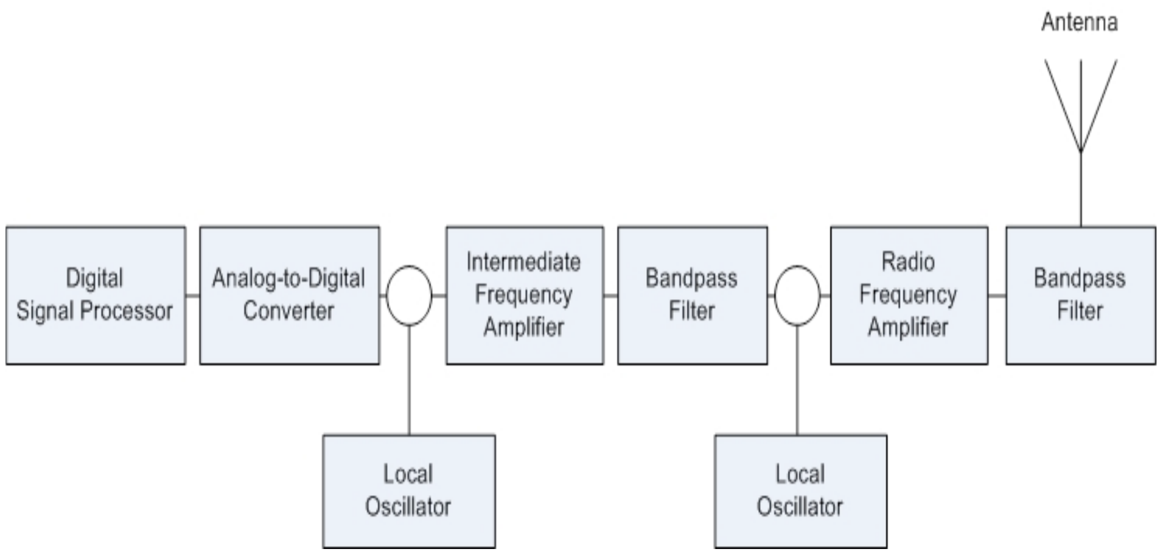

Figure 1: Radio Frequency Generic Model[55]
(adapted from Shinichiro Haruyama, Sony Computer Sciences Laboratories)

Current analog to digital converters cannot process high frequencies without the implementation of filters and oscillating mixers which reduce the rate of the frequency into a more manageable IF or baseband waveform. The down-conversion process may occur as often as necessary to achieve an adequate signal frequency.

[55] http://www.csl.sony.co.jp/ATL/papers/Haruyama_Kluwer_book_chapter6_2000.pdf

1.1 Analog Limitations

For a conventional radio system to maintain multimode, multiband compatibility, it must contain a unique component strand for each mode of operation, a requirement which is simply impractical from a cost, space, power, and efficiency standpoint. A software defined radio aims to integrate multiple components of these stages into a single strand to create the versatility required to make modifications on the fly.

Although the ability does exist to integrate all front-end analog components into a single chip with Monolithic Microwave Integrated Circuit (MMIC) technology, analog components are impractical for wide-band transmissions in a 3G environment, having inherent performance limitations.

In addition to being traditionally narrowband in nature, analog components suffer from the effects of aging, temperature variations, and lack the linearity of their digital counterparts, resulting in several signal integrity issues, including harmonic distortion that arise in the output signal of the analog component. When a signal enters a nonlinear component, the output may contain multiple instances of the original signal, located at spectral intervals near the original frequency of the desired signal.[56] [57]

In an ideal software defined radio, the radio frequency would be converted to a digital format immediately upon entering the system. The main constraint which prohibits this design is the sampling rate required from an A/D to create a digital signal. ADC technology continues to advance, but perhaps not at the same speed of SDR breakthroughs. The Texas Instruments Digital RF Processing (DRP) technology has

[56] http://www.ep.liu.se/exjobb/isy/2003/3448/exjobb.pdf
[57] http://www.csl.sony.co.jp/ATL/papers/Haruyama_Kluwer_book_chapter6_2000.pdf

effectively sampled an RF at a frequency of 2.45 GHz. However, the signal was only 1 MHz wide, a far cry from the 5 MHz channels found in a 3G environment.[58]

The sampling rate for all signal converters is restricted by the Nyquist Theorem which states, “When converting from an analog signal to digital (or otherwise sampling a signal at discrete intervals), the sampling frequency must be greater than twice the highest frequency of the input signal in order to be able to reconstruct the original perfectly from the sampled version.”[59] In other words, if a 50 MHz signal is to be sampled, it must be sampled at a minimum of 100 MHz to accurately re-create the signal.

The Nyquist Theorem expects relatively high amounts of processing power, resulting in a rather tall order for A/D processors to fill. Consequently, for SDR technology to realize compatibility with high-frequency waveforms, an alternative process, known as undersampling, exists. Undersampling eliminates multiple stages of signal down-conversion, and like most aspects of software defined radios, it is a rather complicated process (a continuous theme), enabling the analog-to-digital converter to sample at less than twice the frequency of the signal. Though potentially beneficial for converting higher frequencies, obstacles such as jitter and phase noise can corrupt the undersampling process.[60]

In addition, the emergence of standards with very complex modulation schemes, such as IEEE 802.16e and 802.20 will add even more complexity to the data converter

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[58] http://www.eetimes.com/showArticle.jhtml?articleID=51200491
[59] http://en.wikipedia.org/wiki/Nyquist's_theorem
[60] http://www.pentek.com/support/GetOTD.cfm?Filename=PutUndersamp.pdf

design, requiring developers to create design improvements for data converters in the areas of calibration, higher sampling rates, and a higher speed of signal processing.[61]

2. SDR Possibilities

The ultimate goal of the SDR is complete versatility and programmability. The only way to reach this level of performance is through the continually mentioned elimination of fixed analog components which hinder adaptability and are limited in function. There are countless proposed SDR architectures currently in circulation, and the actual component layout will vary by application. For example, a mobile phone configuration would likely differ from that of a personal computer with SDR capabilities due to the different operating modes of the two devices.

In an ideal SDR architecture, the ideal software defined radio has replaced analog components with digital equivalents, and simplified device design through the compilation of several traditionally independent components into single chips. The antenna is multimode in nature, with the ability to receive a variety of signals. The process of RF down-conversion and digitization occurs immediately upon entry of the signal into the system, and both processes are contained on a single chip.

A theoretical baseband chipset would contain a combination of digital signal processing (DSP) and field programmable gate array (FPGA) units. Due to the relative newness of the technology, the actual number of DSP and FPGA components varies from

[61] http://www.eet.com/showArticle.jhtml?articleID=49901125

system to system, but the general consensus is that multiple microprocessors must co-exist on the baseband chipset for optimal functionality. The Control and Maintenance bus uses the Portable Operating System Interface (POISX) and Common Object Request Broker Architecture (CORBA) interfaces, and will be discussed further. Though a security chipset is not required for all applications, most mobile handsets and base stations will likely contain the necessary security devices to ensure customer privacy and maintain system integrity.

3. Critical SDR Components

"There is no 'right' way or 'wrong' way to design a consumer electronics product. There is only the imperative to get something inexpensive that works, and sells out the door really fast."[62] This ideology holds very true for software defined radio development. The processes required for SDR operation is understood. However there are many roads which lead to a similar destination.

It is inarguable that in an ideal setting, the digital conversion of the desired signal would happen immediately upon entry into the system, though numerous road blocks currently prevent a direct-to-digital scenario. There has been growing debate among experts over the most effective combination of Application Specific Integrated Circuits (ASIC), Field Programmable Gate Arrays (FPGA), and Digital Signal Processors (DSP) to handle the steep system requirements for advanced wireless systems.[63] All of these

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[62] http://www.eetimes.com/showArticle.jhtml?articleID=51200499
[63] http://www.eetimes.com/showArticle.jhtml?articleID=49901142

components are essential for operation, but the actual need for each component will be based upon a needs assessment of the users.

3.1 Digital Signal Processor (DSP)

The heart of the software defined radios rests in the digital signal processing units. These components implement upper layer protocols in a real-time format, and are manipulated by onboard software, allowing for the interpretation of a variety of signals by simply activating the appropriate software.[64] Using a complex series of algorithms, DSP chips perform functions like channel and source encoding/decoding, filtration, error checking, and modulation/demodulation procedures.[65] Containing a high-speed processing block known as a MAC (Multiply and Accumulate), a DSP processes the signal by retrieving instructions and data from memory, performs requested operations, and stores the results back to memory.[66]

The major drawback of DSP units is that they lack the proper processing speeds required for wideband transmissions. To compensate for inadequate performance, some designers suggest that running two DSPs in parallel will result in sufficient function for SDR handsets, and can possibly accommodate the necessary encoding/decoding and symbol processing without the need of ASIC units.[67]

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[64] http://www.telfor.org.yu/telfor2001/radovi/11-15.pdf
[65] http://engnet.anu.edu.au/DEcourses/engn6612/tuta/reports/sdr1_report.pdf
[66] http://www.csl.sony.co.jp/ATL/papers/Haruyama_Kluwer_book_chapter6_2000.pdf
[67] http://www.commsdesign.com/showArticle.jhtml;jsessionid=Q04G4WB3G3ET4QSNDBCSKHSCJUMEKJVN?articleID=49901142

3.2 Application Specific Integrated Circuit (ASIC)

ASICs perform signal downconversion, digital filtration, and perform at higher rates of speed than FPGAs. Traditionally smaller in size, ASIC chips are designed for specific purposes, and therefore, are not reprogrammable. This is almost a blessing in disguise, resulting in a dedicated device which has a far more efficient power requirement than general purpose processors.[68] Due to the operation-specific nature of ASIC chips, each chip must be designed for a specific application, and can then be reproduced rather cost effectively.

3.3 Field Programmable Gate Array (FPGA)

FPGAs are completely programmable devices which can perform a variety of user-defined tasks including digital down-conversion, signal processing, and filtration. Although FPGAs operate slower than ASIC circuits, in terms of embedded memory both are comparable devices. However, when it comes to logic, FPGAs only have a small fraction of the capacity that can be found in ASICs.[69]

Many advocate the use of FPGA chips in SDR applications since they can be implemented “off the shelf,” unlike ASICs which need to be created for each specific product. It is suggested that FPGA chips can be integrated along side a DSP, handling a majority of operations; allowing the DSP to operate closer to the level of performance required for wideband applications by leaving only symbol processing to the DSP. Systems which contain both FPGA and DSP chips can deliver signal-processing

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[68] http://videos.dac.com/videos/40th/46/46_3/46_3.pdf
[69] http://www.us.design-reuse.com/articles/article4360.html

capabilities ten times more efficiently than with a DSP alone, presenting the welcomed advantages in cost, power, and system footprint.[70]

3.4 Moore's Law

Although the current "system on a chip" (SOC) market conveys processing units which hint at the future from a speed and capacity standpoint, these devices benefit from a phenomena known as Moore's Law. This fabled law was established in 1965 by Intel co-founder Gordon Moore who observed, "The number of transistors per square inch on integrated circuits has doubled every year sense the invention of the integrated circuit, and will double every year into the foreseeable future."[71] Though the pace of data density has since slowed down to double on average every 18 months, the basis of this law indicates that performance capabilities will increase. It is anticipated that there will soon be an economical solution to multiband, multimode receivers which will handle wideband channels of communication, maintain affordability, and shall be packaged in a compact and efficient design.

4. Antenna Considerations

Although conventional radio designs traditionally use only a single antenna which is specific to the desired range of frequencies compatible with the device, software defined radios present yet another unique challenge for developers, as multiple antennas,

[70] http://www.commsdesign.com/printableArticle/?articleID=16502395
[71] http://www.webopedia.com/TERM/M/Moores_Law.html

or individual "smart" antennas can be used to intercept the widest range of frequencies possible.

Fortunately, base station design does not hinge on the factor of portability, permitting the feasibility of a multi-antenna design. In the base station, power and system optimization are still a concern, but the stationary nature of these units is more forgiving in these matters. A more complex solution must be found for the other side of the transmission; the mobile unit. Most mobile telephones operate in a fixed frequency range, resulting in the necessity for the utilization of only one antenna. The SDR mobile phone however, aims to operate in various frequency ranges, requiring an innovative solution to the antenna matter.

Consistent designs have not yet emerged, but the potential exists for the user to quickly change antennas depending on the desired function. However, this scenario limits the type of operations able to be performed at one time. Other possibilities include a small antenna array of two antennas, and perhaps ultimately the antenna dilemma will be solved by the price of the unit and the functions desired by the consumer.

5. Framework for Interoperability

Other architectures exist beyond the physical realm. The complexity and limitless potential for SDR configurations requires a model of reference implementation (RI) to establish behavioral criteria and define coding for technical aspects of the device. The Software Communications Architecture (SCA) has been implemented to ensure interoperability between manufacturers. SCA was originally developed by JTRS, but numerous organizations, such as the Communications Research Centre (CRC) of Canada, the SDR Forum, and the Object Management Group (OMG) have collaborated to create a regulated method of software operations. Several versions of the SCA Core Framework exist dependent on desired applications, ranging from generic operation to specific. SCARI, an open-source implementation written in a Java, establishes the core framework, service interfaces, and certain waveform applications. Other versions of SCA also exist, including SCARI2, SCARI-Hybrid, and SCARI ++. SCARI++ is the most flexible software framework program available, allowing dynamic reallocation of resources during runtime and enabling the debugging of waveform applications in addition to logical devices.[72]

This core framework does not define the specific architecture of the modem (combined general purpose processor, DSP, and FPGA devices a manufacturer selects to support specific waveforms.) Instead, the SCA Core Framework establishes a series of regulations designed to standardize the process of waveform object connections related to each unique channel.[73] Using SCA Framework only to identify specific associated waveform objects does not ensure software and hardware interoperability, but it guarantees that defined waveforms will be successfully received.

There are two main operation features of the SCA Core Framework: the Common Object Request Broker Architecture (CORBA) and the Portable Operating System Interface (POSIX). CORBA is what is known as a "middleware," or software that connects different components or applications and allows them to exchange information. It is agreed that the official implementation of CORBA into SDR architectures creates a Unix-like environment and lower cost radios by reducing time for

[72] http://www.crc.ca/en/html/rmsc/home/sdr/projects/scariplus
[73] http://www.spectrumsignal.com/publications/Extending_SCA_Inside_SDR_Modem_Architecture.pdf

design decisions and testing. Other benefits of a standardized middleware include reduced delivery time for future SDR products due to the enhanced adaptability of CORBA, the fault tolerance necessary for a device to operate in a variety of signal conditions, and the optimization of power consumption in battery-operated devices.[74] POSIX is a universal operating system based upon UNIX, a manufacturer-neutral program, which allows for the interoperability of SDR devices. It is also open-source, allowing everyone interested in developing a software defined radio the ability to acquire the operating system without being subjected to unnecessary expenses.

6. Governing SDR Architecture

Over the past decade, there has been an overall migration away from integrated systems in exchange for technologies based upon open architecture designs. Integrated systems are efficient in terms of design and operation, yet their inclusive nature makes them extremely resistant to any modification or update. Open architectures, on the other hand, allow for a more convenient interchange of individual components. This is the essence of SDR, combining multimode and multiband operations with the adaptability to adhere to new standards and requirements, and making SDR a truly versatile technology.

[74] http://www.eetimes.com/printablePressrelease.jhtml?articleID=86748&CompanyId=

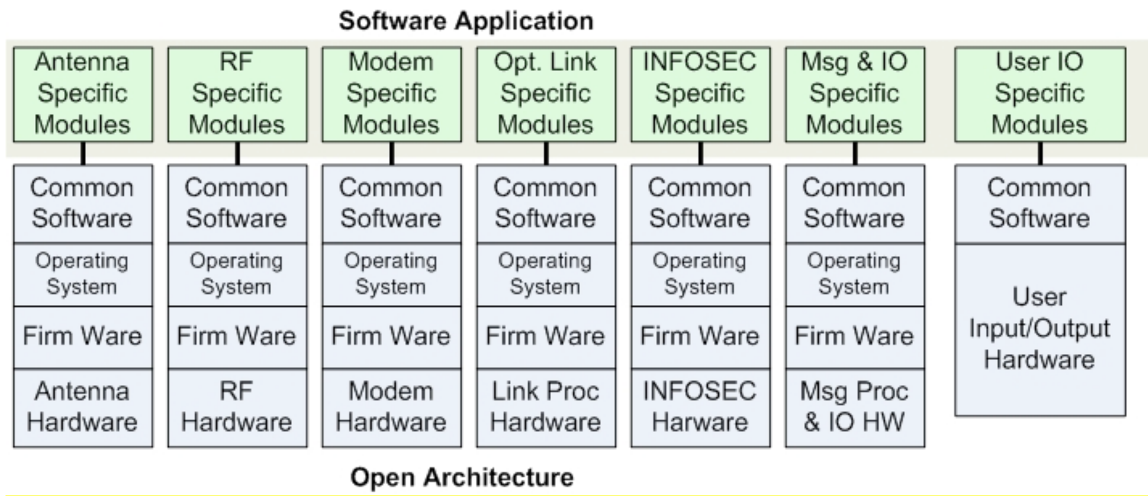

Figure 2: Typical Implementation of SDRF Software and Hardware Open Architecture[75]
(adapted from the Software Defined Radio Forum)

The SDR Forum has proposed a generic open architecture (figure 2) based on seven independent subsystems connected through a control interface (software application). Each subsystem contains necessary hardware, firmware, an operating system, and software modules which manage the function of the subsystem. The actual number of subsystems is dependent upon the role of the hardware; as modes exist that do not require all subsystems for functional operation. Separate interfaces link the subsystems together, and are all managed by a single control layer.

7. Security Implications

In the continuing effort to release innovative products, the technology industry has made sufficient gains from a recently suffering economic environment. However, technological advances always open new opportunities for exploitation. The accessibility and versatility of consumer-driven technology has allowed criminals to utilize it for

[75] http://www.sdrforum.org/sdr_primer.html

personal gain, and this has discouragingly become a growing trend as the number, sophistication, and sheer costs of these attacks are increasing at a constant rate. By August of 2003, computer viruses and worms had already caused businesses and consumers a total of $140 billion in damages and losses for that year alone, almost twice the total of 2002.[76] The software defined radio platform will surely usher in a new series of opportunities for criminal activity, and it is up to the FCC and industry partners to ensure that proper steps are taken to minimize potential damages.

Since its inception, the software defined radio industry has been given legitimate room to grow. The Federal Communications Commission (FCC) was supportive of the initiative and opted to decline the enforcement of security conditions and regulations to allow the technology and its developers make as many advances as possible.

On 13 September 2001, the FCC removed barriers of SDR entry into the marketplace and adopted the Software Defined Radio First Report and Order. In the Report and Order, the FCC announced its position on security and stated that it is vital "to ensure that software changes cannot be made to a radio that will cause it to operate with parameters outside of those that were approved in order to prevent interference to authorized radio services." However, the FCC did leave the window open, stating that “It is possible that we may have to specify more detailed security requirements at a later date as software defined radio technology develops.”[77] Three years have now passed since establishment of the SDR First Report and Order, and legitimate concerns have begun to surface, as the age of SDR implementation draws closer.

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[76] http://www.pbs.org/newshour/bb/science/july-dec03/cw_12-1.html
[77] http://www.enhyper.com/content/sdr.pdf

Traditionally, wireless networks are more susceptible to attack than their wire-line equivalents. In 2001, an attack in Japan sent a malicious email to 13 million users of NTT DoCoMo's i-mode, a phone service with Internet capabilities. When the user would open the infected e-mail, the mobile device would repetitively dial a Japanese emergency service (comparable to United States 9-1-1 service) every 20 minutes.[78]

The programmability of SDR devices could present new opportunities for similar acts to the one mentioned above, in addition to other security violations including account and personal information theft (many mobile phones contain contact names and numbers), network manipulation, and download access. The SDR industry is presented with a difficult challenge, and will likely establish a set of universal guidelines for download, authentication, authorization, system integrity, and confidentiality. With a flexible, programmable device, it is certainly unreasonable to completely prevent all user-oriented attacks, but through the standardization of system operation procedures and a unified industry, significant precautions can be established.

III. Applications, Regulation and Potentials

Software defined radio has immediate ramifications in the military and civil service sectors where the need for an interoperable system has driven forward the development and implementation of the technology. Beyond the scope of these governmental bodies, there is a multitude of changes that will have great impact in the long and short terms as SDR becomes available and grows into an underlying part of the

[78] http://www.enhyper.com/content/sdr.pdf

wireless information and communication infrastructure. This section of the document will address the ramifications of SDR as an agent of change in the wireless telecommunications landscape.

1. Applications

1.1 Civil Sector Services through SDR

As discussed previously, software define radio has been defined in no small part due to the need of the United States military to develop a system of interoperability. The continued use of SDR based systems and solutions for military applications will continue far into the foreseeable future and beyond. A relatively newer and highly critical application that has contributed to the drive towards software defined radio is the need for a unified system in the civil service sector. The needs of police, coast guard, fire, EMT, and other such civil serving agencies, organizations, and entities to have a common communication linkage contributes to what defines the market for SDR within the context of the present time and day.

11 September 2001, as it did in so many other sectors, had a massive impact on the burgeoning development of software defined radio. The inability of fire, police, port authority, and other civil service industries to coordinate plans and the ascension of fire fighting units into the upper floors of the soon-to-collapse World Trade Center towers demonstrated the need for interoperability of communications systems in civil services.

The Homeland Security Act's number two priority calls for the interoperability of public safety communications.[79]

The current problem in civil service communications is caused by the spread of allocations for the different public service entities existing across a wide span of spectrum. Interoperability is not possible under the current architecture. The events of 11 September and this interoperability problem have led such interest groups as the National Volunteer Fire Council and the National Governors Association to support legislative action to further the push towards interoperability.[80][81]

The 1996 Telecommunications Act mandates that RF spectrum currently allocated to broadcasters be made available for civil communications. This action is based on the movement towards digital television standards. Reliance upon this legislative action as a catalyst for change within civil sector communications is problematic. The legislation dictates the year 2006 as a final date for the relinquishing of certain frequency allocations currently utilized by television broadcast operators, but allows a provision that extends that date until a market availability of 85% for digital television sets for end users becomes a reality. This creates some uncertainty about the availability of new spectrum allocations for civil services usage.

The larger problem in reliance upon allocation as the solvent measure for the interoperability problems in the civil service sector is reflective in the very nature of an allocated solution. Allocation attempts to view the RF spectrum as a physical property that can be bought, traded, sold, and bartered between those who would wish to use that

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[79] http://www.all-hands.net/pn/news_index422.html
[80] http://www.nga.org/nga/legislativeUpdate/1,1169,C_ISSUE_BRIEF%5ED_3298,00.html
[81] http://www.nvfc.org/leg/hero_act.html

RF property. As this will be covered in a later section, allocating spectrum does not address how a more diversified spectrum usage can generate greater outcome for the spectrum users.

In terms of civil service operators, continued relegation of each entity into its own sectorized area would only add to the interoperability problem. A common, unified allocation is one conceivable possibility, but this fails to address the investment held in legacy equipment. Furthermore, a common area of allocation would not become wise in the event where intradepartmental or intra-entity communications are required. The reallocation of spectrum to civil services will be a positive for operators in the sector, but only if done within a construct of a spectrum management plan centered on better use of spectrum to permit more throughput for those who require it. Software defined radio provides such a construct.

For the legacy issue, a rudimentary software defined radio system is already being applied towards achieving interoperability within legacy environments. Software vendor Vanu Inc. has developed a software-based interoperability device that can be immediately implemented in the civil service sector, the Software Radio Interoperability Device.[82] Based on a computer, the device can provide virtual connections between different entities by centralizing the communications across the different spectrum allocations being used. Although addressing interoperability, the Software Radio Interoperability Device does not manage the data flow over RF transmission, as it performs functionality of a channeling mechanism. From a functional standpoint, the software functionality is still based upon a hardware solution. In order to achieve interoperability, users still

[82] http://www.vanu.com/publications/TheSoftwareRadioSolutiontoPublicSafetyInteroperability.pdf

require the purchase of hardware. Reliance on hardware does not move into the higher functions of software defined radio that are required to push forward the capabilities of the medium. Figure 3 is a screen capture from this software apparatus in use.

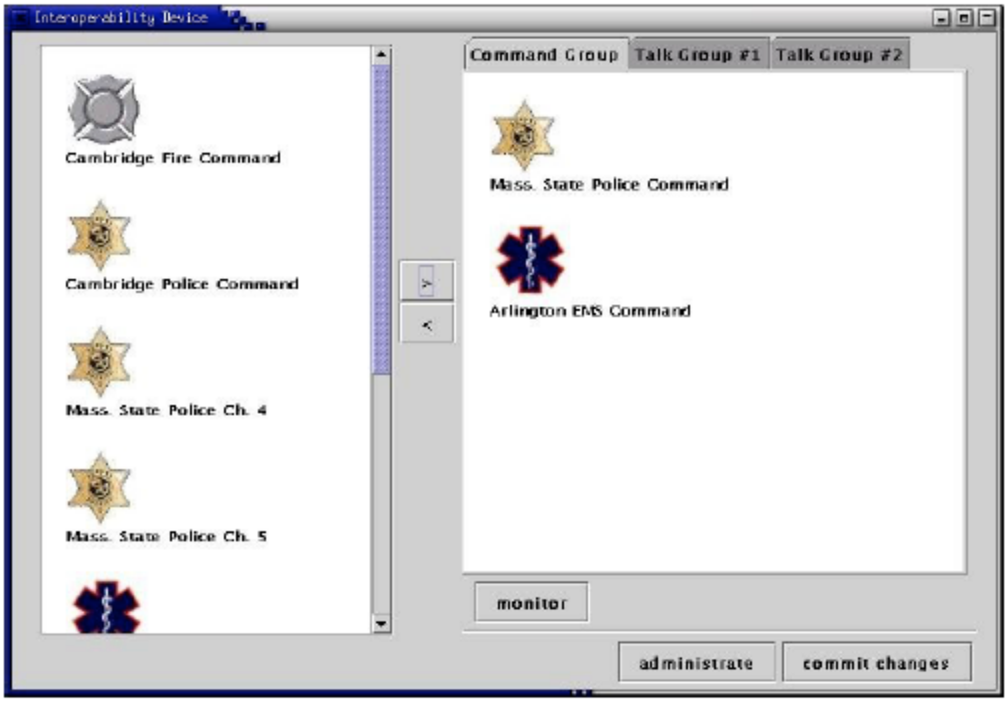

Figure 3: Software Radio Interoperability Device Screen Capture (by Vanu Inc.)[83]

As with allocating more spectrum space, the software solution as suggested by Vanu Inc. is a forward progression, yet it still does not address the larger needs that have developed within the civil service sector. Available radio frequency has a very high ratio of peak to average usage in the civil services sector, meaning that much available RF capacity is dormant for much of the time.[84] As in within other frequency division based systems, much usable throughput of the RF is unused as it is dormant in non-peak times.

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[83] http://www.vanu.com/publications/TheSoftwareRadioSolutiontoPublicSafetyInteroperability.pdf

[84] ftp://ftp.fcc.gov/pub/Bureaus/Engineering_Technology/Documents/cognitive_radio/marcus_public_safety_presentation.ppt

A cognitive, software defined approach that would manage allocation and usage patterns based on a need basis rather than an organization arrangement would allow for more throughput to be utilized and for more providers to utilize RF spectrum as a realistic solution.

Reaching a state at which radio transmissions and reception become totally software based within the civil services sector is still far from reality. As with many other new technologies and implementation plans, military use of SDR has benefited from standardization within the rigid structure of the military. Public services have no overriding agent of authority and standardization that can mandate standards. As the main drive for development lies within the hands of vendors and manufacturers, the plausibility for a mandated set of standards seems unlikely for the foreseeable future. In addition to the problems generated by an undefined set of standards, existing solutions that are available for implementation in the short term are extremely costly. As with any technology in its infancy, the lack of a mass produced solution has created costs in the range of tens of thousands of dollars, out-pricing many entities within civil services that are dependent upon fixed public funding.[85]

1.2 Applications toward Commercial Markets

The reach of SDR into commercial markets carries much potential in both the sense of the impact to be had upon commercial networks and the broader implications it could have upon shifting the regulatory paradigm regarding the manner in which frequency use is allocated. The caveat to SDR is that it is still far from reaching a critical

[85] http://www.embeddedstar.com/press/content/2004/7/embedded15637.html

mass from which to synergize momentum into other market segments. The paradigm for how SDR implementation will make an impact within commercial networks has itself gone through change as SDR moves from conceptualization to implementation. This section shall discuss the implications, players, and challenges in the realm of commercial application of SDR.

The original SDR conceptualization revolved around the end user. Mobile handsets would be utilized in a manner in which they could be reconfigured via software.[86] As discussed with civil service operations, the design implications for a handset would be too cost prohibitive and require too much power to be considered as a viable SDR solution. The current line of thinking shifts emphasis towards implementing smart base stations, implementing SDR on a network operations and infrastructural level. In this sense, SDR rollout in the foreseeable future within a commercial context will be in brethren with the solution put forth by Vanu Inc.

The primary area of emphasis for SDR solutions is wireless telephony. The effects of convergent media and deregulation have created an environment of a buyers market for wireless telephony and information services.[87] The forces of the market dictate that wireless operators must become more aggressive in offerings to cater to the needs of users in order to retain loyalty from those customers. The offering of data services in concert with the normative fare of telephony service is a possible vehicle in which to attain customer loyalty.

The current and short term potential market for SDR takes place within this context. User sets are not in a position to be reconfigured while operators wish to offer

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[86] http://www.spectrumsignal.com/publications/COTS0104_softerside1.pdf
[87] http://www.sdrforum.org/public/approved/03_a_0001_v0_00_business_case_01_28_03.pdf

additional services to users whose sets can support those features as a means of maintaining customer loyalty. Differing standards such as AMPS, GSM, TDMA, and CDMA exist within a framework usage that is in transition between 1st, 2nd, and 3rd generation standards. Network operators require a system of interoperability between the differing modulation schemes and customer needs. Base stations that can be dynamically reconfigured to match network conditions are desirable, and SDR is a viable solution to reach this point.

At this juncture, vendors have developed a small number of base terminals that represent the initial commercial use of software defined radio. Motorola is one such vendor that has a market product based on software that is designed to support legacy GSM and CDMA environments, the Horizon 3G.[88] [89] Airnet Communications is another vendor company that has a market entry with the GSM 850 Base Station System and the AdaptaCell BTS system (2003 Airnet).[90] [91] These SDR solutions provide interoperability with AMPS, TDMA, GSM, GPRS, and EDGE services. These systems provide an environment that supports rapid reconfiguration of the network and allow the foundation for enriched content delivery.

The adaptation of SDR into networks faces challenges in the economics of its rollout. Until units can be produced in mass, prices will be high. The value for operators is that SDR systems provide flexibility and versatility that can outweigh costs, making it a valuable proposition for implementation into networks.

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[88] http://www.motorola.com/content/0,,2225-4454-4793,00.html
[89] http://www.sdrforum.org/MTGS/mtg_25_sep01/01_i_0058_v0_00_usa_trends_09_25_01.pdf
[90] http://www.aircom.com/pr_adaptacell.htm
[91] http://www.aircom.com/pressrel/850-announce.htm

Once implementation becomes a reality, needs beyond interoperability develop. Transparency in the user experience requires that systems by interoperable and have a standardized look, feel, and operation. For this to become a reality, some industry standards must take hold.

As in other new technologies, overall forward momentum is dependent upon forward motion from vendors and end users. Until a critical mass develops in the give and take between vendors and purchasers, standards will not be uniform. To the end of generating forward momentum, the Software Defined Radio Forum has been formed by several stakeholders in the SDR field. This industry consortium is comprised of vendor, service, and user organizations that all share a common stake to gain through the deployment of software defined radio.

For the purposes of understanding the scope and landscape of the SDR field, table 3 lists some stakeholders. This list is derived from the SDR Forum's exhibitor list for the 2004 Software Defined Radio Technical Conference and Product Exposition, which was held in November 2004 in Phoenix, Arizona. The list is by no means inclusive of the totality of SDR stakeholders, but is representative of the types of organizations that have a vested interest in furthering software defined radio.

• General Dynamics C4 Systems	• Elektrobit Ltd.	• Pentland Systems
• Spectrum Signal Processing	• CRC	• AccelChip
• Interactive Circuits and Systems	• Lyrtech	• Zeligsoft
• Greens Hills Software	• PrismTech	• ADC
• Xilinx	• AirNet	• HelloSoft
• Pentek	• Gedae, Inc,	• Eonic
• Red River	• Symplicity	• Navsys
• Vanu, Inc.	• CoWare	• Objective Interface Systems.
• Harris Corporation	• Altera	• The MathWorks
• HYPRES	• Tektronix, Inc.	

Table 3: Vendors and stakeholders in Software Defined Radio[92] (adapted from SDR Forum.)

The number of interested parties acting as stakeholders in software define radio is indicative of the future potentials that exist within the framework of SDR. The challenge for these stakeholders is to create the standards within the regulatory structure available so that SDR can take hold. The next section of this document will discuss that regulatory environment.

[92] http://www.sdrforum.org/sdr04/exhibit_notice.html

3. Regulatory Environment

For SDR to flourish in a commercial realm, a favorable regulatory environment is a requisite. SDR appears to have a favorable environment in the short term as it does not work so much as to modify spectrum allocation, but to maximize efficiency and interoperability in the allocated space. In the long term, the emergence of SDR as a foundational standard makes conceivable the prospect of making the spectrum allocation as it is known today an artifact to be relegated to the past.

In a 2003 report, the Federal Communications Commission (FCC) addressed the problems of spectrum allocation. Rather than look at the problem as a function of too much use demand, the report took the stance that the allocation problem was a function of demand against time. Stated the document, "In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access."[93]

The FCC has taken a proactive stance in the development of software defined radio. In a 2001 press release, the FCC announced plans to push development of SDR by permitting paperwork filings in regard to SDR to be streamlined through the agency. Software changes can now be filled through a "permissive change."[94]

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[93] ftp://ftp.fcc.gov/pub/Bureaus/Engineering_Technology/Documents/cognitive_radio/shared_spectrum_cognitive_radio_technologies_v5_mchenry.ppt

[94] http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2001/nret0106.html

3.1 The Spectrum Allocation Problem

David Reed, an Internet pioneer, believes that SDR will eventually enable the dismemberment of the FCC.[95] Reed suggests that interference is not a natural phenomenon, but is a result of the inability of receivers to discern signals. In this model, problems such as multipath, high signal to noise ratio, and intermodulation are not occurrent in nature, but are a result of scientific application. Reed offers the solution of removing the FCC as a regulatory body overseeing the distribution of spectrum use and opening spectrum to any who would use it. Reed suggests that this option will generate higher throughput capacity through wireless channels but necessitating the development of better transmission methods and receivers.

The Reed model is supportable by a widespread adaptation of software defined radio as a standard. The FCC would be an archaic entity in a SDR based wireless world as the software would perform the function of the FCC. Software would dictate the spectrum to be used, modulation scheme, user access, and power levels for transmission. Under such idealized conditions, much of the current spectrum allocations could be reapportioned without a loss of service. The challenge of this idealized model is that such a level of SDR standardization is far from acceptance.

Much momentum in software defined radio is happening in unlicensed spectrum. One prospective use that offers much potential resides in the unlicensed industrial, science, and medical band. Ultra Wide Band (UWB), a system that offers promising high throughput at close ranges is a logical application of SDR. UWB based systems could use

[95] http://www.salon.com/tech/feature/2003/03/12/spectrum/index.html

SDR to control data flow and to switch into other transmission modes to exchange data. This area development is championed by Dr. Kevin Kahn, an Intel fellow whose research team utilized a software-based UWB experiment to pass 100 megabits of throughput.[96]

SDR theorists such as Reed, and pioneers such as Kahn, demonstrate the capabilities of software defined radio via small steps. For SDR to become a standard, the continued small steps of researchers, vendors, and other stakeholders must accumulate into a critical mass that can address the concerns of quantity of scale production, standards for deployment, universal interfaces, and regulatory distribution. The next segment of this document will address areas of potential development that lie beyond commercial applications.

4. Potentials for SDR

SDR offers much potential that escapes the realms of military, civil service, and terrestrial commercial applications. Software defined radio has application in extra-terrestrial space environments, including satellite communications and within the National Aeronautics and Space Administration. SDR also offers the potential to evolve into cognitive radio.

In the context of extra-terrestrial communications, SDR offers the same benefits of quick network reconfigurability and the ability to implement changes via uploads to orbital communications arrays as it does to terrestrial base stations.[97] This development

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[96] http://www.newswireless.net/articles/020528-kahn.html
[97] http://www.spectrumsignal.com/publications/An_SDR_Platform.pdf

provides prospects for expandability in satellites as hardware changes to satellites are prohibitive due to their high orbital nature.

The National Aeronautics and Space Administration (NASA) has implemented Spectrum Signal Processing's SDR system for the Cross Link Integrated Development Environment (CLIDE) program.[98] This system will allow for inter-satellite communications that can facilitate better earth coverage. This will permit fewer satellites to conduct greater numbers of scientific experiment.

Cognitive radio is the ultimate expression of the theoretical and practical application of software defined radio. Cognitive radio would be a system entirely defined via software that would have added functionality in geolocation and intelligence. According to Bruce Fette Ph.D., Chief Scientist of General Dynamics Decision Systems, cognitive radio is a SDR system that, "knows where it is, knows what services are available, for example, it can identify then use empty spectrum to communicate more efficiently, knows what services interest the user, and knows how to find them, knows the current degree of needs and future likelihood of needs of its user, learns and recognizes usage patterns from the user, and applies 'Model Based Reasoning' about user needs, local content, and environmental context."[99]

Cognitive radio is an extension of software based radio in that not only will the functionality of radio be performed in software, but also the intelligence of the system will no longer be reliant on the operator, but upon the software. Cognitive radio also adds an aura of legitimacy to David Reed's hypothesizing about the future need for the disbandment of the FCC in that cognitive, smart systems will be highly self-regulating.

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[98] http://www.spectrumsignal.com/publications/NASA_Spectrum_sdr.pdf
[99] http://www.gdds.com/radiosystems/pdf/FCC_Cognitive_Radio_Fette_v7.pdf

IV. Conclusion

The market possibilities and the technical feasibilities of software defined radio create an environment in which universal acceptance and deployment of SDR as a widespread wireless standard, is close to reality. The major challenge to push SDR into this inevitable dominant posture requires operators, vendors, user organizations, regulators, and other stakeholders to work together to foster a positive environment for SDR to flourish. The Software Defined Radio Forum provides a strong starting point for this activity. In the absence of an entity dictating more overarching control into the SDR market, the stakeholders that comprise the SDR Forum will continue to move forward in small steps until the critical mass of wide acceptance and momentum is reached that will push SDR and its subsequent natural outgrowth cognitive radio into a position to become the standard for wireless communications. Software Defined Radio is a revolutionary force of change that will further the push toward a wire-free society.

IV. References

AirNet Communications Corporation (2004). *AdaptaCell Broadband, Software-Defined Base Station*. Retrieved on November 15, 2004, from http://www.aircom.com/pr_adaptacell.htm

AirNet Communications Corporation (2004). *AirNet Communications Announces Availability of GSM 850 Base Station System*. Retrieved on November 15, 2004, from http://www.aircom.com/pressrel/850-announce.htm

All Hands Community (2004, February 23). *Homeland Security's Strategic Plan*. Retrieved on November 15, 2004, from http://www.all-hands.net/pn/news_index422.html

ARRL. (2004). *Software Defined Radio*. Retrieved on November 4, 2004, from http://www.arrl.org/tis/info/sdr.html

Bagherzadeh, Nader. (2004). *New DSP technology for multimode wireless.* EE Times. Retrieved on November 9, 2004, from http://www.eetimes.com/showArticle.jhtml?articleID=49901142

Bonser, Wayne. (1998). *SPEAKeasy Military Software Defined Radio*. Presented at the International Symposium on Advanced Radio Technologies. Retrieved on November 2, 2004, from http://www.its.bldrdoc.gov/meetings/art/art98/slides98/bons/bons_s.pdf

Brock, G., Jung, Peter. (2001, March 29). *Software Defined Radio in drahtlosen Endgeraeten*. University lecture at the University of Duisburg, Germany. Retrieved on October 22, 2004, from http://www.uniduisburg.de/FB9/KT/veroeftl/itg_01_03_29.PDF

Communications Research Centre Canada. (2003). *SCARI++*. Retrieved on November 13, 2004, from http://www.crc.ca/en/html/rmsc/home/sdr/projects/scariplus

Communications Research Centre. (2004). *Software Defined Radio.* Retrieved on November 3, 2004, from http://www.crc.ca./en/html/rmsc/home/sdr/sdr?pfon=yes

Cotton, David B. (2004, January). *Will Software Radio Become Real — And When?* Retrieved on November 15, 2004, from http://www.spectrumsignal.com/publications/COTS0104_softerside1.pdf

Dahlbäck, Magnus. (2004). Implementation and evaluation of an RF receiver architecture using an undersampling track-and-hold circuit. *Master's thesis, Linköping Institute of Technology, Sweden.* Retrieved on October 30, 2004, from http://www.ep.liu.se/exjobb/isy/2003/3448/exjobb.pdf

EE Times Business Editors/High-Tech Writers. (2003). PrismTech delivers middleware solution for digital signal processor DSP environments. *EE Times.* Retrieved on November 5, 2004, from http://www.eetimes.com/printablePressrelease.jhtml?articleID=86748&CompanyId

Ekas, Paul. (2003). Keys to reconfigurable SDR system design. *CommsDesign*. Retrieved on November 5, 2004, from http://www.commsdesign.com/printableArticle/?articleID=16502395

Embedded Star. (2004, September 23). *Software Defined Radio Helps Public Safety Sector.* Retrieved on October 31, 2004, from http://www.embeddedstar.com/press/content/2004/7/embedded15637.html

Federal Communications Commission (2004, February 23). *FCC Adopts Rule Changes to Facilitate Deployment of Software Defined Radio Technology*. Retrieved on November 15, 2004, from http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2001/nret0106.html

Federal Communications Commission. (2000, March 17). FCC Begins Inquiry Regarding Software Defined Radio. *FCC News*. Retrieved on October 28, 2004, from http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2000/nret0004.html

Fette, Bruce, Ph.D (2003, May 15). *SDR Technology Implementation for the Cognitive Radio*. Retrieved on November 15, 2004, from http://www.gdds.com/radiosystems/pdf/FCC_Cognitive_Radio_Fette_v7.pdf

Goering, Richard. (2004). Smart design. *EE Times.* Retrieved on November 11, 2004, from http://www.eetimes.com/showArticle.jhtml?articleID=51200499

Hansen, K., & Traylor, K. (2004). Software-defined radio is not yet on call. *EE Times.* Retrieved on November 10, 2004, from http://www.eet.com/showArticle.jhtml?articleID=49901125

Harit, A.,& Tabassum, S. (2003). Software defined radio. *Australian National University*. Retrieved on November 14, 2004, from http://engnet.anu.edu.au/DEcourses/engn6612/tuta/reports/sdr1_report.pdf

Haruyama, Shinichiro.(n.d.). Software-defined radio technologies. *Advanced Telecommunication Laboratory*, *SONY Computer Science Laboratories, Inc.* Retrieved on October 25, 2004, from http://www.csl.sony.co.jp/ATL/papers/Haruyama_Kluwer_book_chapter6_2000.pdf

JTRS. (2004). *Technical Overview – Concept Overview.* Retrieved on November 3, 2004, from http://jtrs.army.mil/sections/technicalinformation/fset_technical.html

JTRS. (2004). *The Joint Tactical Radio System (JTRS) Program*. Retrieved on November 5, 2004, from http://jtrs.army.mil

Kewney, Guy (2002, May 28). *Why Intel is looking at Soft Radio and UWB*. Retrieved on November 15, 2004, from http://www.newswireless.net/articles/020528-kahn.html

Kraft, Rob (2001). *An SDR Platform for Satellite Earth Stations*. Retrieved on November 15, 2004, from http://www.spectrumsignal.com/publications/An_SDR_Platform.pdf

Mannion, Patrick. (2004). Smart radios. *EE Times*. Retrieved on November 12, 2004, from http://www.eetimes.com/showArticle.jhtml?articleID=51200491

Marcus, Sc. D., Michael (2003, May 19).*Cognitive Radio Technologies in the Public Safety & Governmental Arenas*. Retrieved on November 15, 2004, from ftp://ftp.fcc.gov/pub/Bureaus/Engineering_Technology/Documents/cognitive_radio/marcus_public_safety_presentation.ppt

McHale, John (2003, May). *NASA uses Spectrum software defined radio technology for satellite communications*. Retrieved on November 15, 2004, from http://www.spectrumsignal.com/publications/NASA_Spectrum_sdr.pdf

McHenry, Mark (2003, May 19). *Frequency Agile Spectrum Access Technologies*. Retrieved on November 15, 2004, from ftp://ftp.fcc.gov/pub/Bureaus/Engineering_Technology/Documents/cognitive_radio/shared_spectrum_cognitive_radio_technologies_v5_mchenry.ppt

Mitola, Joseph. (n.d.). *Software Radio – Cognitive Radio: Wireless Architectures for the 21st Century*. Retrieved on October 31, 2004, from http://ourworld.compuserve.com/homepages/jmitola/

Mock, David. (2001, September 11). Re-Defining Wireless. *The Feature*. Retrieved on September 26, 2004, from http://www.privateline.com/Switching/sdr.html

Mosher, Rick. (n.d.). FPGA to ASIC strategy for communication SoC designs. *Design and Reuse.* Retrieved on November 5, 2004, from http://www.us.design-reuse.com/articles/article4360.html

Motorola (2004). *UMTS - Horizon 3G*. Retrieved on November 15, 2004, from http://www.motorola.com/content/0,,2225-4454-4793,00.html

Murty, Ravi. (n.d.). *Software-Defined Reconfigurable Radios: Smart, Agile, Cognitive, and Interoperable*. Technology@Intel Magazine. Retrieved on November 3, 2004, from http://www.intel.com/update/contents/wi07031.htm

National Governors Association (2002, April 30). *Homeland Security - Communications*. Retrieved on November 15, 2004, from http://www.nga.org/nga/legislativeUpdate/1,1169,C_ISSUE_BRIEF%5ED_3298,00.html

National Volunteer Fire Council (2004). *Homeland Emergency Response Operations*. Retrieved on November 15, 2004, from http://www.nvfc.org/leg/hero_act.html

Nguyen, Minh. (2003, May 19-22). *Software Radio (R) Evolution and Its Application to Aeronautical Mobile Communications*. Presented at the Integrated CNS Conference. Retrieved on October 22, 2004, from http://www.mitre.org/work/tech_papers/tech_papers_03/nguyen_radio/nguyen.pdf

Online NewsHour. (2003). Worms and viruses. *NewsHour with Jim Lehrer.* Retrieved on November 5, 2004, from http://www.pbs.org/newshour/bb/science/july-dec03/cw_12-1.html.

Pentek, Inc. (n.d.) Putting undersampling to work. Retrieved on November 12, 2004, from http://www.pentek.com/support/GetOTD.cfm?Filename=PutUndersamp.pdf

Powell, John. (2004, April 19). *Software Defined And Cognitive Radio.* Presented in Mainz, Germany. Retrieved on October 26, 2004, from http://www.sdrforum.org/MTGS/mtg_38_apr04/04_i_0036_v0_00_cognitive_radio_04_26_04.pdf

Pucker, L., & Holtt, G. (2004). Extending the SCA Core Framework inside the modem architecture of a software defined radio. *IEEE Radio Communications*. Retrieved on November 17, 2004, from http://www.spectrumsignal.com/publications/Extending_SCA_Inside_SDR_Modem_Architecture.pdf

Puri, R., Stok, L., Cohn, J., Kung, D., Pan, D., Srivastava, A., & Kulkarni, S. (2004). *Pushing ASIC performance in a power envelope*. Retrieved on November 12, 2004, from http://videos.dac.com/videos/40th/46/46_3/46_3.pdf

Riordan, Ken (2001, August 29). *Status and Trends for Commercial SDR Activity in North America*. Retrieved on November 15, 2004, from http://www.sdrforum.org/MTGS/mtg_25_sep01/01_i_0058_v0_00_usa_trends_09_25_01.pdf

SDR Forum (2004). *2004 Software Defined Radio Technical Conference and Product Exposition*. Retrieved on November 15, 2004, from http://www.sdrforum.org/sdr04/exhibit_notice.html

SDR Forum. (2004). *FAQs.* Retrieved on November 1, 2004, from http://www.sdrforum.org/faq.html

SDR Forum. (2004). *SDR Forum Primer*. Retrieved on November 13, 2004, from http://www.sdrforum.org/sdr_primer.html

SDR Forum. (2002). Report on issues and activity in the area of security for software defined radio. *Software Defined Radio Forum.* Retrieved on November 3, 2004, from http://www.enhyper.com/content/sdr.pdf

SDR Forum. (n.d.). *The Software Defined Radio Forum*. Brochure. Retrieved on October 28, 2004, from http://www.sdrforum.org/sdr_brochure_10_24_02.pdf

Steinheider, Jeffrey. (2003, March 1). Software-defined radio comes of age. [Electronic Version]. *Mobile Radio Technology*. March 2003, pages unknown. Retrieved on October 30, 2004, from http://rfdesign.com/mag/radio_software_defined_radio/

SearchTechTarget.com (n.d.). *Software-defined radio*. Retrieved on September 26, 2004, from http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci333184,00.html

Software Defined Radio Forum (2003, January 23).*Business Model for Wireless PCS*. Retrieved on November 15, 2004, from http://www.sdrforum.org/public/approved/03_a_0001_v0_00_business_case_01_28_03.pdf

Vanu Inc. (2003). *The Software Radio Solution to Public Safety Interoperability*. Retrieved on November 15, 2004, from http://www.vanu.com/publications/TheSoftwareRadioSolutiontoPublicSafetyInteroperability.pdf

Webopedia.com (2004). *Moore's law*. Retrieved on November 6, 2004, from http://www.webopedia.com/TERM/M/Moores_Law.html

Weinberger, David (2003, March 12). *The Myth of Interference*. Retrieved on November 15, 2004, from http://www.salon.com/tech/feature/2003/03/12/spectrum/index.html

Wikipedia (2004). *Nyquist-Shannon sampling theorem*. Retrieved on November 14, 2004, from http://en.wikipedia.org/wiki/Nyquist's_theorem

Wikipedia. (2004). *Software-defined radio*. Retrieved on November 14, 2004, from http://en.wikipedia.org/wiki/Software_defined_radio#History

Wipro Ltd. (2004). *Software defined radio - Abstract.* Retrieved on November 2, 2004, from http://www.wipro.com/insights/softwareradio.htm

Wong, Bennett. (n.d.). *Filling The Generation Gap With Software-Defined, Broadband Radio*. Retrieved on November 4, 2004, from http://www.aircom.com/cti-reprint.pdf

Wong, Bennett. (2001, March 19). *Net growth is taking SDR to task*. EE Times. Retrieved on November 6, 2004, from http://www.eetimes.com/design_library/cd/wl/showArticle.jhtml?articleId=12801539&kc=6420

Zgonjanin, D., Mitrevski, K., Faculty of Electrical Engineering, Belgrade, & Zelenbaba, L. (n.d.). *Software radio: principals and overview*. Telfor.org. Retrieved on November 3, 2004, from http://www.telfor.org.yu/telfor2001/radovi/11-15.pdf

Sources used as reference material but not directly cited:

Lane, Bill, Ph. D., PE (2003, May 19). *Cognitive Radio Technologies in the Commercial Arena*. Retrieved on November 15, 2004, from ftp://ftp.fcc.gov/pub/Bureaus/Engineering_Technology/Documents/cognitive_radio/lane_cognitive_radio_5-19-03.ppt

Bose, Vanu (2004, January). *A Software Driven Approach to SDR Design*. Retrieved on November 15, 2004, from http://www.cotsjournalonline.com/home/article.php?id=100056

Whatis.com (2001, July 31). *Software-Defined Radio*. Retrieved on November 15, 2004, from http://searchnetworking.techtarget.com/sDefinition/0,290660,sid7_gci333184,00.html

Fuji-Keizai USA (2004, August 9). *Software Defined Radio Market Survey Current Status and Future Outlook.* Retrieved on November 15, 2004, from http://www.fuji-keizai.com/e/report/SDR2004_e.html

Delson Group (2004). *Fourth Generation Mobile Forum*. Retrieved on November 15, 2004, from http://www.delson.org/4gmobile/wnew.htm

Software Defined Radio Forum (2002, August 6). *Overview and Definition of Software Download for RF Reconfiguration*. Retrieved on November 15, 2004, from http://www.sdrforum.org/public/02_a_0002_v_0_00_dl_dfn_08_06_02.pdf

Owen, Tim (2003, March 13). *Software-Defined Radios Make Their Move*. Retrieved on November 15, 2004, from http://www.spectrumsignal.com/publications/SDR_Make_Move.pdf

Uhm, Manuel (2002, January). *Can Defense Capitalize on Commericial Software Defined Radios?* Retrieved on November 15, 2004, from http://www.spectrumsignal.com/publications/Can_Defense_Capitalize_on_Commercial_SDR