Software Radio: Implications for Wireless Services, Industry Structure, and Public Policy

William Lehr
Fuencisla Merino
Sharon Eisner Gillett

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Massachusetts Institute of Technology
Program on Internet and Telecoms Convergence
(http://itc.mit.edu)

Abstract

Software radio is one of the more important emerging technologies for the future of wireless communication services. By moving radio functionality into software that has previously been implemented in hardware, software radio promises to change the economics of deploying and operating wireless network services. This paper provides an overview of the current status of software radio technology and then examines the implications of wider use of the technology on the wireless value chain.

I. Introduction

Wireless services are increasingly ubiquitous and essential components in our global communications infrastructure. The mobility, flexibility, and reconfigurability of wireless offer compelling complements, or at times, substitutes for wired infrastructure. They enable many new services and expand the usability of old services, extending our ability to stay connected anywhere and anytime we desire.

The proliferation of new wireless services being offered over satellites, over cellular networks, and over wireless LANs (WLANs) is fueling concern over how to allocate (or reallocate) scarce radio frequency (RF) spectrum. The research community and industry have responded to this challenge by developing a host of new technologies to allow spectrum to be used more flexibly and efficiently.[1] Software radio – the focus of this paper -- is one of these technologies. By moving radio functionality into software,

[1] In addition to software radio, important advances have been made in smart antennas, modulation and digital signal processing, multi-user detection (MUD), ad hoc networking, analog-digital converters, and power management, among others.

and by moving the analog/digital interface closer to the air-radio interface at the antenna, software radio promises to change the economics of designing and operating wireless networks. This has important implications for the cost of building and operating networks in the face of rapid innovation and increasingly complex, multi-protocol and congested wireless environments.

Among software radio's likely implications are an increased ability to tolerate and support interoperability across heterogeneous air interface technologies (*e.g.*, different standards for 3G, across 3G and WiFi networks, etc.); support for faster and more flexible network upgrades; the substitution of general-purpose hardware for dedicated hardware; and support for improved congestion management solutions. These implications suggest that software radio may be simultaneously an integrative and disruptive technology. In the short-term, incumbent wireless service providers will benefit from the lower production and deployment costs promised by software radio, while longer term, software radio creates the potential for new open interfaces that could be leveraged by new entrants to change the structure of the wireless services and equipment value chain.

Software radio is a critical enabling technology with important implications for spectrum management. Software radio increases the feasibility of moving towards more flexible spectrum usage models that expand the range of options for implementing secondary markets for spectrum. The ability to modify the user's air interface in real-time to take advantage of a greater range of frequencies or multiple air interface protocols/technologies provides opportunities to improve interference management but also raises important policy challenges for radio certification and enforcement. These and other important implications for industry and public policy are explored in the paper, which draws on recent thesis work prepared by one of the co-authors.[2]

The balance of this paper is organized into four sections. Section II explains what a "software radio" is. Section III discusses key trends that are driving the development and deployment of software radio. Section IV examines the implications of software radio for the industry value chain and for public policy. Section V concludes.

II. What is Software Radio?

A. Traditional Analog, Hardware-based Radio Designs

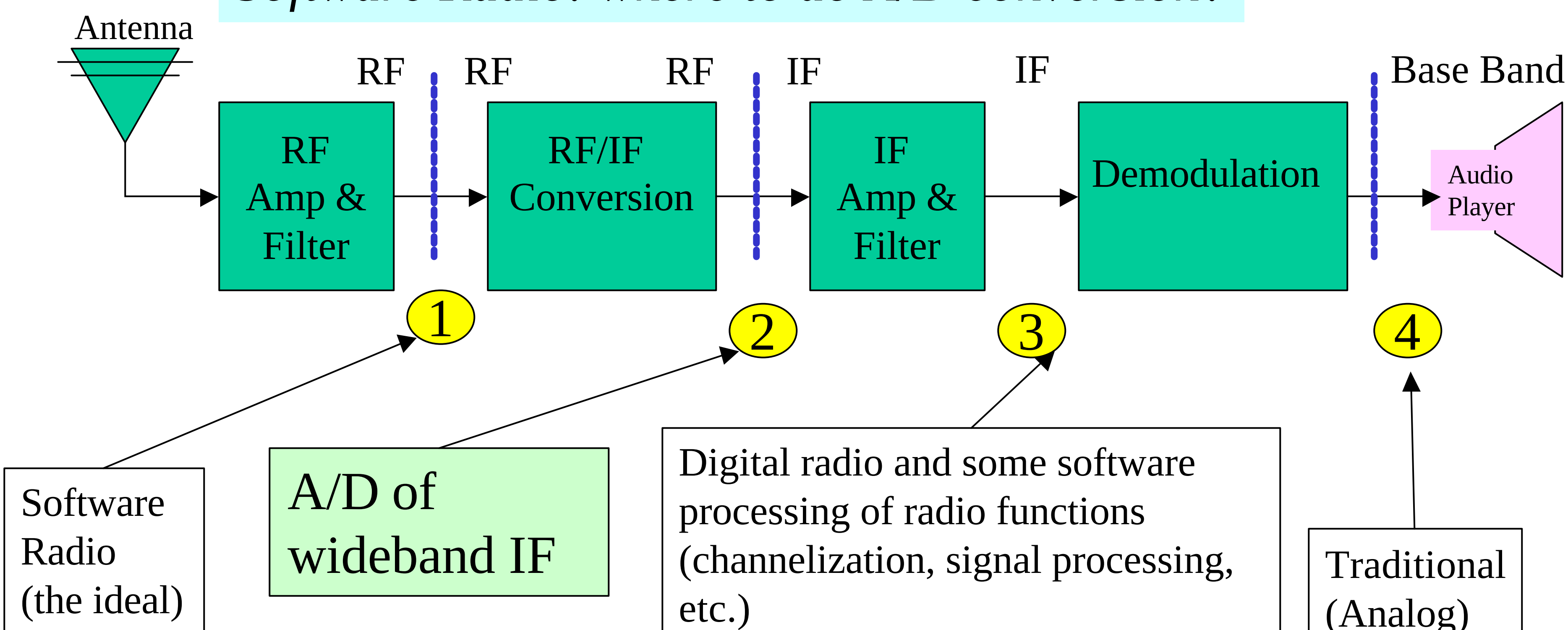
Before explaining what software radio does, it is useful to review the design of a traditional analog, hardware-based radio (see Figure 1). In wireless communications, information is encoded into radio waves. These are collected (or transmitted) from (to) the air by the antenna. The received signal is then passed to a series of components that extract the useful information and convert it into the output of the radio (*e.g.*, a modulated

[2] See Merino Artalejo, Maria Fuencisla, "Market Impact of Software Radio: Benefits and Barriers," Master of Science Thesis, Massachusetts Institute of Technology, June 2002 (available at: http://itc.mit.edu). This thesis provided much of the research on which this paper is based.

Figure #1

Traditional Radio

Software Radio: where to do A/D conversion?



Key Technical Limitations:
(1) Sampling rate (and resolution)
(2) Linear amplification of wideband signal

Key enabling technology: Fast processors and Wideband A/D electrical current to drive audio speakers). The basic design is the same whether the radio signal is destined for a cell phone, microwave repeater, or AM/FM car radio. Traditional radios are based on the super heterodyne (superhet) receiver circuit that was first developed in the early part of the twentieth century.

In the superhet receiver, the incoming signal (at the transmission or "radio" frequency, RF) is first down-converted to a lower intermediate frequency (IF).[3] The IF is then filtered for noise and amplified before being demodulated to produce the baseband (*i.e.*, at 0 Hz) signal that represents the desired information. This analog baseband signal may be passed directly to further downstage processing, or it may first be digitized and subjected to additional signal processing. There are several important reasons for down-converting to a lower and standardized IF: (1) it is easier, and hence less expensive, to build filters and amplifiers – especially linear amplifiers – for a lower frequency signal; (2) use of a common IF enables standardization and hence the realization of scale and scope economies in the design of radio components.

Traditional designs for implementing the superhet receiver architecture were optimized for specific frequencies and applications and each of the stages were implemented in hardware that was closely coupled. This was due largely to the difficulties inherent in and limitations in the state of the art in the design of analog signal processing components. Analog processing is much more complicated than digital processing, which is one of the key reasons why the transition to digital signals is so important.

B. Software radio designs

Software radio alters traditional radio designs in three distinct and complementary ways: it (1) Moves analog/digital (A/D) conversion as close to the receiving antenna as possible; (2) Substitutes software for hardware processing; and, (3) Facilitates a transition from dedicated to general-purpose hardware. Each of these changes has important implications for the economics of wireless services.

1. A/D conversion closer to antenna

First, moving the A/D conversion closer to the antenna makes it possible to apply the advances of digital computing and communication technology sooner in the radio.

[3] The superhet receiver circuit made it possible to build better and cheaper radios because it improved the ability of radios circuits to tune into different frequencies (stations). The superhet receiver circuit, which was invented by Edwin Armstrong in 1918, exploits the physics of RF: when you mix two frequencies together, the output consists of four frequencies – the two original frequencies, the sum of the two frequencies, and (this is the important one) the difference between the two frequencies. In the superhet receiver, an oscillator frequency is tuned to the carrier frequency in such a way that the difference frequency produced is constant and lower. This Intermediate Frequency (IF) is then more easily filtered for noise and amplified. Because building and designing analog filters and amplifiers is expensive, this lowered the cost and improved the performance of radios (for more information, see Parks, Warren, and Kim Parks, "How does a superheterodyne radio work?", available at http://home.attbi.com/~radiowarren/hetbasic.html, last visited August 27, 2002).

This is beneficial directly because digital components are less complex and lower cost than analog components. Additionally, this makes it easier to take advantage of advances in digital signal processing. These include advanced techniques for encoding information and separating signal from noise.

2. *Software, instead of hardware processing*

Second, substituting software for hardware increases flexibility. This flexibility makes customization easier and helps deliver a degree of future-proofing. That is, replacing software – especially if this can be done remotely – is faster and lower-cost than replacing hardware.[4] New features and capabilities can be implemented when available (upgradeability) or when desired (customizability). This can allow services to be changed more rapidly, or equivalently, time to market is reduced. Additionally, the reliance on software processing can eliminate redundant hardware chains, as found in dual-mode phones, for example.[5]

3. *General-purpose, not specialized hardware*

Third, software radio facilitates the transition from specialized to general-purpose hardware. Initially, dedicated hardware embodied in Application Specific Integrated Circuits (ASICs) may be replaced by Field Programmable Gate Arrays (FPGAs)[6] and Digital Signal Processors (DSPs)[7] – which are even more commodity-like and flexible.

Prospectively, there is a hope that general-purpose computing platforms (e.g., a PC running on a commodity CPU) will be able to support software radios.[8] At any given point in time, a specialized chipset will typically achieve higher performance than a general-purpose processor. However, once Moore's Law drives the general-purpose processor past a performance threshold such that it can perform the necessary radio functions well enough, the advantages of general-purpose hardware come to the forefront. These advantages include broader applicability and therefore the scale economies enabled by larger markets, the ability to perform multiple functions (not just radio processing) leading to integration and scope economies, and predictable

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[4] It is worth noting, however, that the lifecycle costs of software-based products are not necessarily lower than for hardware. Software development can have substantial upfront costs that may exceed those for hardware design, even though the subsequent incremental costs for producing and distributing additional copies of the software are likely to be substantially lower than for hardware.

[5] For example, if A/D conversion occurs at the baseband, then separate A/D converters are required for each baseband that is received. With earlier A/D conversion, multiple signals may be digitized at once. (See for example, Perez-Neira, Anna, Xavier Mestre, and Javier Fonollosa, "Smart Antennas in Software Radio Base Stations," IEEE Communications Magazine, February 2001, 166-173.)

[6] FPGAs remain expensive and are most often used in prototypes. Their chief advantage is that they are programmable and hence their functioning may be altered after they are installed via software.

[7] DSPs are optimized to perform standard digital communication functions very fast and efficiently, and are produced at low cost in large quantities.

[8] See Bose, Vanu, Michael Ismert, Matt Welborn, and John Guttag, "Virtual Radios," *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 4 (April 1999) 591-602.

improvements in performance over time. In this sense, Moore's Law drives both the feasibility of and benefits from software radio.

The transition to general-purpose hardware also makes it more likely that there will be open interfaces. That is, general-purpose hardware derives its value from its ability to be combined into systems for many different purposes. This requires the ability to "mix and match" the hardware with diverse complementary hardware and software. This, in turn, is facilitated by standardized open interfaces.

Taken together, these effects prospectively lower costs, lower entry barriers, and expand the range of services that can be offered *and* the range of architectures capable of delivering those services. Therefore, the transition to general-purpose hardware is likely to increase competition in several ways. First, it expands the range of potential suppliers by adding vendors of general-purpose hardware. Second, because general-purpose hardware is designed to support multiple applications, there are more likely to be open interfaces. The increased choice of suppliers and open interfaces reduce supplier lock-in. Competition intensifies.

4. Performance and Power Limitations

The transition from hardware to software radios is not without problems. First, performance generally declines in the shift from dedicated to general-purpose hardware. If cost and time are no object, it is usually the case that custom hardware will perform faster and better than will general-purpose hardware because it is specifically optimized for the task at hand.[9] Whether the loss in performance is important or not depends on what you are trying to do. As discussed further below, the viability of software radio in commercial (non-military or other high value, niche applications) depends on the fact that general-purpose hardware is only now becoming fast enough to offer an acceptable alternative to dedicated hardware for many current wireless applications (e.g., GSM service).

Second, the transition from hardware to software processing results in a substantial increase in computation which has its attendant cost in increased power requirements. This reduces battery life and is one of the key reasons why software radios will not be deployed first in end-user devices such as cell phones, but rather in base stations which can take advantage of external power sources.

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[9] However, because it takes time and is costly to develop dedicated hardware (i.e., cost cannot be shared over multiple products/applications), general-purpose hardware may actually be less expensive and faster to use. It already exists, its development costs are shared across multiple applications, and it can be quickly reconfigured via software. For these reasons, use of general-purpose hardware may be especially appropriate in research and prototyping applications (see Bose, Vanu, Michael Ismert, Matt Welborn, and John Guttag, "Virtual Radios," *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 4 (April 1999) 591-602).

C. Software radio today and tomorrow

The ultimate goal for software radio is to perform the A/D conversion directly at the antenna so that all signal processing could be done in software. However, that is not practical today (as will be discussed further below). The question of where one does the A/D conversion determines what radio functions can be moved into software and what types of hardware are required. What is feasible is a moving target, as radio and its complementary technologies continue to improve. Disagreements about what will be feasible when and at what cost have led to disagreements about the proper definition for software radio. At one extreme, one might consider calling it software radio if software is used at any stage within the radio. By this definition, a multi-mode cell phone that uses software to control which hardware chain is operational during a call (*e.g.*, digital CDMA or analog AMPS?) may be construed as a software radio, or perhaps, software defined radio. At the other extreme, one might choose to reserve the term software radio for only the narrowest of cases – A/D conversion at the antenna with all radio functionality implemented in software running on general-purpose hardware.

For our purposes, we stake out a middle ground that we feel balances the need to capture what is really different and innovative about software radio with the limitations of current and near-current technology. Therefore, we consider it software radio if it involves A/D conversion at (at least) the IF stage with the capability to support software processing thereafter.[10] Whether subsequent stages are implemented in dedicated or general-purpose hardware is not critical to the definition of software radio, but certainly, the earlier A/D conversion and software implementation makes it more feasible to shift to general-purpose hardware.

Two key technical limitations make it infeasible to do the A/D conversion at the antenna. First, digitization of the RF signal requires the incoming signal to be sampled, which results in the conversion of the waveform data into a sequence of numbers corresponding to each sample. The higher the frequency, the higher the required rate of sampling to accurately represent the signal.[11] Additionally, the more information in the signal, the higher the resolution required to capture the information (that is, the more bits that must be represented per sample). Taken together, this means that high bandwidth (high resolution), high frequency RF transmissions require very high sampling rates (bits per second). The ability to support very high sampling rates, which is especially critical with the use of higher frequency signals (in the GHz range, instead of MHz or KHz used for older wireless applications), limits the range of what can be digitized. Indeed, it is only recently that sufficiently fast DSPs and wideband A/D chipsets have become

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[10] By this definition, we exclude radio designs that may include substantial software elements. With the transition to digital radio, software has been used increasingly intensively in downstream radio functions such as channelization, signal processing, and hardware control.

[11] According to the Nyquist sampling theorem, to accurately sample a signal of frequency F you must sample at a rate of at least 2F, where F is the highest frequency included in the incoming waveform that you are interested in sampling (see Proakis, John, *Digital Communications*, Fourth Edition, McGraw-Hill: New York, 2001).

available at affordable prices to make it feasible to contemplate A/D conversion of the IF rather than the baseband signal.

Second, it is difficult to design linear amplifiers that can amplify the wideband signal at the antenna without distortion. Linear amplification is needed to keep the signal from being lost in the noise that accompanies the signal received at the antenna. Although new amplifier designs and pre- and post-amp signal processing techniques can alleviate some of these difficulties, employing these increases the cost of the radio.

Over time, we expect software radio to evolve such that the point of digital conversion moves closer to the antenna, and antennas become able to receive a wider swath of the useable RF spectrum. This will increase the spectrum agility of future radio designs, as digitization shifts from baseband (possible with the digital precursors to software radio) to IF (possible with today's emerging generation of software radios) to the goal of RF digitization at the antenna (point 1 in Figure 1). Concurrently, we expect to see a shift from the current generation of dedicated hardware embodied in ASICs, to programmable ASICs, then to DSPs, and finally, to more general-purpose computing platforms such as PDA or PC CPUs.

The current frontier for software radio research is focused on what is referred to as "cognitive radio."[12] The basic idea is to make radio receivers and transmitters more intelligent (via software, including Artificial Intelligence) and adaptive so that they can respond to changes in their local environment. These may include adapting to changing interference or congestion conditions, or adapting to facilitate interoperability among diverse devices, or adapting to accommodate the requirements of changing applications (e.g., from wireless email to video to voice). Cognitive radios would be self-configuring. The increased adaptability to local conditions would greatly expand the range of services that could be offered and the range of congestion management (*i.e.*, to address spectrum scarcity concerns) strategies that might be employed. Although what would be possible with cognitive radio would be much more dramatic than the much more limited conceptualization of software radio discussed here, the key economic implications are apparent already with software radio.

III. Benefits and Drivers

The benefits of moving to software radio to realize increased flexibility (upgradeability, customization, faster-time-to-market, and adaptability) and lower costs (from positive network externalities, scale & scope economies, and increased modularity) are compelling. Moreover, a number of market factors are working together today to push software radio closer to realization in commercial markets. These factors are discussed further below.

[12] See Mitola, Joseph, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," Doctor of Technology Dissertation, Royal Institute of Technology, Sweden, 2000.

A. Technology makes feasible (also more necessary)

One of the chief reasons for moving to software radio today is because we can: technology now makes it feasible to contemplate doing in software and general-purpose hardware what previously could only be accomplished by dedicated hardware chains. Moore's Law has finally reduced the cost of computation to the point where it becomes feasible to digitize relatively wide bands of RF for direct digital signal processing.

In addition, software radio makes it feasible to implement many of the complementary advances in wireless technology that have occurred in recent years, including smart antennas, adaptive power management, or new modulation and signal processing techniques. Therefore, just as technology makes it now feasible to adopt software radio, so technology makes adopting software radio more necessary.

B. Multiplicity of standards

The multiplicity of air interface technologies and standards that must co-exist today fuels demand for software radio. For example, in the U.S., most cell phones roam by falling back on AMPS; although some newer models support two digital standards (as well as AMPS). These "tri-mode" phones are more expensive to manufacture than dual or single mode phones, and they still lack the capability to support the GSM technology that is common in Europe and much of the rest of the world. Moreover, the proliferation of air interfaces for cellular phones is not getting better as we move towards 3G services.

The proliferation of standards is due to many factors. First, globalization makes it desirable to have devices that will operate in many countries, which may have quite different spectrum allocations, or even if the same spectrum is used, may employ different protocols. Second, the rapid pace of innovation shortens the lifecycle of each technology. This raises the premium for upgradeability and means that multiple generations are more likely to overlap, co-existing at the same time. Third, the general movement towards increased reliance on market control (via managed competition) instead of direct regulatory oversight may make it more likely that competing service providers will fail to adopt common or interoperable standards.[13]

C. Multimedia services and new devices

The growth of diverse wireless services (voice, data, streaming content) and platforms (satellite, cellular, WLANs) increases the diversity of potential wireless devices and services that may need to be integrated or may compete as substitutes. This fuels demand for multiprotocol-capable, reconfigurable end-user devices and network

[13] Software radio can make it easier to support multiple standards, but only if the intellectual property rights (if any) associated with those standards does not prevent their implementation in software by third parties.

infrastructure. The cost advantage of supporting multiple protocols via software instead of hardware increases rapidly as the number of standards increases.[14]

Moreover, the trend towards multimedia services increases the need for the ability to integrate multiple technologies and to support enhanced adaptability. For example, some service providers may discover it is cost effective to mix wireless media for delivering different types of services. Streaming media might be delivered via satellite while 2-way interactive communications may be supported via cellular. Alternatively, 3G providers may seek to seamlessly integrate hotspot (WiFi) services into their offerings. Furthermore, because different applications have very different quality of service requirements (bandwidth, latency, error tolerance), software radios may facilitate supporting diverse QoS.

D. Congestion management and spectrum management reform

The success of wireless brings its own problems. As wireless services proliferate and use increases, congestion problems will arise. Software radio ameliorates the congestion problem in three important ways. First, software radio reduces the cost of expanding capacity on existing infrastructure. It is easier to add channels or move to a higher capacity network protocol if this entails a software rather than a hardware upgrade. Second, software radios facilitate the implementation of quality of service (QoS) schemes – as already noted above – and make it easier to engage in dynamic capacity allocation. Third, software radio facilitates the adoption of distributed, adaptive, dynamic interference management solutions (*e.g.*, two base stations that need to communicate agree in real time to change their air interface protocol to accommodate an increase in local interference).

The desire to facilitate more efficient spectrum usage, which would alleviate the congestion problem, is also encouraging spectrum reform. Software radios are a key enabling technology to facilitate the transition towards liberalized spectrum markets, as will be discussed further below.

E. Commercial market opportunities

The military has been interested in software radio for some time, and not surprisingly, some of the first implementations have been in military applications.[15] First, they have a pressing need to be able to support multiple protocols to allow their radios to work around the globe and to be capable of integrating signals from many RF sources

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[14] See Merino Artelejo, Maria Fuencisla, "Market Impact of Software Radio: Benefits and Barriers," M.S. Thesis, Technology and Policy Program, Massachusetts Institute of Technology, 2002, p. 97; and Mitola III, Joseph, *Software Radio Architecture: Object-Oriented Approaches to Wireless Systems Engineering*, Wiley, 2000.

[15] See Lackey, Raymond and Donald Upmal, "Speakeasy: the military software radio," *IEEE Communications Magazine*, May 1995, 56-61.

(satellite, terrestrial, etc.).[16] Second, they have a strong need for security and need to be able to protect their ability to communicate in hostile environments (e.g., in the face of jamming by enemy and congested battlefield conditions). Third, and perhaps most important, the need for a strong defense makes the military much less price sensitive than the typical consumer of commercial applications.[17]

However, with technical progress, it is now feasible for software radio to be used in commercial applications. Software radios will be deployed first in transportation applications and in commercial wireless service networks, and only later, in consumer electronics (see Figure 2).

1. Transportation Network Applications

Telematics (i.e. use of computing and communications in vehicles) will be one of the earliest commercial applications of software radio. In vehicular environments, power and cost are less of an issue, and easy upgradeability a compelling benefit. Power is less of an issue because external sources of power (or heavier batteries than would be feasible in a portable device) are more readily available. Cost is less of an issue because the cost of the radio relative to the total cost of the unit (car, train, plane) represents a much smaller share and/or the value of the enhanced functionality is greater.

Upgradeability is especially important in this context because the product development cycle and useful life of cars, trucks, trains, buses, and planes are much longer than the life cycle of the communications devices increasingly embedded in them. Software radio can effectively decouple these life cycles, allowing details of telematics functionality (such as which air interface to support) to be decided closer to product launch time. Furthermore, those details can change during the useful life of the product through software upgrades. The ability to perform such upgrades remotely is especially attractive given both that the products (cars etc.) are physically dispersed, and that upgrading them over time may provide an ongoing source of revenue to auto makers. For these reasons, automotive manufacturers are one of the leading sources of research and development funding for software radios.

Commercial transportation network service providers (trains, planes, trucks, and buses), face many of the same issues as do military forces, albeit with a reduced tolerance for cost – that is, the need to manage a dispersed fleet of vehicles in a heterogeneous wireless environment efficiently. Commercial airlines are perhaps closest to the military analogy. In addition, the move to general-purpose hardware has the added advantage of reducing the weight and size of maintaining multiple hardware computers.[18]

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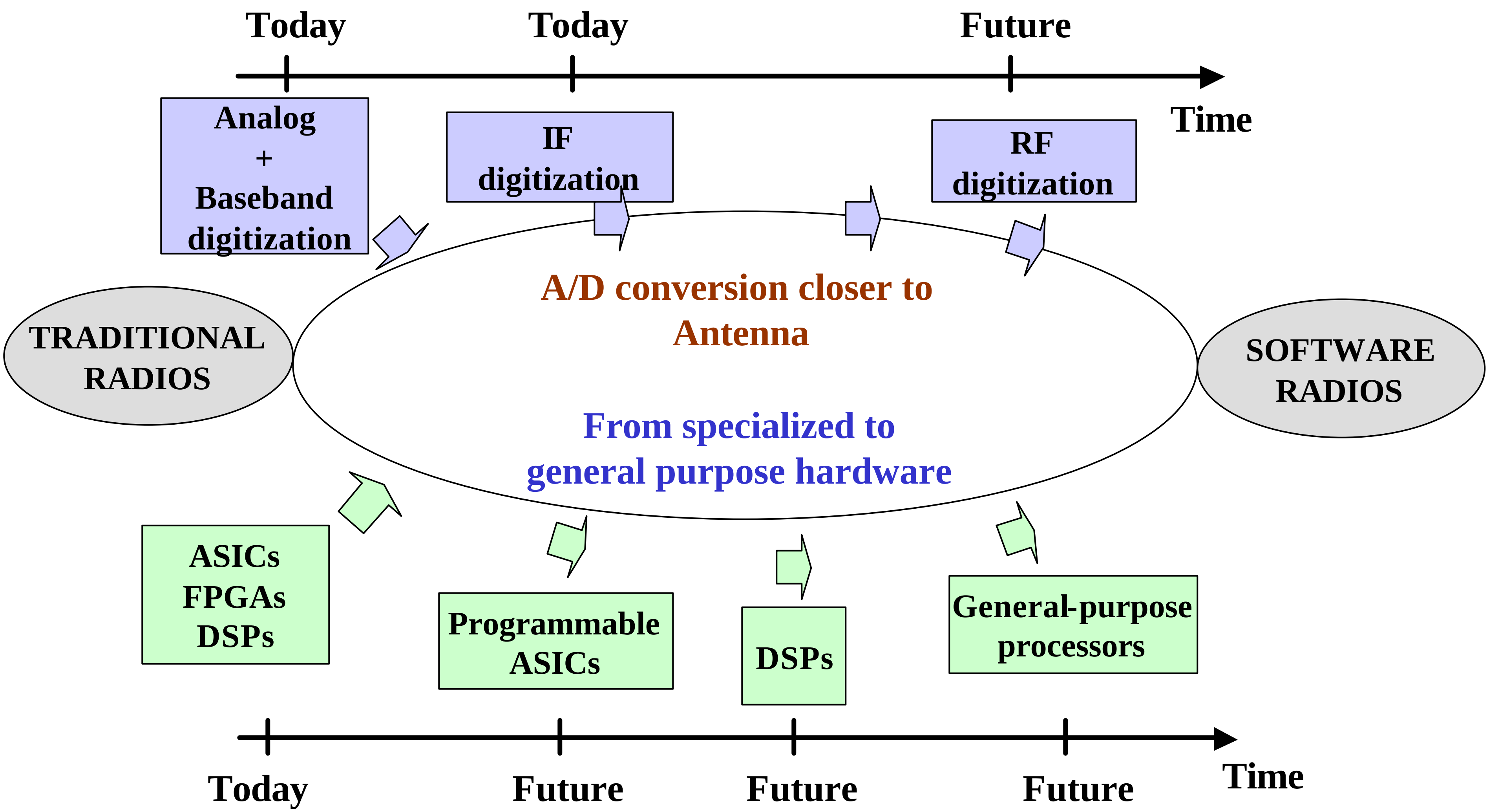
[16] For example, to facilitate communication among battlefield participants (tanks, aircraft, infantry) and allow the integration of remote sensing intelligence (satellite) information.

[17] Similar reduced sensitivity to cost may be true for emergency services (police, ambulance, and fire).

[18] Because of safety concerns, certifying software for aircraft use – either military or commercial – raises additional challenges for the deployment of software radio.

Figure #2

Evolution over time



2. Communication Service Provider Infrastructure

Not surprisingly, wireless service operators and equipment manufacturers are especially interested in software radio. For reasons analogous to those mentioned above, we should expect to see software radio appearing first in base station equipment. The ability to upgrade software remotely can substantially reduce the cost of deploying and maintaining a wireless network. Software radios will be deployed to reduce these costs, to facilitate congestion management, and to enhance the ability of service providers to modify their service offerings quickly in response to changing market conditions. The longer term implications of software radios for the communications sector's value chain are discussed more fully below.

3. Consumer electronics

Software radios hold great promise for wireless consumer devices because they can facilitate meeting form factor and convenience goals. A software radio can help reduce device size by eliminating redundant hardware chains. Because it can support multi-function operation, software radio can eliminate the need for multiple devices.[19] Unfortunately, the increased power requirements for software radio pose a challenge for their inclusion in consumer electronics. This challenge is one of cost (margins on consumer electronics are narrow), but even more importantly, usability (batteries are heavy and do not last long).

One application where this is less likely to be an issue is in wireless home networks. Therefore, we may see software radios being deployed in home networking hubs or desk-top computers, before we see their application in portable personal communication/computation appliances (cell phones, PDAs, MP3 players).

IV. Implications for Industry Structure and Policy

Software radio technology changes the economics of building and operating wireless networks. In the following three sub-sections, we consider the implications of these changes for industry structure and public policy. We first discuss how software radio creates new possible organizations of the wireless value chain by expanding the number of potential interfaces that, if defined and open, could change how radios are designed, manufactured, and used. In the second sub-section, we consider how industry participants might respond to these possibilities. In the final subsection, we discuss the implications for public policy.

A. The space of possibilities: An unbundled, more competitive value chain

It is not unreasonable to consider software radio as a disruptive technology, with the potential for radically altering the structure of the industry within which radios are designed, manufactured, deployed and operated. Two properties of software radio underlie its disruptive capacity: the transition that it enables to general-purpose hardware,

[19] That is, a single multipurpose device serves as a portable telephone, PDA, computer, etc.

and its affordance of new interfaces. These properties lead to increased competitive intensity in both horizontal and vertical senses – allowing new types of firms to emerge and a reallocation of market power along the value chain.

As discussed above, the transition to general-purpose hardware implies greater commoditization of radio components. This is likely to lead to more intensive horizontal competition, not only among traditional radio component suppliers but also from new entrants with strengths in general-purpose hardware components.

Software radio technology affords new interfaces in several ways. First, it is easier to create interfaces in software than in hardware, and the performance penalty for modularization may be lower in software as well. Second, as Figure 1 illustrates, software radio essentially enables the re-architecting of radio systems, changing their traditional division into components and thereby potentially creating new interfaces. Third, software radio entails the incorporation of more general-purpose hardware into radio systems. Because of its general-purpose nature, that hardware is likely to already have more interfaces than the specialized components it replaces.

If the potential for new interfaces is realized, and if these interfaces are openly defined and standardized, they will allow the radio to be unbundled into its constituent components in a manner analogous to the personal computer.[20] This facilitates the mixing and matching of system components, which expands the space of ways in which radios may be designed, implemented, and operated, as well as the services that may be supported. For example, a standardized interface at points 1 or 2 in Figure 1 could allow a combined antenna assembly plus RF front end to be developed and sold separately from other components that comprise the radio.[21] Similarly, such an interface, in the form of a reasonably standardized operating system, could allow application-oriented software (e.g., the software that implements cell phone functionality beyond signal transmission and reception) to be developed and distributed by companies unaffiliated with a radio hardware vendor, including those wishing to experiment with entirely new types of services.

Aside from their effect on industry shape, the modularizing effects of software radio are also likely to drive a faster industry "clockspeed."[22] Innovation can accelerate, because the pieces to be changed are smaller and less dependent on each other, reducing the need for time-consuming coordination. This can also lead to shorter product life cycles, aided by the relative ease of upgrading software that makes it less costly for customers to adopt new technology, or for vendors to deliver them automatically (e.g.

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[20] Users can purchase a complete PC or assemble one from components (monitor, keyboard, motherboard, disk drive, etc.). The PC may come with bundled software or the user may add applications and other software elements as desired.

[21] That is, a wide band antenna with the RF filter and amplifier and RF/IF conversion elements. The rest of the radio may be sold separately and be comprised of bundles of software and general-purpose elements.

[22] See the horizontal-modular vs. vertical-integral industry structure framework developed in Fine, Charles H., *Clockspeed : Winning Industry Control in the Age of Temporary Advantage*. Perseus, 1999.

features and bug fixes can be delivered remotely to distributed hardware in the field without requiring manual intervention). Adoption costs are also reduced because software radio enhances interoperability with legacy systems.[23]

System unbundling – if it occurs – will affect the design and operation of the entire wireless value chain – not just the manufacturing of radios and the components that comprise them. The unbundling can provide the basis for opening the value chain to new forms of competition, giving rise to mixed component-level and systems competition. Firms can specialize in a component niche or remain vertically integrated and compete on systems. The opportunity to compete at the component level lowers entry barriers because it means that potential competitors with capabilities in only a subset of the elements that comprise the value chain can still compete in the market (assuming that there are no bottleneck components). To understand the potential importance of such mixed competition and the role of open interfaces, it is sufficient to recall how the open architecture of the personal computer enabled Microsoft and Intel to capture leadership of the computer industry from IBM.

These changes suggest potential new dynamics for vertical industry competition, in addition to the intensified horizontal competition discussed above. Once the pieces of the value chain are broken apart, they have the potential to recombine in new ways. For example, with the shift to software radio one could imagine a new vertically integrated systems provider arising by building on strengths in the general-purpose computing market (e.g. Dell, HP/Compaq, Microsoft, or a leading real-time operating systems vendor such as WindRiver) to challenge the traditional wireless communications systems vendors (e.g. Nortel, Lucent, Nokia, etc.). Alternatively, such a firm may integrate into only some of the layers of the value chain, posing additional horizontal competition to firms that specialize in each of these layers. If that firm leverages market power in one layer to compete in another, this may actually reduce overall market competition (the obvious analogy being Microsoft's dominance over PC application software and attempted domination of Web services based on their dominant position in the PC operating system market).

If competition increases along the value chain, then consumers will be the principal beneficiaries. Consumers should benefit as suppliers are forced to compete more aggressively. This more aggressive competition ought to expand the space of available products and services, improve service quality, and lower prices (and costs). More of the available surplus will be captured by consumers as the market approaches a competitive equilibrium.

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[23] Because software radio can support multiple protocols, the fact that there is not general agreement on a single protocol is less important. Software radio reduces the costs of achieving interoperability across diverse service and infrastructure platforms, which also helps drive convergence.

[25] Absent interoperability, consumers withhold demand for fear of being locked in. Additionally, interoperability facilitates the realization of positive network externality benefits.

B. Constraints on the possibility space: Industry response

Just because software radio makes it technically feasible to define interfaces in new locations, there is no guarantee that this will occur, or that, if defined, these interfaces will be open. First, at the current stage of development, there is no general agreement as to what these interfaces ought to look like. Much of the confusion over what ought to be regarded as software radio results from disagreements over what functionality ought to be included in the software radio. Resolving these disputes is a necessary first step in progressing towards the definition of open interfaces. Second, participants in the wireless value chain are not disinterested parties and their participation in the industry standardization processes by which open interfaces are defined will be governed by their strategic interests.

The long-run vision presented above, of increased competition based on open interfaces and unbundled systems, will not arrive overnight. In the near term, it seems more likely that software radio will be used in an effort to enhance firms' efforts to differentiate themselves. Firms will be induced to cooperate in the definition of open interfaces to achieve the interoperability needed to expand the potential market for their products.[25] At the same time, they will seek competitive advantage through the richer opportunities for product differentiation that arise from the greater ease of introducing variation into software than hardware.

While it is premature to predict exactly how software radio will impact existing players in the wireless value chain, we can offer some reasonable speculations based on industry economics and the analysis above. We offer these by focusing on three important sectors in the value chain for wireless communication services: semiconductors, network equipment, and network service providers (see Figure 3).

1. Semiconductors

Semiconductor components are critical elements for the manufacture of radio transceivers and receivers. The substitution of software for hardware and the earlier digitization of radio waves will affect the types of semiconductors that are used in radios. As noted earlier, traditional radios rely on dedicated hardware, which today is provided in the form of ASICs. These ASICs implement parts of the various wireless standards that are used in the radios included in cellular handsets, base stations, and other wireless network equipment.

In the nearer term, software radio threatens to substitute FPGAs and DSPs for ASICs. Because of the more specialized nature of ASICs, the total available market for each type of ASIC is much smaller than for a general-purpose commodity product such as a DSP. The DSPs (and, to a lesser extent FPGAs) benefit from greater scale, scope, and learning economies than are available for each type of ASIC which helps in reducing the cost of semiconductors. Moreover, because different firms participate in each of these markets, the shift to software radio has implications for the allocation of market shares among semiconductor producers. For example, the big three ASIC producers are IBM, Lucent/Agere,[26] and LSI Logic; while the big three DSP producers are Texas Instruments, Lucent/Agere, and Motorola; and the big three FPGA producers are Xilinx, Altera, and Lattice (with Lucent/Agere with a smaller share). The shift to DSPs would favor Texas Instruments relative to IBM.

Moreover, the transition from specialized ASICs to general-purpose FPGAs and DSPs will reduce the extent to which the semiconductors and wireless equipment in which they are used are "co-specialized." This will reduce the extent to which equipment makers are locked in to purchasing from a particular semiconductor manufacturer. As the degree of lock-in and co-specialization is reduced, incentives to vertically integrate or produce complete radio systems instead of component sub-assemblies is reduced.

Longer term, as general-purpose hardware in the form of PCs running general-purpose CPUs will begin to substitute for FPGAs and DSPs which will further commoditize the hardware used in radios and will introduce yet another set of semiconductor participants (*e.g.*, Intel).

2. Network Equipment

Software radio will also have important implications for the manufacturers of network equipment. As noted above, the move to software radio will make it less necessary to be vertically integrated. In the short term, we would expect to see equipment manufacturers benefiting from the deployment of software radio because it will (1) reduce their lock-in to particular dedicated-hardware manufacturers of sub-components (*e.g.*, chips); (2) ease their ability to provide system upgrades; and (3) expand opportunities for them to differentiate their offerings by adding new services and capabilities.

The increased flexibility offered by software radio will benefit both equipment manufacturers and their customers, network operators. It will reduce deployment costs (which will expand demand for equipment) and will facilitate upgradability. The ability to less expensively modify equipment after its installation in the field may facilitate earlier roll-out, further accelerating the innovation cycle. It is also likely to alter system architectures as designers take into account the fact that the core hardware components will need to be replaced less frequently[27] while the functioning of those components will be modified more frequently (via software).

Because it will take time to define appropriate software radio interfaces, we should not be surprised if in the near term software radios are closely coupled to equipment from particular manufacturers. Indeed, manufacturers may resist any trend towards unbundling and opening of new interfaces in network equipment for fear that this

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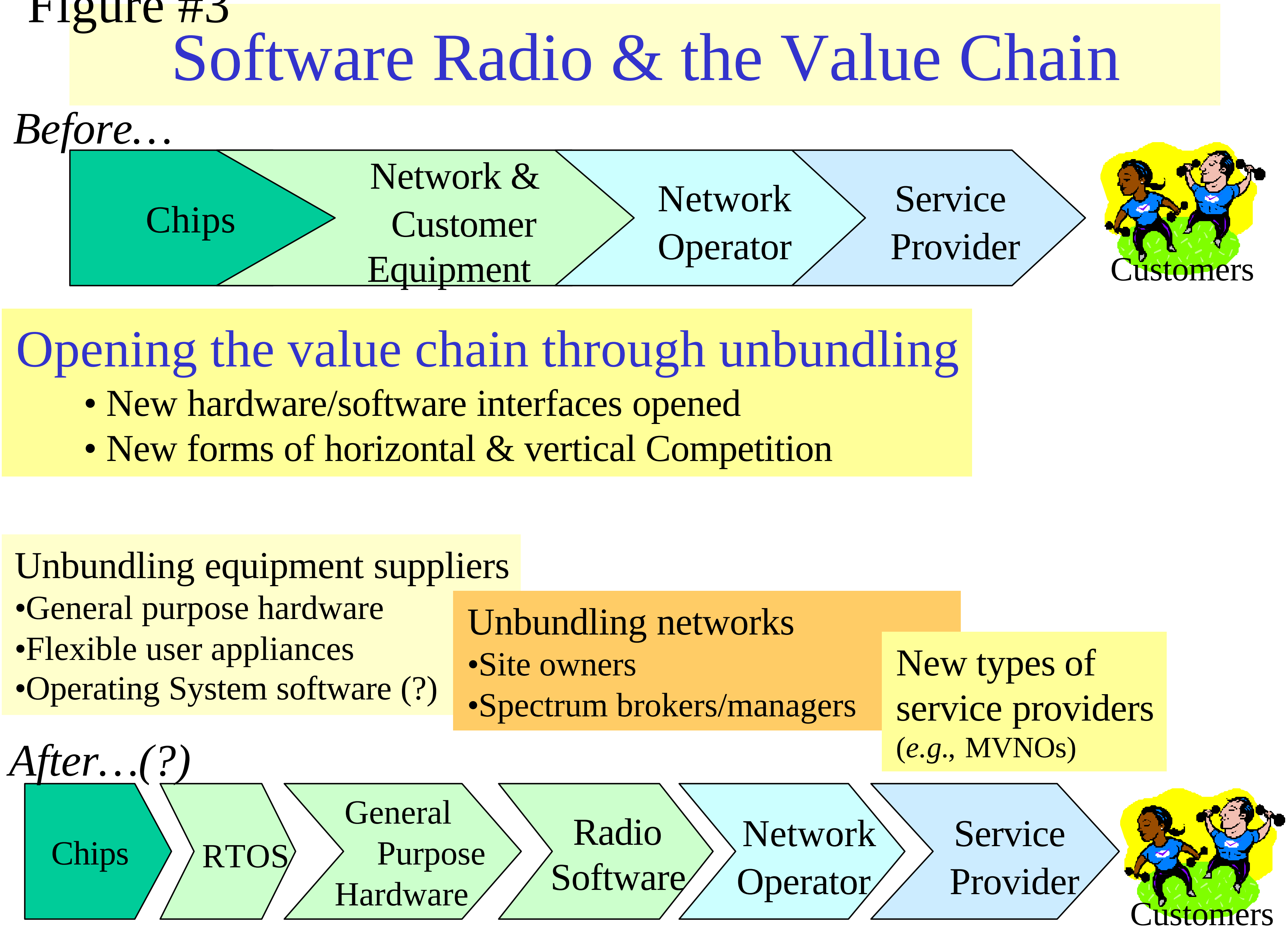
[26] In 2001, Lucent spun-off its optical and semiconductor component operations as Agere.

[27] For example, one may install excess memory or processing capacity in the hardware portion of the radio, in anticipation that future radio software will require this capacity.

Figure #3


Software Radio & the Value Chain
Before…
Chips
Network & Customer Equipment
Network Operator
Service Provider
Customers
Opening the value chain through unbundling
• New hardware/software interfaces opened
• New forms of horizontal & vertical Competition
Unbundling equipment suppliers
•General purpose hardware
•Flexible user appliances
•Operating System software (?)
Unbundling networks
•Site owners
•Spectrum brokers/managers
New types of service providers
(e.g., MVNOs)
After…(?)
Chips
RTOS
General Purpose Hardware
Radio Software
Network Operator
Service Provider
Customers

will provide an opening to new competition or additional pressure to commoditize their products. Manufacturers are likely to view software radio as providing additional opportunities to product differentiate, and thereby, further attenuate competition among manufacturers.

As noted above, manufacturers are likely to support software radio standardization that enhances interoperability to expand the potential markets for their equipment and to address their customers' fears of being locked in. Increased interoperability makes it easier for a vendor to penetrate a customer account with legacy equipment or who is using a competitors' equipment. This could increase competition among equipment vendors.

We should not be surprised if we see vendors supporting standardization of open interfaces to achieve basic interoperability, while at the same time, relying on proprietary software add-ons for the "bells and whistles" that they will use to differentiate their products. This is analogous to the case of Cisco which is a strong supporter of standardization that commoditizes the basic hardware and software elements of networking equipment, while using proprietary add-ons to implement higher-margin features.

Longer term, if software radio realizes its potential, we do not expect such efforts to be successful. The increased reliance on software and the shift to general-purpose hardware will make it increasingly feasible for new types of non-traditional vendors to participate in the market. For example, the traditional vendors of network equipment such as Ericsson, Motorola, Nokia, Lucent, and Nortel may face competition from PC manufacturers like Compaq/HP and IBM. The unbundling of network infrastructure can create opportunities for new types of participants in network equipment vendor markets. For example, providers of (Real time) Operating Systems and specialized radio software providers (e.g., companies like Vanu, Inc.) may become important players. And, as noted earlier, general-purpose hardware is more likely to be associated with open interfaces.

Finally, another factor to consider is that the shift from hardware to software also alters the types of human factor and capital resources that are required to produce new equipment. There are significant differences in the development, manufacture, and distribution of hardware and software systems. Different types of engineers and management practices are required. Thus, even if the same firms continue to dominant network equipment in the future, they are likely to be organized and operate differently.

3. Network Service Providers

In the near term, network service providers ought to be the biggest beneficiaries of software radios. The cost of installing and maintaining a wireless network is significant. By enhancing upgradability, software radios increase the life of network assets and decrease operating and maintenance costs (e.g., downloading bug fixes remotely is much cheaper than sending out a technician in a truck).

The opportunity to customize services and modify radio behavior in the future is also attractive to network service operators. We do not know what the killer applications may be for broadband infrastructure. This uncertainty means there is a substantial real options value associated with the flexibility promised by software radio. This directly reduces the cost of investing in long-lived and largely sunk assets such as those associated with a 3G wireless network. Furthermore, the ability to dynamically modify radio behavior will be helpful in managing congestion (e.g., to dynamically reallocate system capacity).

Longer term, software radios will facilitate unbundling of the service provider portion of the wireless value chain. Today, most wireless services are provided by the same firms that own the underlying infrastructure – although there is a growing class of wireless resellers that lease capacity from network operators. Software radio increases the feasibility of separating ownership of the network assets (spectrum, rights of way, towers, and radio equipment) from the retail services that are provided over that infrastructure. Software radio allows the wireless infrastructure to be more general purpose, which means that the same plant may be used to support services from multiple service providers. Additionally, software radio raises opportunities to unbundle the components of network infrastructure. We could envisage separate companies owning tower sites or spectrum rights[28] that would provide service to multiple service providers. A provider could take advantage of the increased spectrum agility offered by software radios to shift to different RF channels. Alternatively, a site owner could mount the general-purpose hardware and allow service providers to load their own software radios to support whatever sort of network they desired. The site owner could be an expert in local real estate conditions and leave the networking issues to the service provider/network operator.

With the development of open interfaces, software radio will reduce the extent to which network operators are locked in to a particular equipment manufacturer or service providers are locked into a particular network operator. The ability to support interoperability across multiple air interfaces reduces the extent to which a network is locked in to equipment and technology from a single manufacturer. On the other hand, software radio facilitates the building of multi-function, multi-protocol end user devices. Equipment makers of such terminals may be able to capture rents currently being earned by service providers in a fashion analogous to the way in which PBX vendors cannibalized telecommunication service revenues. As software radios move into consumer goods and end-user equipment, any market power that may exist for network operators/service providers will be reduced.

In the more distant future, software radio and other wireless technologies may support the emergence of more ad hoc networking, where users communicate directly and the service operator function is shifted to the edges of the network. This fundamentally redefines what it is to be a service provider.

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[28] For further discussion of how spectrum and services might be unbundled see Noam, Eli, "The Next Frontier for Openness: Wireless Communications," draft paper presented at 2001 Telecommunications Policy Research Conference, Alexandria, VA, October 2001; or, Lehr, William and Lee McKnight, "Wireless Internet Access: WiFi vs. 3G?" paper prepared for ITS Conference, Madrid, September 2002.

C. Policy Challenges

Software radio is a key enabling technology for the continuation of the wireless revolution. As such, it poses a number of challenges for policy makers. Some of these challenges are general and indirect. For example, the implications of software radio for industry structure and competition along the wireless value chain will determine which (if any) segments of value chain will need to be regulated in the future. If software radio does facilitate the emergence of new competition from wireless providers for wireline access services, then it will reduce concerns about a continuing local access bottleneck, and hence, may provide a sound foundation for further deregulation of incumbent local exchange carriers.

There are three areas in which policy will have a direct effect on and be affected by further developments in software radio: (1) equipment certification; (2) standardization; and (3) spectrum management.

1. Short-term: Certification

In recognition of its importance, the Federal Communications Commission initiated a proceeding in May 1999 to evaluate the state of the art for software radio and to determine what its implications are for communications policy.[29] One issue that emerged as of critical importance in the near term was the certification process for software radios.

The FCC's equipment certification process presumes that any software is bundled with hardware and that both need to be certified together. This limits the potential for software radio both because it may be provided separately from the hardware (unbundled) and because much of the benefit of software radio is its ability to be easily changed. Of course, the changeability of software poses a serious challenge to the certification process. How can the FCC guarantee that software it certifies is not altered after certification? On the other hand, because the certification process is cumbersome and time consuming, requiring re-certification every time the software is modified would greatly diminish the flexibility of software radio.

The goal of certification is to assure that equipment operates appropriately in its allotted bands. This protects consumers from potentially dangerous radiation and spectrum users from illegal interference. Because it is relatively difficult to modify hardware without detection and the deployment of new hardware radios occurs relatively infrequently, the traditional certification approach provided a reasonable mechanism for controlling interference.

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[29] See Federal Communications Commission, "*First Report and Order*", ET Docket No. 00-47, FCC 01-264, Adopted September 13, 2001, Released September 14, 2001. In this proceeding, the FCC solicited opinions about the role of software radio in improving interoperability between radio services, improving spectrum efficiency and sharing, and the equipment approval process.

To address the issue of software radio, the FCC created a new certification procedure. The original version of the software radio has to be certified with the equipment on which it will run (making certification the responsibility of the equipment vendor). However, under the new rules, software changes that affect radio frequency, power, and modulation are subject to a more stream-lined certification process. Under these expedited changes, it will not be necessary to change the license number on the FCC certification label that must be attached to all wireless equipment. In addition, to deal with the liability issue, the FCC does not certify modifications made by third party software vendors. All modifications are the responsibility of the manufacturer whose hardware/software radio bundle was originally certified. Thus, the current rules require independent radio software providers to work via the equipment manufacturers.

While this may work well at this stage, it does limit the potential development of software radios and, perhaps, gives too much power to traditional equipment vendors which will limit the emergence of new types of business models and competition.

Even without further reforms, certifying software radios will pose a significant challenge because of the inherent difficulty associated with software certification. In the aerospace industry, certifying software for air control systems requires extremely expensive and time consuming tests because of the difficulty of predicting every possible way in which software may behave (or misbehave). At the other extreme, certification may involve no more than specifying compliance with specific standards. The latter approach, while less expensive and faster, provides far less protection against the software behaving inappropriately.

One approach would be to partition the functionality of the software radio into elements that require greater or less certification to provide adequate protection against illicit behavior. The software architecture could be partitioned into different components that might be subject to different certification rules. For example, operating system software may be subject to more stringent rules under the presumption that these are changed less often. And, if additional checks and controls are embedded in the operating system to control perverse higher-level behavior, then this would offer a form of distributed protection (i.e., the OS would check to see that the higher-level radio software was not attempting to do something that was prohibited by FCC rules). Then, radio software applications may be subject to less stringent rules.[30]

2. Longer-term: Standardization

Standardization is another area where software radio is likely to have an important impact. In the near-term, there are unlikely to be open interfaces and software radios are likely to be closely bundled with network equipment from the traditional vendors. However, longer-term, the possibility of defining additional open interfaces and further

[30] A proposal with an analogous flavor was advanced on behalf of Vanu, Inc. (see Lazarus, Mitchell, "*Petition for clarification or partial reconsideration of Vanu, Inc*.", ET Docket No. 00-47, Fletcher, Heald & Hildreth, P.L.C., November 5, 2001).

unbundling of the value chain offers the opportunity for new business models, new types of services, and increased competition.

These open interfaces may not emerge on their own. Equipment manufacturers may seek to prevent the adoption of open software radio interfaces to limit the impact of competition from non-vertically integrated participants. In this case, policy-makers may have an important role to play in promoting the emergence of open interface standards. At this stage, it is premature to determine what if any sort of public action may be desirable. Certainly, the trend in recent years has been in favor of increased reliance on competitive market processes to select which interfaces will be defined and what technologies will be adopted. Because policy-makers are unlikely to be as well informed as market participants regarding the costs and benefits of alternatives, and because government action may be cumbersome and vulnerable to rent-seeking by vested interests, the predisposition in favor of market-driven standardization seems appropriate. However, in light of the role of software radio as an enabling technology and the potential that incumbents may seek to manipulate the evolution of technology to protect their market positions, policy-makers will need to continue to keep a watchful eye to see that the definition of open software radio interfaces is not unduly delayed.

At a higher-level, software radio reduces the costs of living with incompatible standards. It provides a "gateway technology" that can facilitate interoperability across heterogeneous networking technologies. Previously, many analysts believed that wireless development in Europe was strongly favored by the fact that Europe coordinated on a single 2G mobile standard, GSM. This is in contrast to the U.S., where each provider selected a different technology.[31] The incompatible standards make it difficult for customers to roam or change service providers without changing their handsets. If everyone had software radio handset (which, of course, is not possible today – as noted above), then the lack of a common standard would be less problematic. Thus, software radio may reduce the costs of failing to adopt a single standard.

3. Longer-term: Spectrum Management

Historic policies for allocating spectrum resources are no longer efficient, resulting in too much spectrum being used for some applications, while not enough is available for others. The traditional regime involves a two-step process in which blocks of RF spectrum are allocated to specific uses to serve specific types of applications. Then, the rights to use spectrum in specific allocations (RF bands) are licensed. The licenses impose many restrictions, which may include prohibitions from selling or transferring the license to a another party, specifications of what technologies may be used or services offered via the licenses, and build-out requirements. Both the allocation and licensing regime were overly cumbersome. Moreover, with the advance of technology, historic

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[31] Another very important factor in the faster development of wireless in Europe than in the U.S. is how telecommunication services are priced. In Europe, users typically pay usage sensitive prices for fixed line telephone calls; while in the U.S., these are usually subject to a flat rate tariff. Furthermore, in Europe, only the calling party pays for mobile calls, while in the U.S., the called party also pays. These two differences mean that the relative price of mobile calling (compared to fixed line) was lower in Europe than in the U.S.

allocations have proved to be overly generous,[32] and hence, much of the existing spectrum is being used inefficiently. In recognition of this, there has been growing pressure to reform spectrum management policies in order to facilitate greater reliance on markets and competition to allocate spectrum resources.[33]

One hope of these policy trends is that spectrum will be used more intensively (that is, more users will be able to share the same spectrum without destructive interference) and that there will be increased competition among wireless providers. Software radio is one of the key enabling technologies to realize both of these goals. First, software radio facilitates adopting adaptive interference management schemes (*e.g.*, base station changes its operating protocol in real time to address temporary congestion[34]). Second, as the same services are supported over a wider range of the RF spectrum (*e.g.*, telephone over multiple cellular services, satellite or WLAN services), frequency agile network and end-user devices will become more important. Software radio makes this feasible. It can also play an important role in enabling the unbundling of the wireless value chain, as discussed previously.

V. Conclusions and Future Research Directions

Software radio is one of the key enabling technologies for the wireless revolution. It enhances flexibility and lowers the costs of constructing and operating wireless infrastructure. By enabling digital conversion closer to the antenna, software radio facilitates the exploitation of new techniques in wireless communications ranging from smart antennas to adaptive power management to advanced digital signal processing. By substituting software for hardware, software radio increases flexibility in the form of enhanced upgradeability, customizability, and dynamic adaptability. This in turn facilitates the replacement of dedicated hardware with general-purpose hardware. This lowers entry barriers, facilitates system unbundling, and increases scale and scope economies.

The long-term effect is likely to be increased competition all along the wireless value chain, from semiconductors through to wireless service provisioning. Consumers are likely to be the ultimate long-term beneficiaries from the increased competition. They will benefit from the expansion of the product space, reduced provider lock-in, and lower prices. Of course, realization of these benefits depends on the continued evolution of

[32] For example, the 6MHz channel allocations for TV broadcasters were based on old technology. Today, it is possible to deliver the same amount of information using much less bandwidth. Nevertheless, TV broadcasters continue to control significant allotments of bandwidth that would be very useful for advanced communication services.

[33] See Hazlett, Thomas, "The Wireless Craze, the Unlimited Bandwidth Myth, the Spectrum Auction Faux Pas, and the Punchline to Ronald Coase's "Big Joke": An Essay on Airwave Allocation Policy," AEI-Brookings Joint Center for Regulatory Studies Working Paper 01-01, January 2001; or, *Comments of 37 Concerned Economists*, In the Matter of Promoting Efficient use of Spectrum through Elimination of Barriers to the Development of Secondary Markets, Before the Federal Communications Commission, WT Docket No. 00-230, February 7, 2001.

[34] This may occur by adapting transmission power, changing modulation technique, or some other means.

software radio and the emergence of an open-interface architecture. Whether this will occur or not remains an open question, but in either case, software radio is likely to be an important technology in the years to come.

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