# Market Impact of Software Radio: Benefits and Barriers

by

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## Abstract

Software radio (SR) is a new technology where signal-processing software running over general-purpose hardware platforms performs the radio functions. This approach promises to solve the issues that traditional radios face today, enhance competitiveness and accelerate the development of wireless communications. Lots of expectations have been put on SR. Nevertheless, SR is a still developing technology whose capabilities and implications have not been deeply studied.

This thesis puts some clarity on the impact of SR through four steps: first, considering the technical constraints of SR and how they may affect its evolution; second, evaluating the SR benefits assuming that there are neither regulatory nor economic hurdles; third, analyzing the impact of SR on the stakeholders; and fourth, discussing the current regulatory framework and proposing changes to reduce barriers to SR development.

This thesis finds that SR capabilities may be applied to multiple commercial sectors. A/D converters and semiconductors capacity limit the full implementation of these scenarios. Battery life is a further problem for SR devices.

SR disrupts the traditional wireless value chain: general-purpose processors will capture market share from dedicated semiconductors; traditional radio manufacturers will compete against general-purpose platforms vendors, operating system designers and software programmers. Such changes modify the upper layers. In the cellular industry, SR reduces deployment costs in at least 33% per standard and operation costs in at least 47% per standard, promotes VMNOs, modifies the business model of players like site owners and improves roaming.

In the short-term, FCC certification rules may damage SR development and adoption. In the long-term, software radio might provide the means to relax the need for standardization and improve spectrum management policies.

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# Chapter 1. Introduction

## 1.1 The context

Wireless communication services have experienced an impressive development in the last decade. After the success of the first analog systems, digital standards entered the market to provide higher capacity and better quality. The growth has been especially important in the market for cellular communications, which reached high success between mass-market consumers all over the world. By 2001, worldwide cellular penetration had reached 15% and was over 44% in Europe and Oceania, with many countries in Europe having penetration rates in excess of 70% (see Figure 21 and Figure 22). In 1991, the first digital cellular network was installed in Germany. Seven years later, there were 50 million subscribers only in Europe. Fixed telephone subscribers were 50 million only after 50 years of operation. Cellular communications have even surpassed the Internet, which required 15 years to gain 50 million users [34].

As a consequence of the demand growth, the wireless industry has been accelerated: new standards, services and applications reach the market at faster pace than ten years ago. The industry acceleration provides improved services and promotes competition. However, such benefits are slowed down by the high cost imposed by hardware equipment and the spectrum scarcity. Wireless equipment and devices must be replaced at enormous costs when new standards, services and applications are adopted. High costs discourage innovation. Generally, new wireless systems are heavy spectrum consumers. Spectrum is a scarce resource and therefore, allocating spectrum to particular standards and services may prevent the development of future systems. Consequently, regulators are extremely cautious in providing spectrum for new services, which reduces market innovation.

## 1.2 The problem

Software radio (SR) arises in this challenging stage of the wireless industry. SR proposes a new way of building wireless equipment. Radio infrastructure is not hardware-based any more but software-oriented. General-purpose processors run software that performs radio functions through highly efficient signal processing techniques. This approach promises to solve most of the issues that wireless actors face today. First, equipment may be software upgraded to keep the path of new standard, services and applications without costly replacements. Physical radios might function over different services providing seamless operation. More efficient use of spectrum could be achieved since the same piece of equipment can operate over different standards as needed. Highly discussed spectrum management strategies such as secondary markets for spectrum could be implemented.

Lots of expectations have been put on SR. Nevertheless, SR is a still developing technology whose definition, capabilities and implications have not been deeply studied. Most SR literature makes general descriptions of the technology and superficially describes some of software radio benefits. Other works focus on highly specific technical aspects of SR implementation. Numerous companies take advantage of the expectations that software radios have levered and market their products under SR labels. Regulations designed under the characteristics of traditional wireless equipment may not fit SR particularities and might hurt its development and adoption. There is some confusion about SR and its future. None piece of literature that has done a comprehensive study of the benefits and implications of SR and how current conditions may affect it.

## 1.3 Thesis objective

The objective of this thesis is to put some clarity on the impact that SR may have on the wireless industry through four steps: first, considering the technical constraints of SR and how they may affect its evolution; second, evaluating the full benefit of SR assuming that there are neither regulatory nor economic hurdles; third, analyzing the impact of SR on the different stakeholders; and fourth, discussing the current regulatory framework and proposing changes to reduce barriers to the development of SR.

## 1.4 Summary of findings

This thesis finds that SR capabilities may be applied to multiple commercial sectors. A/D converters and semiconductors capacity limit the full implementation of these scenarios. Battery life is a further problem for SR devices.

SR disrupts the traditional wireless value chain: general-purpose processors will capture market share from dedicated semiconductors; traditional radio manufacturers will compete against general-purpose platforms vendors, operating system designers and software programmers. Such changes modify the upper layers. In the cellular industry, SR reduces deployment costs in at least 33% per standard and operation costs in at least 47% per standard, promotes VMNOs, modifies the business model of players like site owners and improves roaming.

In the short-term, FCC certification rules may damage SR development and adoption. In the long-term, software radio might provide the means to relax the need for standardization and improve spectrum management policies.

## 1.5 Thesis structure

This thesis is organized in six chapters. Chapter 1, which corresponds to this introduction, gives the context, states the problem and defines the thesis objective. Chapter 2 reviews the technology background, focusing on the definition of software radios. Chapter 3 presents the assumptions and discusses the capabilities and applications of SR as well as their timeline. Chapter 4 analyzes the impact of SR on the wireless industry. The chapter provides a deeper insight of its effects on the cellular industry and uses a cost model to quantify SR benefits in the deployment and operation of cellular networks. Chapter 5 examines the regulatory issues related with SR. Finally, Chapter 6 summarizes the conclusions and gives directions for further research.

A set of four appendixes provides details about some of the subjects discussed in the thesis. Appendix A makes a high-level review of the radio principles for non-technical readers. Appendix B summarizes the data used to run the cost model and provides an example of dimensioning. Appendix C reviews the spectrum management schemes resulting of FCC policies. Appendix D sums up the FCC regulatory process on software radios.

# Chapter 2. Technology background

Software radios (SR) may change the market for wireless communications. A full assessment of their impact and benefits requires a basic understanding of the technology. Before presenting SR, Section 2.1 introduces the non-technical reader to the basis of traditional radios and the limitations of their hardware-based approach. SR technology arises as a solution to such limitations. Section 2.2 introduces the concept of software radio and how its capabilities can surmount the problems of traditional radios.

SR is still in development and presents limitations originated by the state of the art of other technologies like analog to digital converters (A/D) and semiconductors. Sections 2.3 and 2.4 discuss how such limitations affect two critical issues of SR design: the point of digitalization and the type of processor that runs the software. Figure 1 summarizes the steps in the migration from traditional towards software radios and their time scale. After presenting the technology, this chapter makes a complete definition of software radios and discusses the terms SR (Software Radio) and SDR (Software Defined Radio) and their use in the industry.

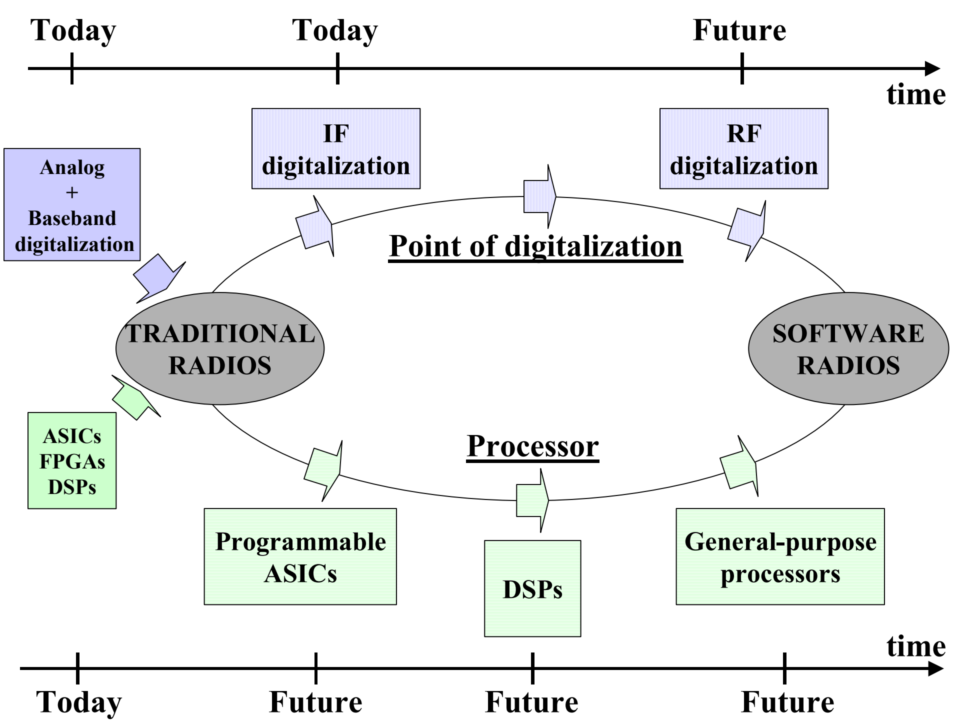


**Figure 1. Technical evolution: from traditional to software radios.**

## 2.1 Traditional radios: a hardware-based approach

Before dealing with SR technology, this section reviews the basics of traditional radio equipment and its hardware-oriented approach. This background provides non-technical readers with a foundation to understand SR principles. Readers familiar with radio concepts may skip such explanation. Appendix A deepens in the high-level concepts presented here. The second part of this section discusses how the hardware-based approach causes traditional radios to have low flexibility, long times and high costs of development and manufacturing and to be limited in the number of services they can offer.

Wireless signals are radio waves, usually in the MHz and more recently GHz bands, in which information has been inserted. Receivers extract the information from the radio waves and present it in a suitable form like audio or video to the final user. Transmitters perform the inverse function. This process requires multiple steps that are carried out in a chain of hardware pieces. Figure 2 exhibits a simplified model of the hardware chain for a traditional radio receiver. The antenna collects the radio waves in the MHz or GHz bands, called radio frequency (RF) signals. In the case of a GSM base station, the antenna receives 124 channels of 200 KHz each situated in 890-915MHz band. The antenna presents the RF signal to the receiver.

Extracting information directly from an RF signal is difficult and expensive since a mix of channels is received at the antenna. In consequence, several steps separate the targeted signal, for example, the channel 32 in the GSM base station, from the rest of received signals. First, a RF filter selects the desired channel. In the GSM base station, a filter limits the RF signal to the 200 KHz of channel 32. The RF filter must be tunable, i.e. it must be able to select channel 32 but also channel 43 if the communication changes to that channel. Manufacturing accurate tunable filters is expensive. Cheap filters are usually placed at the RF stage. In consequence, the output of the filter is not of high quality. In the GSM example, the signal resulting of filtering channel 32 has more than 200 KHz, i.e. has part of the adjacent channels (31 and 33). To eliminate the adjacent bands, the signal is first down converted to a lower and fixed frequency called intermediate frequency (IF). The channel 32, for example, would be down converted from the 900 MHz to 3 MHz. At this point, the signal is filtered again by an IF filter to eliminate adjacent components. Because all channels are down converted to the same IF, the filter does not need to be tunable and can be highly accurate at lower prices. Information is easily extracted from IF through demodulation techniques.[1]

This simplified scheme covers the functions carried out by simple devices like traditional AM/FM receivers. Modern transceivers such as base stations and cellular phones require added hardware components that perform more complicated functions such as equalization, frequency hopping and error detection. These modules require more time-consuming and more expensive development and production processes.

The transmission chain is similar to the reception chain. The user information follows the inverse path. The signal is modulated into an intermediate frequency and upconverted to the required RF band to be transmitted by the antenna.

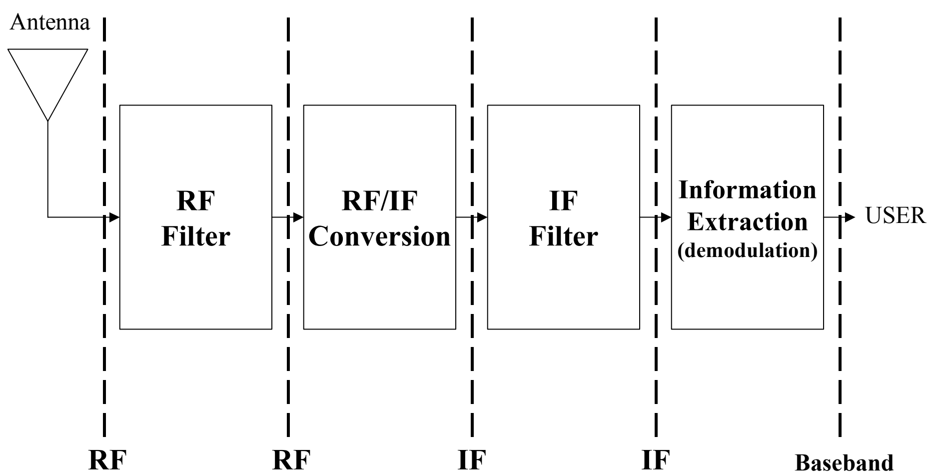


**Figure 2. Simplified hardware chain for a traditional radio receiver.**

The hardware-oriented approach of traditional radios imposes a set of limitations. First, traditional radios have *low flexibility to adapt to new services and standards*. As shown in the previous paragraphs, each hardware element of the radio chain performs a radio function. These components are designed to operate in a particular frequency band

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[1] For a more detailed explanation of this functions and the principles of radio communications, refer to Appendix A.

(RF) and standard. When the frequency or any of the parameters of the standard changes, traditional radios cannot correctly extract the information. Before being able to operate under the new conditions, the system must be redesigned and hardware modules have to be replaced. Redesigning, manufacturing and replacing hardware components require high times and costs. Traditional radios present *long times and high costs for the development and manufacturing of new products*.

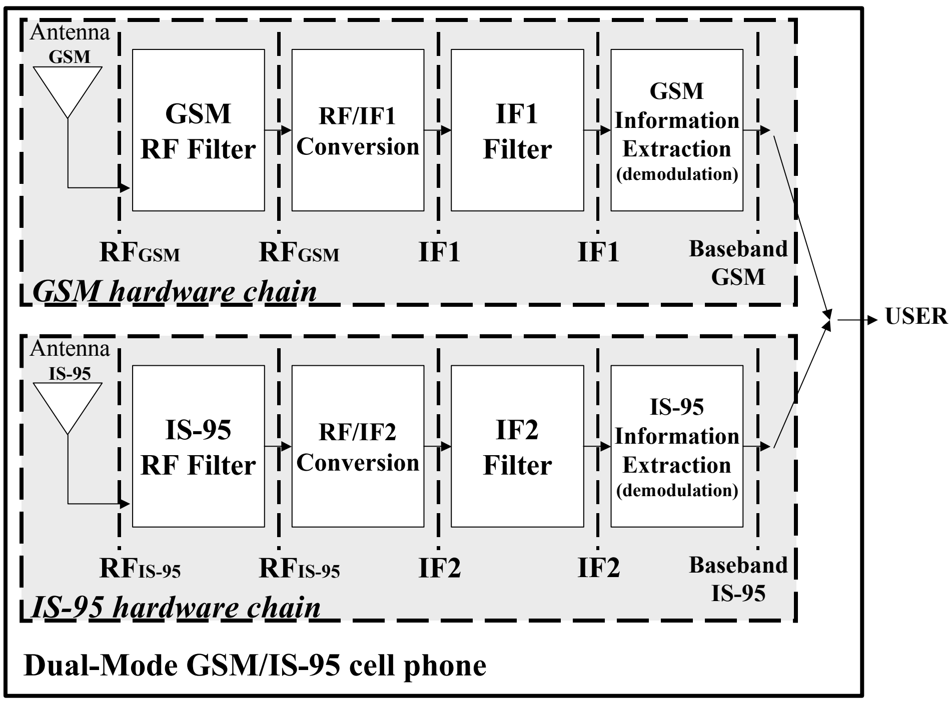


**Figure 3. Hardware-oriented dual-mode GSM/IS-95 cellular phone.**

Traditional radios are also *limited in the number of services they can provide*. When two or more services need to be integrated in the same device, to provide GSM and IS-95 over the same phone for example, one hardware chain is necessary for each service.[2] Figure 3 shows the simplified implementation of a cellular phone that can operate in GSM and IS-95. Two separate hardware chains are used, one to extract GSM information, the other to extract IS-95 information. The physical phone is composed of two independent phones collocated in the same box. Cost, space and battery limit the

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[2] This statement cannot be totally exact in particular cases. For example, for services operating in the same or adjacent bands, both chains may share the antenna, the RF stages and some of the IF components.

number of chains that can be integrated in a device. Nowadays, wireless infrastructure equipment performs a unique standard while handset devices like cell phones are limited to a maximum of three different services.

## 2.2 Software radios: a software-based approach

As explained in the previous section, radio functions have traditionally been implemented in hardware. Dedicated hardware has to be designed for each particular application. This approach imposes low flexibility, long times and high costs of development and manufacturing and limitations in the number of services on a radio. Contrary to traditional technology, SR follows a software-based approach that could remove current radios' drawbacks. Software pieces and not hardware components treat the signals to extract the information. This section gives an overview of how information extraction happens and the implications of the software approach. The details of extraction procedures are analyzed further in this chapter (see Section 2.3). Chapter 3 makes a complete discussion of the capabilities and applications that the software approach makes possible. Chapter 4 analyses how this approach may affect the industry structure and 0 discusses its regulatory implications.

In SR receivers, analog-to-digital converters (A/D) digitalize the analog RF signals. Signal processing techniques extract the information from the digitalized samples. As in traditional radios, the information is presented with the aid of digital-to-analog converters (D/A) in a suitable form like audio or video to the final user. In software radios, general-purpose processors that run special software, together with A/Ds and D/As, replace the chain of hardware components of traditional radios. SR software carries out not only usual radio functions, but also advanced features like channel selection and error correction. Figure 4 shows a simplified scheme of the implementation of both traditional and software radio receivers. In practice, the SR scheme for receivers gets more complicated due to current limitations on A/Ds. Sections 2.3 discusses such problems.

The use of general-purpose processors and signal-processing software increases the flexibility to adapt to new services and standards. New software is installed and hardware pieces do not need to be replaced. Software development and production require lower times and costs than the development of hardware modules (see Chapter 3). Finally, software radio receivers can store software able to operate on different bands and standards and increase the number of services that a single piece of equipment and device can provide. However, the use of general-purpose processors increases the requirements in computational capacity. Since processors are not optimized to perform a particular operation but a set of instructions, they require larger capacity to perform the same functions than specific chips. The improvement of processors' capacity through Moore's Law in the last years has allowed the development of SR technology. Nevertheless, computational capacity limitations still remain (see Section 2.4). Flexibility and efficacy are an important trade-off.

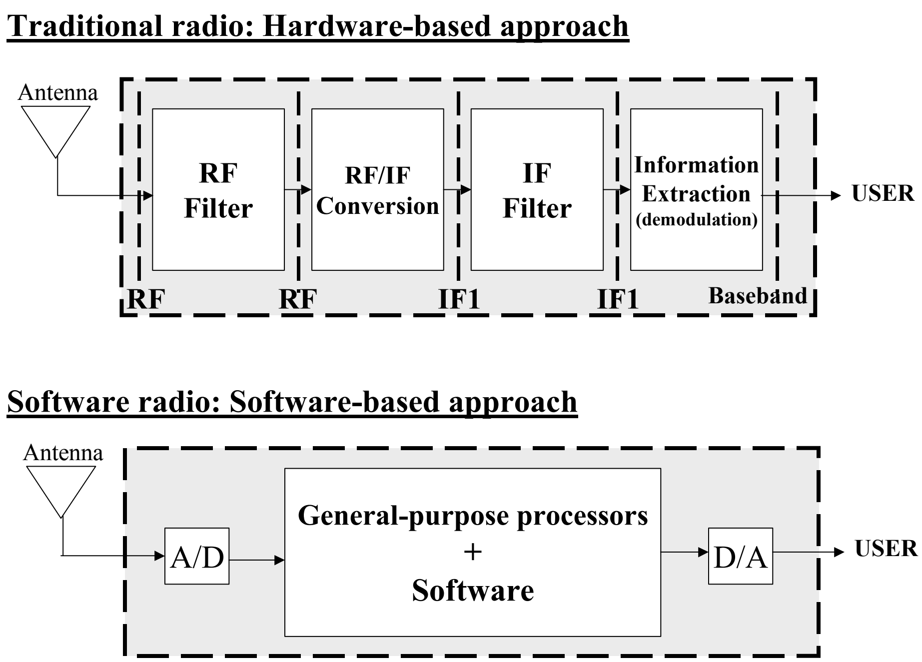


**Figure 4. Hardware approach versus software approach in radio equipment.**

Transmitters are implemented following the same approach. A/D converters digitalize the user information and provide the software running over general-purpose processors with the digital samples. These samples are treated and D/A converters generate the signal to be transmitted by the antenna. Because the user's signal is in baseband, the D/A converters do not suffer from the limitations of the A/Ds placed after the antenna (see Section 2.3). Processing capacity is also less demanding since channel selection is not required in transmission (see Section 2.4). For these reasons, this thesis focuses on the most limiting sense, the reception.

## 2.3 Digitalization

Digitalization converts the analog signals received at the antenna into digital samples. Signal processing techniques treat the samples to extract the information. Digitalization right after the antenna, i.e. before the RF filter (see Figure 2), is the most flexible approach since it allows treating the signal fully in software. However, this kind of digitalization is currently impossible to implement due to the state of the art of analog-digital converters (A/D) and the limitations on computational capacity of present processors. Digitalization may take place at other points of the traditional radio chain: after the IF filter or after the demodulator at the baseband stage (see Figure 2). Traditional radios use no digitalization or baseband digitalization. IF digitalization is the solution currently implemented in software radios. This section explains each configuration and discusses their advantages, disadvantages and limitations in the frame of software radios. Figure 5 shows the digitalization steps in the migration from traditional to software radios.

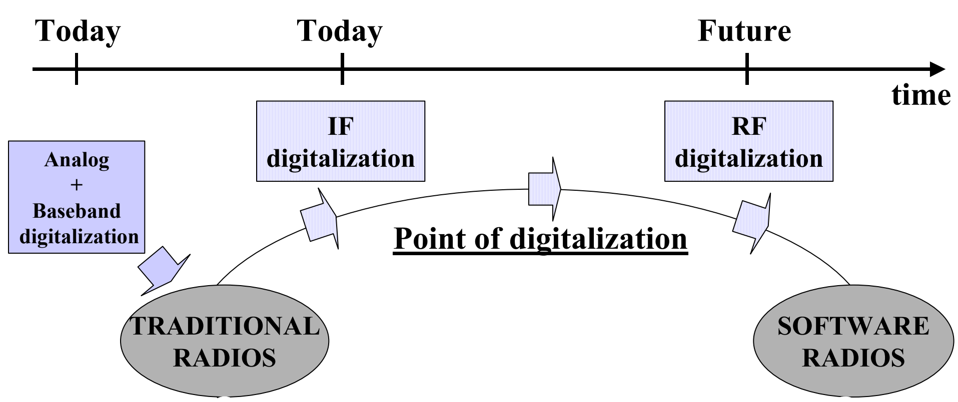


**Figure 5. Evolution in the digitalization point from traditional toward software radios.**

### 2.3.1 RF digitalization

In RF digitalization, an analog-digital converter (A/D) digitalizes the radio waves collected at the antenna. Signal processing software running over general-purpose processors extracts the information from the digital samples. A/D converters, general-purpose processors and signal processing software replace the whole radio chain. Figure 6 compares such architecture with the traditional radio model presented in Figure 2. This approach is highly flexible because the same piece of equipment may be used for any new frequency, standard and application with simple software upgrades but is limited by the present state of the art of A/D converters and the limitations on computational capacity of present processors.

Present A/D converters are limited in speed[3] and resolution[4] at high frequencies such as GHz. Moreover, when A/D converters are placed right after the antenna, sampling is done over signals with very different strengths: the dynamic range of the signals may vary from μvolts to volts. Current A/D resolutions are not able to cover such dynamic ranges. The edge of the technology today seems to be situated at 8 Gsamples/s with a resolution of 8 bits (prototype developed by Stanford University [21]). Commercial products have lower performance. The fastest A/D in the market is a MAXIM chip that samples at 1.5 Gsamples/s with a resolution of 8 bits. For higher resolutions, the commercial limit is 100 Msamples/s with 12 to 14 bits [15]. Nevertheless, important research efforts are taking place to surmount this problem. The company Tektronix recently developed a new digital oscilloscope that samples 3 GHz signals at a rate of 10Gsamples/s with a resolution of 8 bits [82]. Analog Devices lately announced that they

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[3] The term *speed* refers to how fast the A/D converter can sample a signal at a given frequency. Sampling has similar effect that analog downconverting, i.e. moving the signal to lower frequency bands. Downconverting pushes the signal to intermediate frequencies. Digital sampling moves the signal to the lowest frequency band, the baseband. However, only if the analog signal is sampled at a minimum of twice its bandwidth, the set of samples fully represents it (Nyquist theorem). Other effects such as aliasing may recommend increasing the sample rate over two times the bandwidth.

In consequence, A/D converters must sample at a minimum of two times the signal bandwidth. For example, a GSM channel situated at 900 MHz and with a bandwidth of 200 KHz must be sampled at a minimum rate of 400 KHz (two times 200KHz). This process downconverts the GSM channel to 100 KHz baseband. The sample rate of A/D converters diminishes when the frequency where the signal is situated increases.

[4] *Resolution* refers to the number of bits used to represent each sample. Signals with small level variations (small dynamic range) are accurately represented with a few levels and in consequence, with a few bits. However, if field strength suffers high variations, higher number of levels must be represented, requiring more bits.

have developed a technique to eliminate IF digitalization but the company has not offered further details [82].

Speed and power consumption are also a tradeoff in A/D converters. Fast A/D converters exhibit higher consumption that slower ones. If power consumption is very high, the A/D converter could dissipate too much and overheat the device. This issue is particularly critical in mobile devices, where refrigeration systems cannot be installed and the battery life is a extremely limiting factor. In fact, for mobile devices, the A/D power consumption should be within the range of 50 to 150 mw.

Nowadays, there are two trends in the A/D research. On the one hand, some researchers direct their efforts to achieve high speeds. On the other hand, different groups focus on reducing the power consumption. For a complete description of the state of the art in both trends see [44].[5]

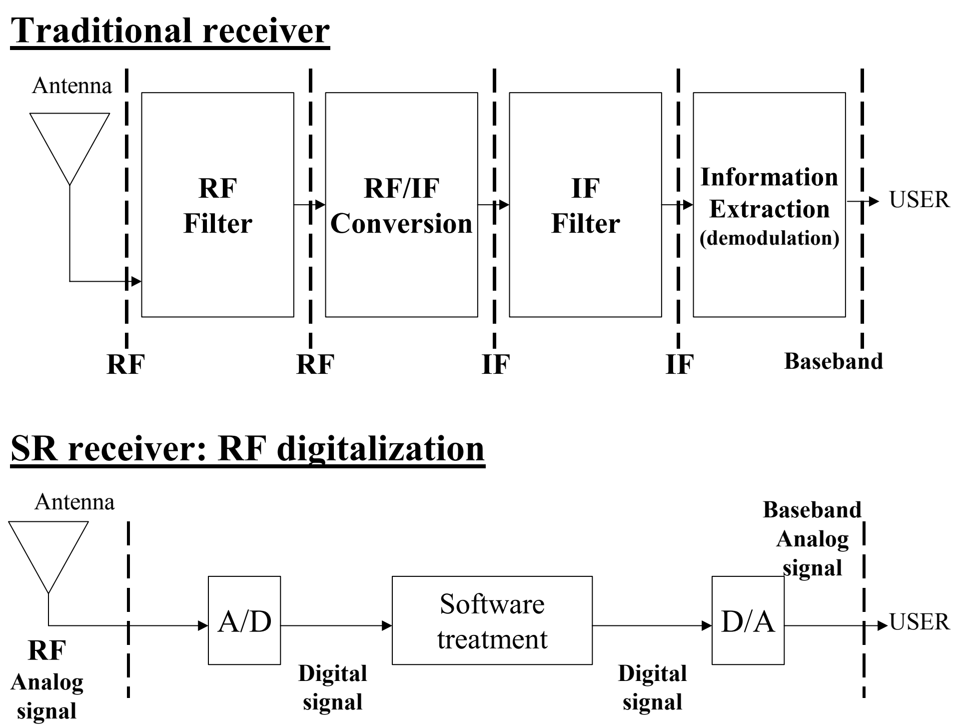


**Figure 6. Traditional receiver versus SR receiver with RF digitalization.**

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[5] The designs presented in this conference were built and tested in laboratory.

Another problem concerns computational capacity. When placing an A/D right after the antenna, the converter digitalizes the whole band (from baseband to several GHz). The software must filter the samples to select the targeted signals. Such filtering has enormous computational cost that only multiple processors can provide today. Using several processors increases the final cost of the radio. The limitations in current processors are further discussed in Section 2.4.

### 2.3.2 IF digitalization

To surmount the present problems of RF digitalization, SR designers place A/D converters after the IF stage. This design requires an RF front-end, which consists of an RF filter, an RF/IF converter and an IF filter (see Figure 7). The RF front-end selects and converts the signal to IF as do traditional radios. Before demodulation, an A/D converter digitalizes the signal. Signal processing running over general-purpose processors extracts the information.

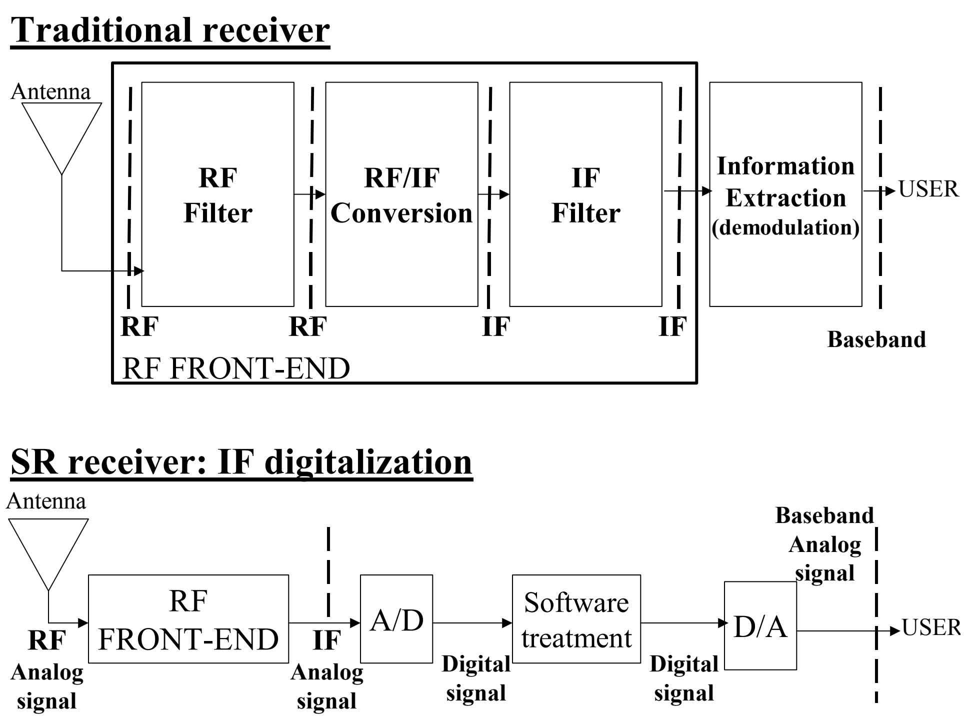


**Figure 7. Traditional receiver versus SR receiver with IF digitalization.**

Two are the main advantages of this configuration. First, current A/D converters can achieve enough speed and resolution at IF frequencies. Second, this design requires less computational resources because the tunable RF filter of the front-end limits the number of received channels reducing the burden of software channel selection.[6]

### 2.3.3 Baseband digitalization

Digitalization at baseband level is common in traditional transceivers. Information is analogically extracted and baseband sampling is used in subsequent stages to profit from signal processing techniques such as music equalization. This is a common practice in widely used devices such as car radios. Because none of the radio functions for information extraction is carried out in software, radios using baseband digitalization are not considered software radios but traditional equipment.

As Figure 8 shows, baseband digitalization does not change the traditional radio chain of Figure 2 but adds specific hardware, usually dedicated integrated circuits (ICs), to perform signal processing over the recovered signal. These modules improve the quality of the received information but also increase the cost of the radio.

[6] Just as an example, Vanu, Inc., a startup that develops SR technology (see [74]), uses for one of its demonstrations a Watkin-Johson RF front-end that receives signals between 2 MHz and 2.5 GHz. This band is converted to IF. IF bandwidth can vary between 2 and 45 MHz. The IF signal is digitalized with an A/D converter of 60 Msamples/s and a resolution of 14 bits. The same general-purpose platform, a 700MHz Pentium III provided with the previous front-end and an A/D converter, handles FM radio, family radio service (FRS) radios, Project 25 law enforcement systems, NTSC television signals and AMPS, TDMA and GSM calls.

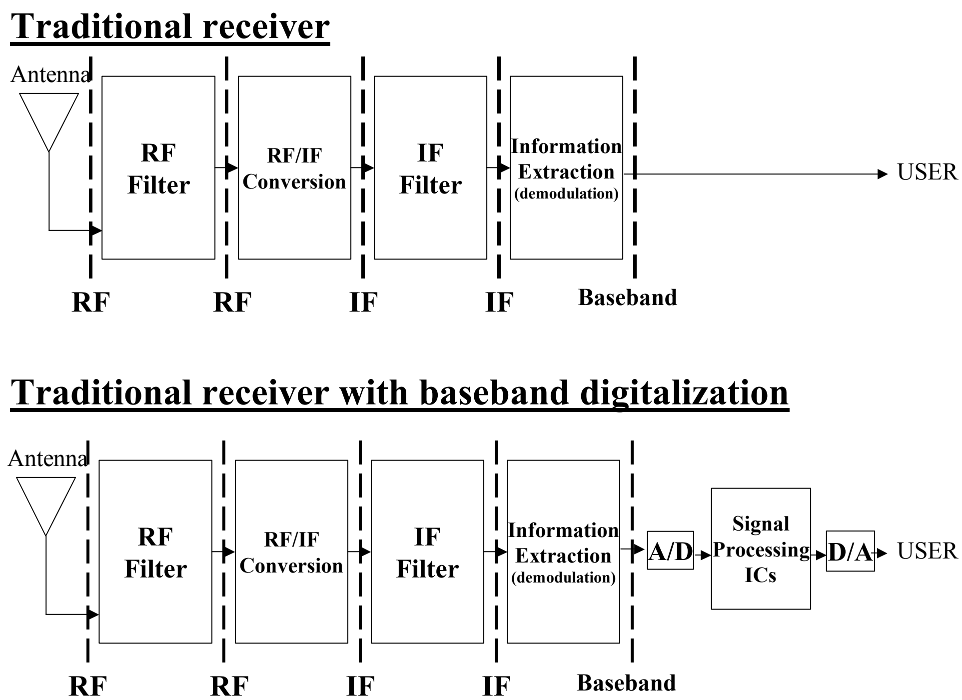


**Figure 8. Baseband digitalization in traditional radios.**

## 2.4 Processors[7]

Processors are a key element in SR technology. Their processing capacity has to be sufficient to perform all the radio functions in software. They also have to be flexible enough for the installation of new software as standards and services change. Processors have to achieve such goals at costs and marketing times that will allow commercialization. Traditional processors like ASICs (Application Specific Integrated Circuits), FPGAs (Field Programmable Gate Arrays) and DSPs (Digital Signal Processors) have revealed insufficient to cover such expectations. Several start-ups are developing or adopting new solutions like programmable ASICs, improved DSPs and general-purpose processors as base of SR products to meet the new demand (see Figure 9).

[7] This section's analysis and data is based on private conversations with industry experts from Qualcomm, Intel and Morphics.

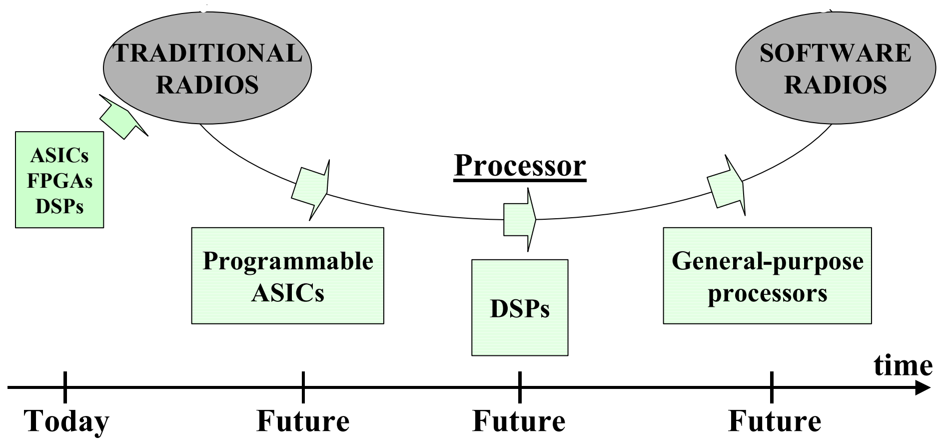


**Figure 9. Evolution in the processor from traditional toward software radios.**

This section describes the processors that implement the hardware chain in traditional radios (ASICs, FPGAs and DSPs) and explains why these chips cannot fulfill the conflicting goals imposed by the acceleration of the path for wireless communications and, particularly by 3G. Finally, this section describes the new processors used in SR technology and their capacity to accomplish such demanding requirements.

### 2.4.1 Traditional communication processors

Radio functions have traditionally been implemented in specific semiconductor ICs[8] (Integrated Circuits) called **ASICs** (Application Specific Integrated Circuits). ASICs can achieve high efficiency because their hardware is optimized to perform a particular task. However, they have long design times and cannot be modified to behave differently. New applications require design and manufacture of new chips. ASIC design is costly in time and money. Only mass production reduces cost. Early adopters of new wireless standards must afford expensive ASICs until demand reaches significant levels and chips become commodities.

The acceleration of the migration path for wireless communications and the demand for cost reduction pushed manufacturers to develop more flexible solutions. Programmable processors, i.e. processors whose behavior is determined and can be

[8] The reader can find in the Glossary the expansion and a brief explanation of the acronyms of this section and others commonly used in SR literature.

modified through software, such as FPGAs and DSPs reached the market to provide some kind of flexibility. These processors were designed to avoid replacing the whole radio chain when minor standard changes take place. Field Programmable Gate Arrays or **FPGAs** are semiconductor devices easy to program. They can be used for a variety of applications but are severely limited in capacity and are expensive even under mass production. FPGAs are frequently used in the development of prototypes. Xilinx and Altera are the market leader for FPGAs.

**DSPs** (Digital Signal Processors) perform common functions of digital communications systems very efficiently. DSPs from Texas Instruments, Motorola and Lucent became increasingly popular due to their programmability, high operating frequencies and capacity. These semiconductor devices are less expensive than FPGAs and meet the needs of demanding applications like the 2.5G generation of wireless communications. Motorola and Texas Instruments are the principal marketers of DSP products. Table 1 summarizes the processors and market leaders in the current cellular market. See Section 4.2.3 for more detailed information about the ASIC, DSP and FPGA market including cellular and other applications.

**Table 1. Processor products and markets leaders in the cellular sector.**

| Products | Market leaders |
|---|---|
| FPGAs | Xilinx, Altera |
| GSM ASICs | Motorola, Lucent/Altera |
| 2G CDMA ASICs | Qualcomm |
| DSPs | Texas Instruments, Motorola, Lucent |
| 3G ASICS | Qualcomm |

### 2.4.2 New computational requirements

The demand for wireless communications has increased exponentially in the last decade and is migrating from voice to data. Data applications rapidly evolve requiring higher data rates. To meet this demand, new generations of wireless standards are being designed. Each generation entails higher computational power. This phenomenon can be clearly observed in the family of cellular standards (1G to 2G to 2.5G to 3G). When data rates increase with each generation, so does algorithmic complexity. Implementing each new generation of algorithms demands exponentially higher processing power. Processing power can be measured in MOPS (Millions of Operations Per Second). Figure 10 shows the growth of computing power requirements from 1G to 4G.[9] From 1G to 2.5G the number of MOPS remains almost flat. An exponential increment starts with 3G and increases for 4G.

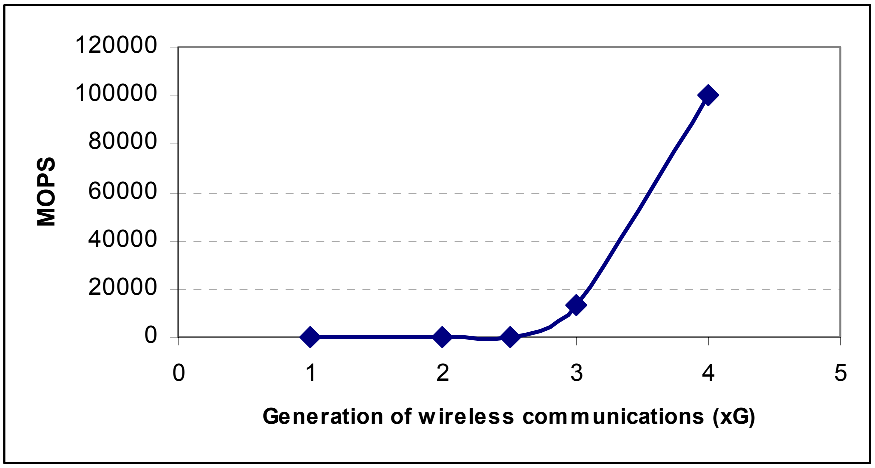


**Figure 10. Computational power versus wireless standards evolution [65].**

Equipment manufacturers currently face 3G. They find that traditional ASICs, FPGAs and DSPs cannot meet 3G computational requirements and provide enough flexibility to follow the fast changes in standardization without continuously replacing hardware pieces. Some manufacturers try to develop solutions based on traditional processors. DSPs leaders such as Texas Instruments, Motorola and Lucent, focus on increasing the operating frequency. Qualcomm is one of the few companies that build traditional ASICs for 3G standards. The firm holds numerous patents on CDMA technology. CDMA is used in most of the new generations of wireless standards. Companies willing to develop CDMA related products need Qualcomm permission to use the patents. Licensing patent rights is an important part of Qualcomm's revenue.

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[9] The fourth generation of wireless communications (4G) is not clearly defined yet. The main goal of 4G is to provide multimedia services over the air interface. In order to do that, 4G will supply data rates over 34 Mbps. Different organizations are already working on 4G issues. The European Commission carries out a project for the definition of 4G systems called RACE. The European Radiocommunications Office (ERO) has already studied the spectrum needs of 4G systems. Finally, the European Conference of Postal and Telecommunications Administration (CEPT) has proposed the 60 GHz band for 4G systems due to its high attenuation by oxygen absorption, which allows frequency reuse every few kilometers.

Traditional radio designs implemented with improved ASICs and DSPs may increase computational capacity and be short-term solutions to 3G. However, this approach is not able to meet the conflicting goals imposed by 3G: *performance*, *flexibility*, *speed to market* and *cost*. ASICs achieve high performance but cannot be programmed. They require high investments and long development times. DSPs are programmable but they only perform some operations and demand long time for software writing. Figure 11 shows the conflicting goals of wireless processors: performance, flexibility, speed to market and cost. The figure compares the characteristics of traditional ICs. These processors do not address the cost of network operators upgrading and moving between standards, a fundamental factor for 3G wireless service providers, especially since the cost of buying spectrum in some countries has been at stratospheric levels (see Table 3 in Chapter 4). The situation favors the entry of more flexible and cheaper approaches such as SR technology.

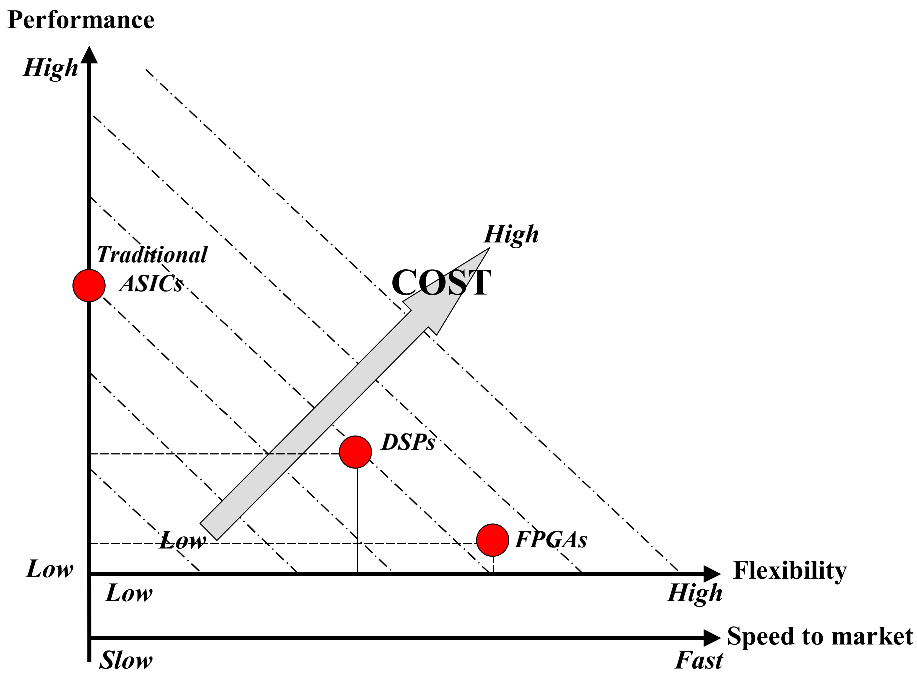


**Figure 11. Processors conflicting goals.**

### 2.4.3 Software radio processors

As explained in the previous section, chip manufacturers struggle with 3G'sconflicting goals: *performance*, *flexibility*, *speed to market* and *cost.* In this context, numerous startups are developing or adopting new solutions like programmable ASICs, improved DSPs and general-purpose processors as base of SR products to meet the new demand. On the one hand, companies like Chameleon, QuickSilver and Morphics stand in the hardware end of SR solutions, focusing on programmable ASICs, which provide high performance, but low flexibility. On the other hand, companies such as Vanu, Inc. are situated on the software side and offer complete SR solutions that concentrate on general-purpose processors with high flexibility and lower performance. In the middle position, companies like RadioScape combine DSPs and software to achieve equally weighted goals. The following paragraphs briefly refer to these companies and discuss the main differences between their products.

### Programmable ASICs: Chameleon, Morphics and QuickSilver

Chameleon [8], Morphics [54] and QuickSilver [65] are hardware oriented SR companies. They design and manufacture highly specialized 3G chips that can deal with an elevated number of WCDMA channels (*high performance*) such as the Chameleon RCP (Reconfigurable Communications Processor) and the QuickSilver ACM (Adaptable Computing Machine). This approach lies on semiconductors properties and benefits from Moore's Law. When semiconductor evolution allows higher integration of transistors, new chips must be designed and manufactured to take advantage of improved materials. Manufacturing *costs* are *high*, especially in the first stages of the product. Costs may be reduced for mass production but the fast generational change of 3G standards and semiconductors makes unlikely to achieve high levels of sales for one chip.

Chameleon, Morphics and QuickSilver products are evolved ASICs with some degree of programmability (programmable ASICs). Chameleon RCPs include low-level software tools to reconfigure the chips. Instructions are very close to assembly language, making difficult and long the reconfiguration (*low flexibility* and *slow speed to market*). Morphics chips follow the same approach but include a high-level software platform that hides assembly language to the designer. *Flexibility* is still quite *low* but the *speed to market is improved*. QuickSilver's approach is unclear. The company's publicity talks about dynamic hardware reconfiguration but the explanations of what this means are misleading.

General-purpose processors: Vanu, Inc.

Vanu, Inc. [91] is a software-oriented company. Its goal is to design totally portable software that runs over general-purpose hardware platforms like PCs. As a result, Vanu products are *highly flexible*. They can operate in different standards and frequency bands with simple software upgrades. As the previously mentioned companies, Vanu, Inc. benefits from Moore's law: faster processors improve software performance. The main difference is that Vanu, Inc. does not need to rewrite its code each time a new generation of semiconductors reaches the market but only install the software in the new processors.

Contrary to the previous companies, which create semiconductors to implement traditional signal processing algorithms as fast as possible, Vanu, Inc. reengineers these algorithms to fit the modus operandi of general-purpose processors. In this way, the software fully benefits from computing capacity. Through the use of mass-produced processors, Vanu, Inc. can profit from lower prices (*lower costs*). Vanu, Inc. software requires hardware platforms provided with an operating system. Once this requirement is accomplished, the choice of hardware platform depends on cost and availability of C++ compilers and comfortable debugging tools. These tools allow software designers to fast develop new applications improving the *speed to market*.

DSPs: RadioScape

Some startups have situated themselves in a middle point where they write software to be run on others companies hardware. This is the case of RadioScape [66], which has chosen Texas Instruments' DSPs to implement its code. These companies try to benefit from the low cost of mass-produced hardware while adding flexibility through software. However, engineers must tailor the software for each particular piece of hardware and rewrite it for each generation of DSPs. *Performance* and *flexibility-speed to market* are equally favored.

Figure 12 compares the characteristics of new and traditional processors. Hardware oriented approaches like programmable ASICs have higher performances. Software oriented products like general-purpose processors are more flexible. In the future, More's law will allow software-oriented solutions to improve their performance and flexibility at lower costs.

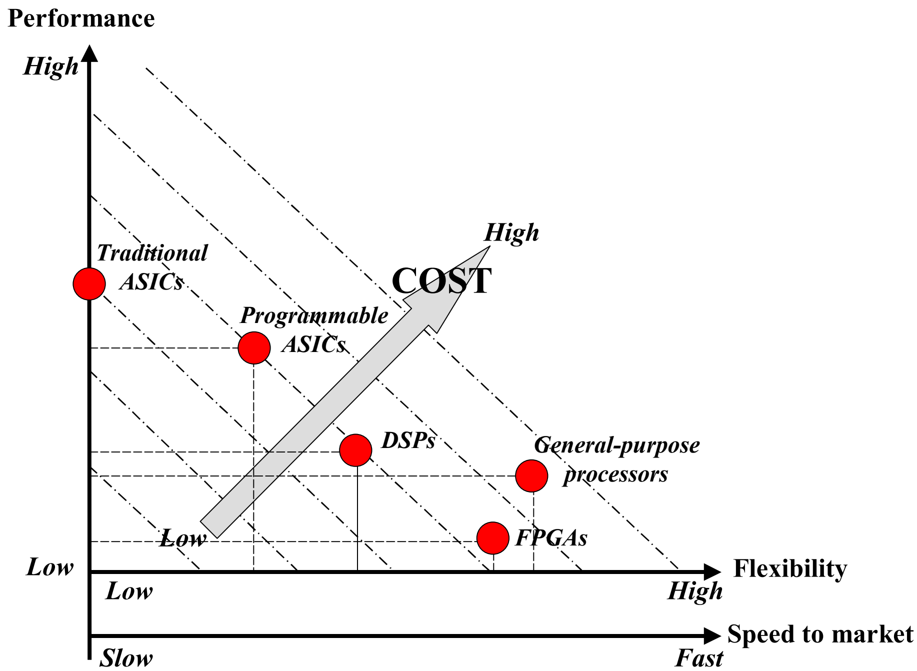


**Figure 12. Comparison of traditional and SR processors.**

## 2.5 Other technical barriers to SR

Not only *A/D converters* and *processors* limit SR development. Other technical barriers slow down the development of SR technology.

*Batteries* are an important problem for SR handsets. As explained in Section 2.3, A/D converters have high consumption. Signal processing requires lots of computation that also imposes high power consumption. Power supply is not usually a problem in network equipment but it is in handsets, where autonomous operation could be limited to one or two hours with current batteries.

The second barrier is *amplification*. The RF filters not only limit in frequency the signal received at the antenna but also amplify it to compensate the attenuation due to the propagation over the air. Quality and bandwidth are amplification trade-offs. If the bandwidth of the signal is large, amplifiers may cause distortion on the edges of the bandwidth. This problem is particularly important in software radios using an RF front end, where the filters have to amplify signals of larger bandwidth than in traditional radios. Important research efforts are being dedicated to obtain high quality amplification over extensive bandwidths.

Finally, *cost* is a discouraging component for SR handsets. Nowadays, for up to three standards, traditional implementations are less expensive than SR. For four and more standards, SR handsets are cheaper.[10]

## 2.6 Software radio definition: SR and SDR

After presenting the basics of SR technology, this section defines software radios. There is not a unique definition of software radio. Wireless players have maintained an intense discussion about this matter during the FCC procedure of rule making for software radios (see 0). The literature contains several of these (see [3], [77], [86], [91] and [93]). This section gives some examples of literature definitions and makes a summary of the elements that a SR must exhibit. Finally, this section discusses the terms SR (Software Radio) and SDR (Software Defined Radio) and their use in the industry.

The American National Standard definition of its Telecom Glossary 2000 is the closest to the principles explained in Section 2.3.1:

" *A software radio is a receiver and/or transmitter with the following properties: (a) the received signal is digitized and then processed using software-programmable digital signal processing techniques (digitization may occur at the RF, IF or baseband); and (b) the modulated signal to be transmitted is generated as a digital signal using software-programmable digital signal processing techniques. The digital signal is then converted to an analog signal for transmission (the conversion to analog may occur at baseband, IF or RF).*" [3]

The SDR Forum, a non-profit association of different SR players, has defined software radios as:

"*radios that provide software control of a variety of modulation techniques, wide-band or narrow operation, communications security functions (such as hopping), and*

[10] Source: Vanu, Inc. internal presentation [91].

*waveform requirements of current and evolving standards over a broad frequency range. The frequency bands covered may still be constrained at the front-end requiring a switch in the antenna system.*" [77]

Several definitions can be found across companies, organizations and individuals. Most of these definitions contain a common set of characteristics:

- Digitalization of the analog signal: Digitalization may take place at RF or IF level. Baseband digitalization is a point of controversy. Traditional radios frequently use digitalization after demodulation stages to profit from signal processing benefits (refer to Section 2.3 for further details).
- Software based: Software pieces perform signal processing and control the radio parameters, particularly frequency, modulation and power.
- General-purpose processors: General-purpose processors run the software in charge of signal processing and radio control. The particular kind of processor depends on the approach adopted by different companies and the state of the art of the technology. This issue is widely discussed in Section 2.4.
- Software upgradeable: Software upgrades allow radios to operate in other bands, perform different radio functions and provide added services.
- No hardware replacement: Radios that require partial or total hardware replacements of the elements that control the radio functions to be upgraded are not considered software radios.
- Multi-operation: Software radios may operate in multiple bands, standards and applications.
- On field upgrades: Some players uphold that the capacity to be upgraded on the field is part of SR definition. Others like the FCC (see Appendix D, Section III) do not agree with this requirement.
- Dynamic adaptation to the environment: The future of software radios looks to dynamic adaptation to the environment. Radios will listen to the available signals

at a given moment and use the adequate standard. This is an advanced feature that today is not part of SR definitions.

In the radio industry, the terms SDR (Software Defined Radio) and SR (Software Radio) are generally used as substitutes to refer to radios exhibiting the above characteristics. The term SDR has become more popular and is commonly used in technical literature and regulatory documents. This thesis most frequently uses the term SR.

Given the expectations created by SR technology in the last years and the need of companies, especially startups, to differentiate their offerings, numerous products are marketed under SR tags. Most of these products exhibit some SR behaviors in particular conditions but are not real software radios. Radios provided with software pieces that control radio aspects but do not perform signal processing on software are an example of this situation. This is commonly the case of multi-frequency and multi-standard cellular phones. In these phones, separate and traditional radio hardware chains implement each band or standard. Dedicated integrated circuits carry out signal processing functions. The software only selects the chain that must operate in each situation. Figure 13 shows an example of this kind of design for a GSM/IS-95 dual-mode cell phone. The telephone can operate in two different standards, GSM and IS-95, but cannot be software upgraded to operate in a new standard like DCS. For operating in DCS, not only new software must be installed on the phone but also another hardware chain must be added.

The same dual-mode cellular telephone implemented in SR would only have one hardware chain. The software is in charge of reconfiguring this chain to perform the signal processing functions corresponding to GSM and IS-95. To upgrade the telephone to operate over DCS, only new software has to be added (see Figure 14).

Some differences in the use of the terms SR and SDR may be found in the literature. Vanu, Inc. [91], for example, uses the term SR to refer to software radios as defined in this section and SDR to point out multiple hardware chains controlled by software such as the cellular telephone presented in Figure 13).

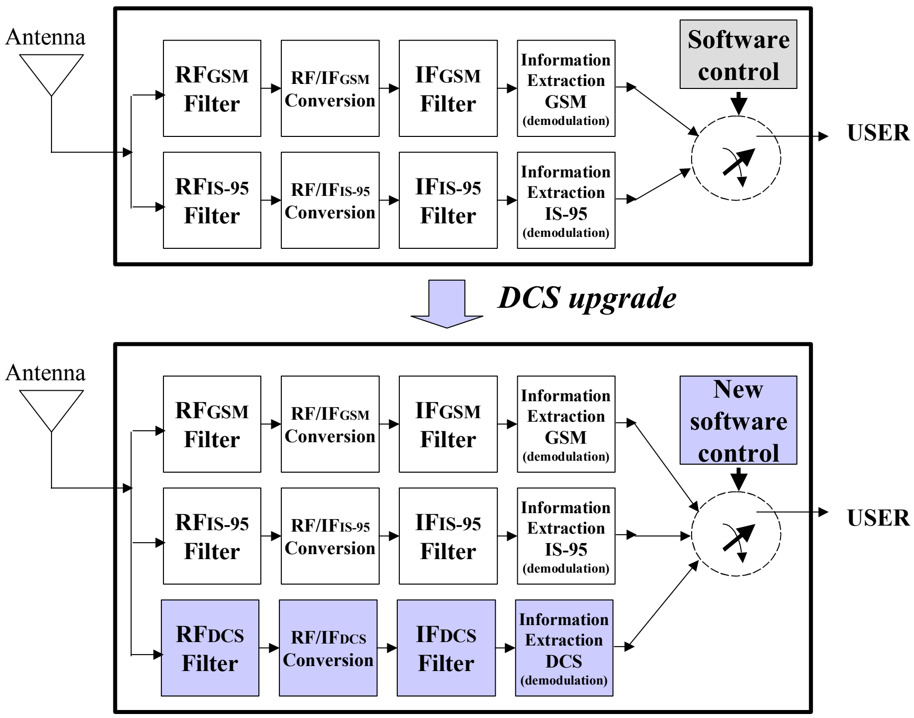


**Figure 13. Traditional design for a GSM/IS-95 dual-mode cell phone with control software.**

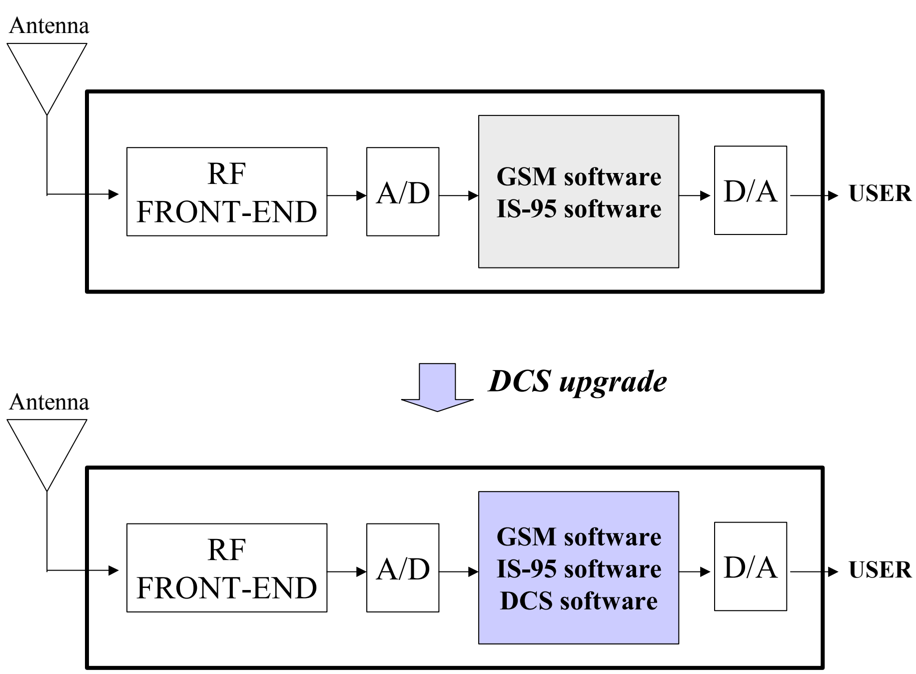


**Figure 14. SR design for a GSM/IS-95 dual-mode cell phone.**

# Chapter 3. Impacts of SR

The separation of hardware and software that software radios propose will have important impacts in the capabilities and applications of wireless technology as well as in the industry structure. Chapter 3 looks into the future to assess those impacts. Some assumptions are made to facilitate the analysis. Section 3.1 details such assumptions while Section 3.2 evaluates SR impacts.

## 3.1 Assumptions

Chapter 3 is an exercise that looks into the future of SR technology and discusses the impacts that SR technology may have. Some assumptions are made for this analysis. The first assumption establishes that there are no regulatory nor market barriers to the development and adoption of SR technology. This supposition allows looking far into the future without the difficulties of dealing with external factors. The first supposition is taken away in Chapter 4 and 0, which analyze how industry and policy barriers may damage the future of SR and propose some solutions. The second assumption establishes that digitalization is done before the baseband stage, i.e. at the RF or IF stages (see Figure 6 and Figure 7).

## 3.2 Hardware and Software separation: a new open interface

As explained in Chapter 2, traditional wireless equipment performs radio functions in dedicated hardware. Specialized integrated circuits carry out analog and signal processing treatments. This situation changes in software radios, where RF or IF signals are digitalized and processed in software over general-purpose hardware. A new open interface is created between hardware and software: both entities become independent and exchangeable pieces of the radio chain. Hardware and software disjunction has important consequences on the radio capabilities, radio applications and the industry structure. This section explains the consequences on capabilities and applications while 0 discusses the changes on the industry structure. Even if particular examples are provided to clarify the impact of software radios, this section gives a general view without analyzing a particular sector of the industry.

### 3.2.1 Capabilities

Hardware and software separation has an important impact in the functions that radios may perform. New functions are the most obvious benefits for the wide public. However, other SR features such as reduced time and cost to develop and manufacture new products, reduced risk of obsolescence and improved distribution channels have comparable consequences for the industry. Figure 15 summarizes these new capabilities.

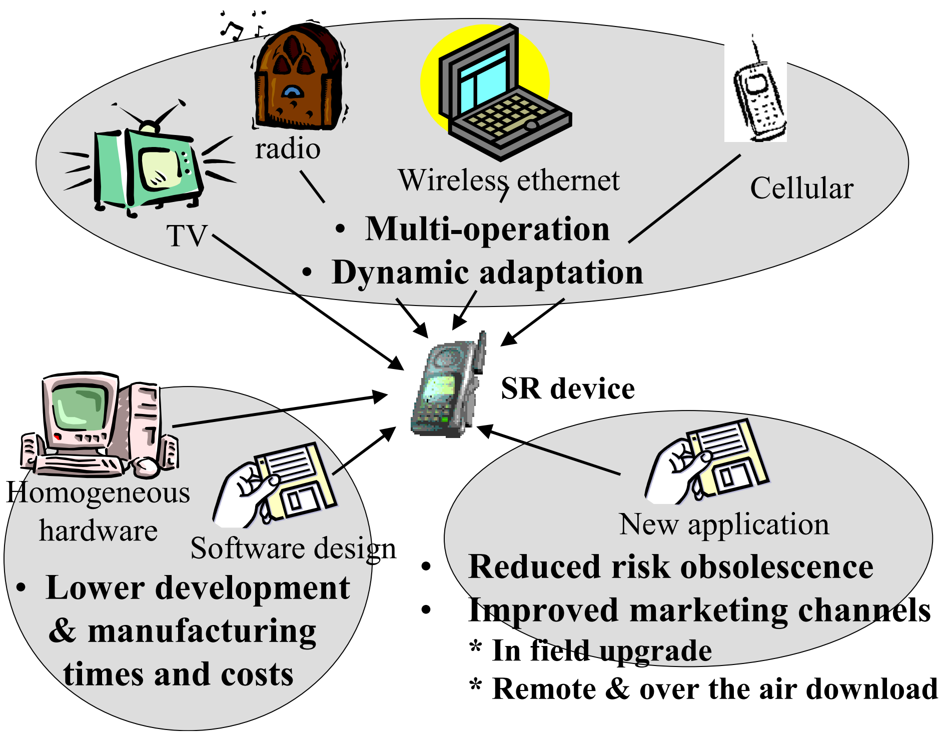


**Figure 15. Software radio capabilities.**

New functions

One of the most appealing functions of software radios is their capacity to perform *multi-operation* over different bands, standards and applications. A consumer might use the same device as cell-phone, garage door opener and baby monitor. The future looks even further. Software radios will *dynamically adapt to the environment*. Future radios will transfer the control of the radio from humans to software. Radios will automatically monitor the environment and select the adequate bands, standards and applications to meet the user needs. While present multiple-mode devices, like GSM/IS-95 cellular phones, can already operate over two different standards and select the adequate service for a given location, they are limited to two or three standards providing the same or similar services. Software radios expand the number and type of standards that can share the same physical device. For example, in an environment provided with data cellular networks and wireless local area networks, an intelligent radio will select the most convenient service for the user application at a given moment. If case of surfing the web, high data rates will be chosen. For email applications, less performing rates will meet the needs.

Reduced development and manufacturing times and costs

As wireless technologies improve, new products reach the market at a faster pace. Manufacturers must market innovative features at a quicker rhythm to meet the demand and compete. However, numerous products do not achieve market success. Under hardware approaches and with technology improvement, the time and cost of development increase exponentially. This is a risky situation for manufacturers. They must accelerate the marketing of innovative products to compete in the industry but at the same time the probabilities of a product being successful are low. Producers make high investments but the risk of not recovering them is important. This situation also diminishes consumers' choice. Moving to SR approaches has the advantage of reducing development times and costs. Required investments per product are lower and manufacturers can afford to market more new products. This strategy reduces manufacturers' risk. SR capability to develop products in a faster and less expensive way will allow manufacturers to keep the pace of the changing demand. But this effect is cyclic, as manufacturers market new items faster, there will be an acceleration of wireless technologies that will demand faster development of new products.

The first element that reduces time and cost is the use of *homogeneous hardware* for multiple devices. The same piece of hardware, for example, may implement base stations for two standards, GSM and IS-95. In consequence, less expensive production resources will be required. Cheaper general assembling lines will replace more expensive and specialized ones. Since most products will share the same basic hardware, production planning will be less critical. Inventories can be smaller and less diverse and hardware development times for new products are eliminated or reduced to hardware improvements.

The second element is *software design*. Under SR approach, developing a new product mainly involve writing new code. Development is faster and cheaper for software products than for hardware items. Software mass production requires less resources and organizational structure. Moreover, with a modular design that permits code portability across processors, software pieces may be reused in different products and therefore, only small portions of software have to be addressed when implementing innovative products. For example, filtering modules from previous standards could be use in the development of software for a new standard that operates in the same frequency band.

#### Reduced risk of obsolescence

The fast pace of wireless technologies makes that wireless infrastructure and devices become obsolete in short periods of time. Dedicated committees continuously review wireless standards and add new features. A good example is the two hundred modifications that the 3G European UMTS standard has suffered in the last two years. Standards cannot be improved infinitely to meet the evolving needs of the industry. Therefore, more performing standards are specified. This is the case of the transition from GSM to UMTS in Europe. In both cases, standard upgrade and new standards, and under a traditional approach, equipment and devices must be replaced to benefit from the new features. This replacement imposes enormous costs in all types of consumers. With SR technology, hardware replacements are not necessary. Software radios can be *software upgraded*, like a PC, to operate a new application. Thus, operators like AT&T, migrating from TDMA to GSM/GPRS, could keep their infrastructure through software upgrade if using SR base stations. AT&T customers provided with SR handsets would also be able to keep their telephones to operate over the new standard.

#### Improved marketing channels

Another problem of the acceleration of the wireless evolution is the difficulty for new products to reach consumers. There are two reasons for this situation. First, devices have to be upgraded to operate over the new service, which imposes costs and delays in the marketing of products. Second, users do not have time to look for new products that they do not immediately need. Customers are also invaded by advertising and it is difficult to get their attention. *Remote and over the air download* appear as a significant improvement to both problems. On the one hand, upgrading software over the Internet and over the air interface reduces the cost and time to make an upgrade. Users for example, do not need to go to specialized stores to upgrade their devices. On the other hand, operators may push new services to their customers with substantial reductions in advertising and distribution expenses. Cellular service providers, for example, will deliver new products such as games through the air interface to their customers for trial promotions. Users will be instantaneously reached.

Replacing, repairing and upgrading hardware-based equipment requires enormous operational expenses from transportation of physical equipment and human teams. SR infrastructure also provides a palliative through *in field upgrade*. The pieces of wireless infrastructure can be directly upgraded on the field, saving a substantial part of costs.

### 3.2.2 Applications

The most evident applications of SR are *mass-market communication devices* and *wireless infrastructure*, which will clearly benefit from the capabilities presented in the previous section. However, SR technology will likely find further applications as technology spreads.[11] The most relevant of these applications are summarized in Figure 16.

One of the players most interested in SR today is the *military*. On the one hand, the FCC has traditionally allocated wide bands for military use. However, under the growing demand for commercial spectrum, the FCC and military sectors are being pressured to reallocate military bands to civil uses. The most popular case is the negotiations that the FCC engaged to liberate the 2 GHz band for 3G communications, mostly occupied by the

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[11] Industry members provided a large part of the information contained in this section through private conversations. The names of particular companies are omitted to guaranty the confidentiality of firms' activities with strategic value.

military and governmental organisms. The military are willing to adopt new technologies that use more efficiently their increasingly scare spectrum. On the other hand, wireless communications have extraordinary strategic importance. The ability to communicate in the battlefield can decide the winning side. In consequence, militaries search to assure their communications at any given moment. Nevertheless, dedicated bands cannot be expected to be available in the battlefield. Interferences make difficult communications. Moreover, different corps of the same army and different international forces commonly use incompatible radio systems and make difficult their joint operation.

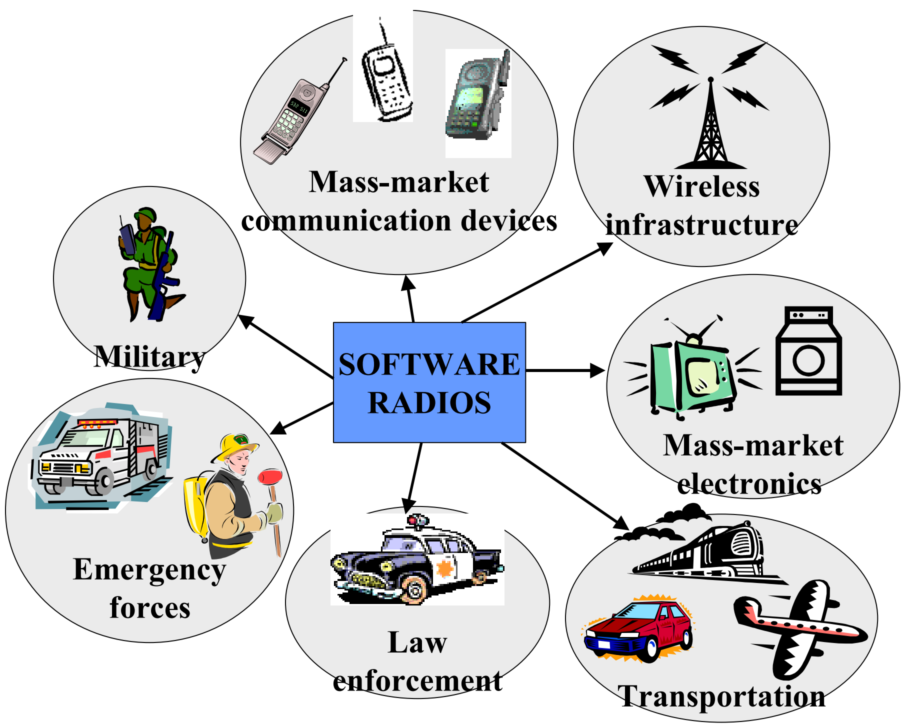


**Figure 16. Software radio applications.**

Software radios provide solutions to some of the military problems. First, software radios facilitate the communication between incompatible radio systems through the installation of new software. In critical situations, software download could even take place over the air. Second, SR also provides a more efficient use of the available spectrum, which is a fundamental strategic advantage in the battlefield. SR capacity to switch bands, standards and applications guaranties the communications in situations of high occupation and interferences.

The military are key drivers of SR technology, which was born from the military research project SPEAKeasy [48] carried out in the early 1990's. As early adopter, the military is willing to afford enormous costs to obtain new performances. Battery limitations also are less important for military radios than for civil devices. In the battlefield, performances are the key point and heavy pieces of communication equipment are commonly used. Vehicles and soldiers can carry out large batteries.

*Emergency forces* like medical services and firemen are frequently provided with incompatible systems, which make difficult their coordination in emergency situations. Like in the military, forces using software radios and software operating over the same standards can intercommunicate and better manage the radio resources. For example, if a fire takes place in a commercial center, SR base stations may block normal cellular calls and allocate additional band resources to firemen and emergency calls. In the same example, firemen and medical services provided with software radios and software to operate over the same standards might be able to communicate directly. If radios are not provided with the same standards, software download could take place over the air interface. As in the military, batteries are not a main problem in this type of applications. Pieces of radio equipment installed on vehicles have a continuous power supply and emergency professionals are prepared to carry out radios of large size if necessary.

The ability of software radios to operate over multiple bands, standards and applications make them a perfect scanner: all types of communications may be intercepted. *Law enforcement departments* could use SR terminals to listen to criminal conversations under judicial authorization. Software radios also provide interoperability between incompatible radio systems of enforcement different departments. As in the military and emergency forces, battery life and weight are secondary problems because the radios are installed on vehicles or carried out by prepared specialists. Some USA departments have started funding SR research in the last years.

The *transportation* industry is another sector interested in SR technology. Designing and manufacturing new vehicles is a long and costly process. Communications systems have traditionally been a small part of such design. In the automobile industry for example, AM and FM radios are secondary criteria for users to select a car and their cost is small in comparison with the whole cost of the car. Nevertheless, the importance of communication systems is increasing as wireless systems evolve and may grow to become an important part of vehicle costs. The demand for communication equipment on vehicles is accelerating and is difficult to anticipate for the time the vehicle will be manufactured. Car manufacturers may wonder which new radio bands will offer broadband services in some years or if Internet access will be a key issue in future vehicles. This situation creates problems of parts supply. Vehicle manufacturers have to order communication hardware long before the car is manufactured. Software radios offer a flexible way to implement such communications system. Since the hardware chain is common, manufacturers can wait until the manufacturing stage before deciding which communications will be provided in the vehicle.

The automobile industry is one of the first adopters and is already funding product development projects. In the future, other transportation systems like trains and plains may adopt SR technology. Software radios may be particularly useful in trains, where important problems of operation obligate to use several radios over the same locomotive. European trains, for example, have to use a different radio each time they cross a border because each country uses its proprietary standard. Solutions like the GSM-R (Railway GSM) were proposed but did not reach much success [52]. Train and plain applications are more sensitive than car radios since they involve important security issues. Nowadays, software systems are considered less reliable than hardware equipment. In consequence, train, plain and other sensible transportation applications may wait until SR technology will be fully developed and tested in other scenarios to adopt it.

*Mass-market consumer electronics* may be a sector of application for software radios in the far future. If the most futuristic previsions take place, the electrical household appliances will be linked through local networks and the Internet to home and outside computers. These appliances will likely need from wireless links to talk to the networks and different devices. After the full development and adoption of SR, prices could be so low that SR will be used in these mass-market consumer electronics to provide wireless communications.

The realization of such scenarios will depend on the degree of development of SR technology. As explained in the previous paragraphs, early adopters are willing to afford high prices, large pieces of equipment and short battery life. As technology improves, new players will adopt software radios. Figure 17 summarizes the timeline for the different applications.

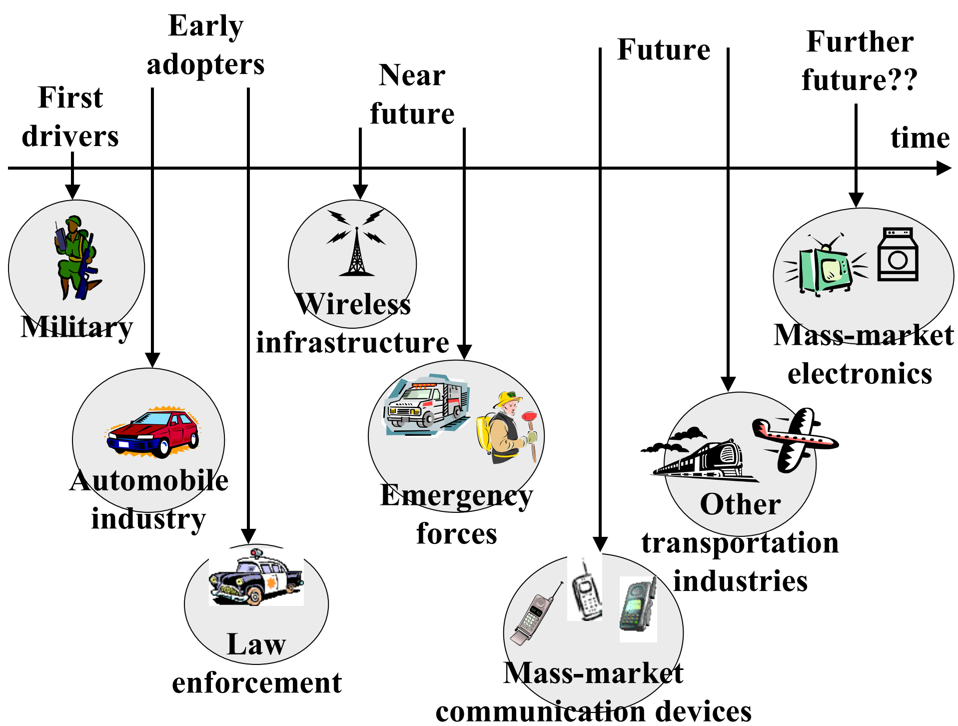


**Figure 17. Timeline for SR applications.**

# Chapter 4. SR and the wireless value chain

SR may have a profound impact on the value chain for the wireless industry. SR is likely to enhance prospects for entry, intensify competition, change and engender new business models and expand the range and quality of wireless services. The first section of this chapter discusses the implications of the separation of hardware and software that SR makes possible for the semiconductor, network equipment and radio handset manufacturing stages in the wireless value chain. The first section also reviews the early adopters of SR through the SDR Forum members. The second section then considers the implications of these changes for cellular services.

## 4.1 Hardware and software separation: a new industry structure

The separation between hardware and software facilitated by SR changes both the capabilities of radio equipment and the structure of the industry that produces the radio equipment. SR will disrupt the traditional relationship between semiconductor producers and radio equipment/handset manufacturers. First, general-purpose processors such as microprocessors will capture market share from dedicated semiconductors. Second, traditional radio equipment and device manufacturers will find themselves increasingly competing against general-purpose platforms vendors, operating system designers and software programmers. These transformations, summarized in Figure 18, are likely to have important implications for the higher layers in the wireless value chain. In Figure 18, the general term “customer” represents those upper layers. In the case of the cellular industry, interpret "customer" to mean network operators, service providers; in the case of military applications, interpret the "customer" as the army.

The hardware-oriented approach of traditional radios defines the current structure of the wireless industry: semiconductor vendors like Lucent/Agere[12] design and produce specialized chips (ASICs) that implement parts of particular wireless standards (see Figure 26 for the largest ASIC vendors and their market share). Equipment and handset

[12] In 2001, Lucent Technologies spun off its optical component and semiconductor unit under the name Agere.

manufacturers like Ericsson, Nokia and Motorola use these chips to fabricate standard-specific infrastructure and devices, which are marketed to different customers such as network operators, service providers and individual users (see Figure 18).

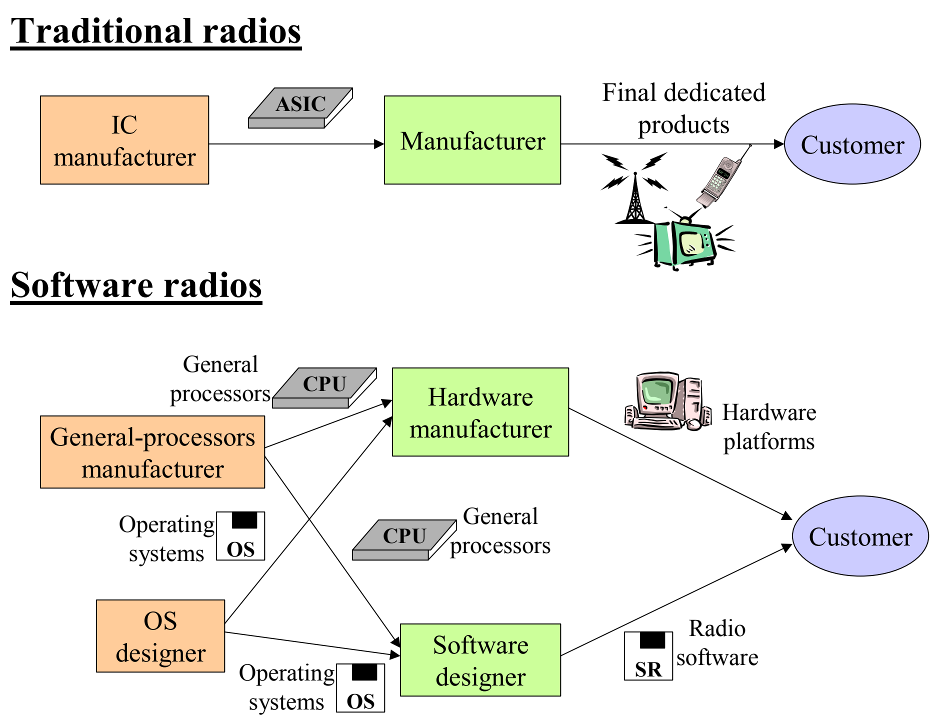


**Figure 18. Value chain for traditional and software radios.**

SR proposes a new way of building radios in which signal-processing software running over general-purpose processors replaces dedicated semiconductors. Software and hardware becomes distinct and exchangeable pieces of the radio, which can be "mixed-and-matched" across a new open interface. This new interface favors the entry of *new players in the industry*.

At the semiconductor level, substitutes and new entrants are likely to capture market share from specialized chips. Among the substitutes, communications-oriented processors with some degree of programmability like DSPs, which are currently serving as substitutes for ASICs in some applications, will implement some of the first SR designs. SR will facilitate the competition of DSP manufacturers like Texas Instruments against ASIC manufacturers. However, future software radios are likely to make increasing use of *general-purpose processors* like the CPUs used in PCs, which heretofore have nor been used in the wireless communications market (see Section 2.4). Players of other industries like Intel may find themselves in new entrant positions in the wireless industry as suppliers of general-purpose processors.

At the infrastructure and device manufacturing level, the standard-specific products will increasingly be competing with *general-purpose hardware platforms* and *signal processing software*. Companies that manufacture equipment for software-oriented industries such as Compaq, Sun, HP and Dell have the opportunity to enter the wireless market as general-hardware platforms vendors. *Operating system designers* will become important in the wireless market to provide operating system software platforms for radio applications.

In general, the new players -- from general-purpose processor manufacturers to software designers -- are less specialized than traditional manufacturers. Their expertise and capabilities are spread out among a larger number of companies. Their entrance will promote market fragmentation since a market for hardware-oriented products will remain. Hardware systems have inherent benefits because their dedicated approach allows higher performance. These products will remain important in two sectors: highly demanding and specialized products like space communications, where performance is the main parameter, and, those new wireless systems where general-purpose processors' capacity does not still allow their software implementation.[13] The market fragmentation will *increase competition* among hardware and software-oriented products. As semiconductor capacity improves, the hardware approach will need to be more innovative to surpass the software offer and to defend its part of wireless market.

All types of consumers, from network operators to particular users, will be able to combine hardware and software products from different companies. A private user, for example, might buy her personal wireless device from a general hardware manufacturer, purchase communications software from an independent software designer and obtain her

[13] In general, new systems involves higher data rates and improved services, which require more complex signal processing algorithms and therefore, more computing capacity (see Figure 10 for the case of cellular standards).

games from a second software designer. Hardware manufacturers and software designers will also have *more incentives to develop compatible products* since the ability to work with the diverse array of hardware and software components will become critical components for market success.

*Regulation* is an important part of the wireless industry. The changes promoted by SR will require the redesign of fundamental regulatory policies like spectrum allocation and equipment certification. Given the importance of this topic, 0 is dedicated to analyze its implications.

Aware of the potential of software radios, numerous players are becoming interested in the development and adoption of the technology. The most important effort towards SR adoption is the SDR Forum [75]. The main goal of this forum is to create an open architecture for software radios. As explained in Section 3.2.2, SR technology started as a way of intercommunication between military services with the SPEAKeasy project [48]. Used by the US military for many years, rapidly gained popularity in corporate circles due its potential commercial use. The MMITS forum was created in March 1996 to promote and develop SR. The forum changed its name to SDR Forum in 1998 and currently has more than 130 members from all the value chain layers (see Table 2).

The military is still the first adopter and main driver of SR. Most of the SDR Forum members are linked to the military: a high number of research centers, technical consulting, electronics and aerospace companies carry out military activities (see Table 2). As Figure 19 shows, the second most frequent activity of SDR Forum members is semiconductor manufacturing. Not only traditional wireless players like ASIC, DSP and FPGA vendors participate of this forum but also potential entrants like Intel. Top-level infrastructure vendors like Lucent, Motorola, Nortel and Siemens are forum members. However, the largest players, Ericsson and Nokia, do not participate in the forum activities. Important cellular service providers from Europe, Japan, Taiwan and North America belong to the group. Nevertheless, large North American operators like AT&T Wireless and Verizon are not SDR forum members. This absent is particularly important since, as explained in the following sections, these operators are the most likely to benefit from SR technology due to their interoperability problems. Regulators are practically absent from this organization. Only the National Telecommunications and Information Administration (NTIA), from the USA, is represented in the forum.

**Table 2. Activity description of the SDR Forum members.**[14]

| Activity | Description |
|---|---|
| Research / Universities | Non-American universities. Mainly Japanese and Korean universities. Numerous American **military** centers. Some American private research companies. |
| Semiconductors | All kinds of players are represented: from traditional ASICs to FPGAs to general processors (**Intel**) to SR oriented chips. |
| Technical consulting | Very technical consulting, network design, systems integration. Some associated with **military** activities. |
| Military | Principally America, Canada, England and Australia military research. |
| Network infrastructure | Main players included: **Lucent, Motorola, Nortel** and **Siemens**. SR infrastructure players: **Airvana** and **Airnet**. **Missing: Ericsson & Nokia**. |
| Electronics | Some associated with the **military** and aerospace. Missing important players like **Philips.** |
| Software | Includes main SR startups. In general, only focused on software, no hardware. **No military** oriented. |
| Service provision | Principally **Europe** (FT, Telefónica, Orange, Sonera), **Japan**, **Taiwan** and **America** (Sprint, Cingular, VoiceStream). |
| Aerospace | Mainly related to **military** research (**except Boeing**). |
| Handsets / devices | Mainly Japanese companies. **Missing: Nokia**. |
| Regulation | **Only one: NTIA.** |

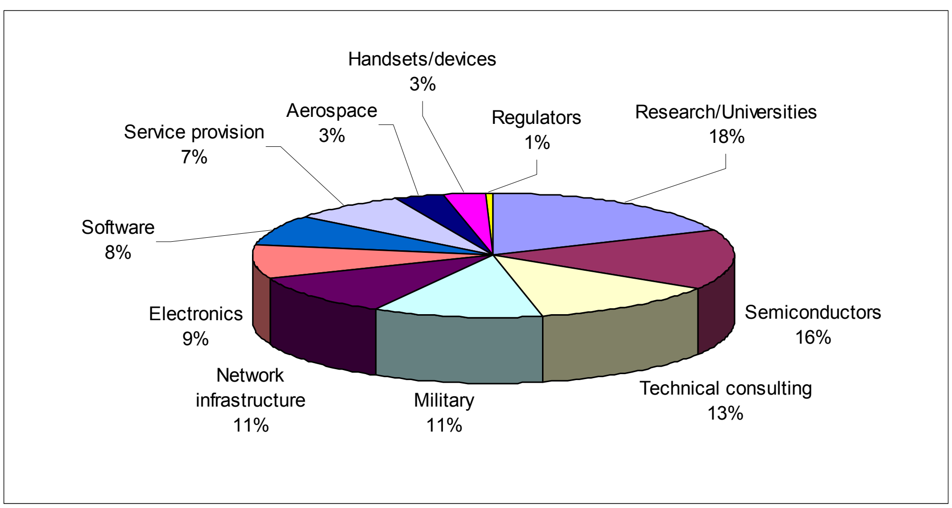


**Figure 19. Distribution by activity of the SDR Forum members.**

[14] The criteria to establish such differentiations are quite qualitative and are based on the descriptions that companies and organizations make of their activities in their own websites. Criteria are not exclusive. A company or organization may be registered under different activities.

## 4.2 The cellular sector

This section applies the previous model to discuss the impact of SR on the structure of a particular wireless sector, the cellular industry, which has experienced one of the fastest growths in the history of telecommunications. In 1991, the first GSM network was installed in Germany. Seven years later, there were 50 million subscribers only in Europe. Fixed telephone subscribers were 50 million only after 50 years of operation. Cellular communications have even surpassed the Internet, which required 15 years to gain 50 million users [34].

The rest of this section is organized into three sub-sections. The first provides an overview of the evolution of the cellular industry and its standardization issues. The second describes the traditional value chain for the industry. The third explains how the cellular industry value chain is likely to change as a consequence of the adoption of SR.

### 4.2.1 Evolution of the cellular industry

The first generation (1G) of cellular communications was based on analog standards and provided customers with low quality voice services. Given the low capacity of 1G standards, networks could only supply a small number of consumers. This situation made expensive to provide 1G services and, consequently, led providers to set high prices for the services. The high prices, the poor quality of service and the capacity problems limited market penetration. Consequently, a second generation of digital standards (2G) arose to overcome the problems of analog systems. 2G standards provide improved voice quality and higher network capacity as well as low rate data services and lower prices. Multiple incompatible 2G standards reached the market and 2G services have been quite successful as in the consumer mass market. The most important 2G standards were GSM, CDMA and TDMA (see Figure 20). By 2001, worldwide penetration of 2G services had reached 15% and was over 44% in Europe and Oceania, with many countries in Europe having penetration rates in excess of 70% (see Figure 21 and Figure 22).

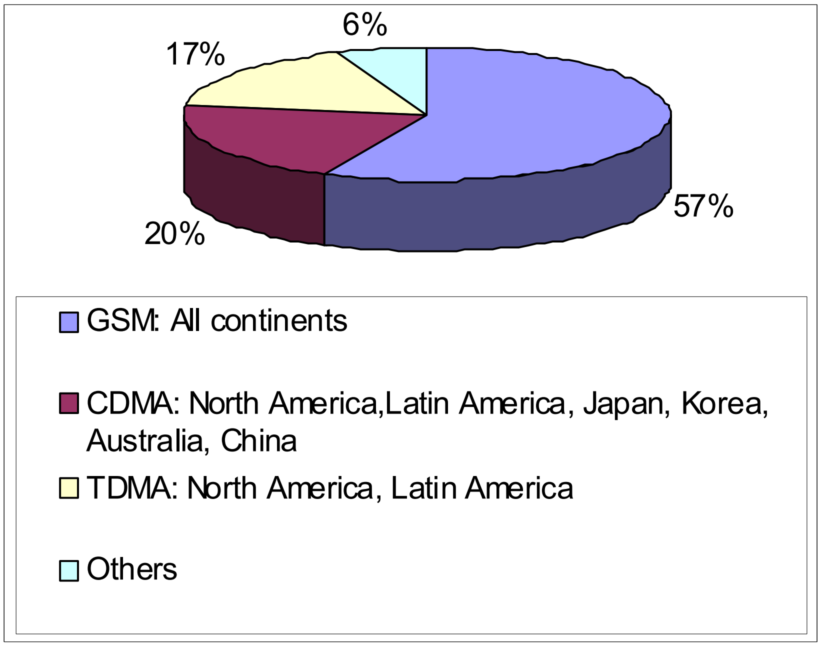


**Figure 20. Market distribution of 2G cellular standards [34].**

High penetration rates are leading to the saturation of the available 2G spectrum. Moreover, 2G data rates are insufficient to supply the increasing demand for data services. A new generation of cellular standards (3G) is being developed to solve these problems. 3G standards are based on the same multiplexing technique (CDMA) but differ in other features. Three main versions of 3G have been specified: the Japanese Wideband CDMA (WCDMA), developed by the Association for Radio Industry and Business (ARIB), the European WCDMA, called UMTS, of the European Telecommunications Standards Institute (ETSI), and the US Cdma2000, developed by the Telecommunications Industry Association (TIA) to be compatible with the American system IS-95 (see Figure 23). The Japanese and European standards present some differences but are easily adaptable and are planned to be compatible. Cdma2000, to be adopted by some North American operators, is incompatible with the European and Japanese versions. The three versions are planned to offer full coverage and mobility for 384 kbps and limited coverage and mobility for 2 Mbps. Cdma2000 is expected to be able to provide up to 5.2 Mbps (see Figure 24).[15]

[15] To learn more about these standards refer to [43], [57] and [33].

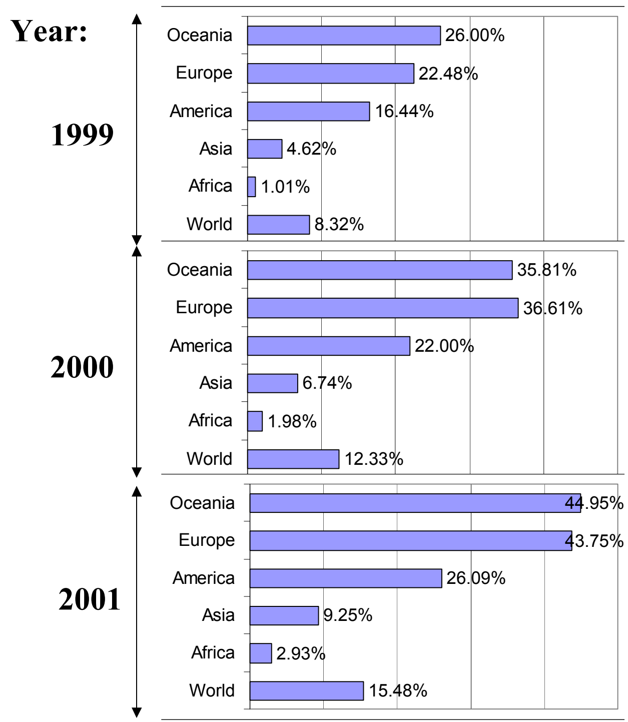


**Figure 21. Worldwide mobile penetration worldwide (cellular subscribers per 100 habitants) [45].**

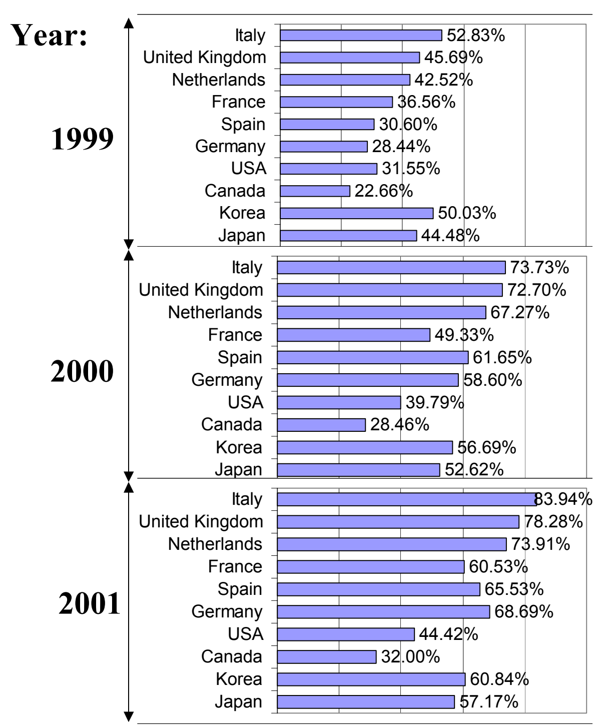


**Figure 22. Major markets mobile penetration (cellular subscribers per 100 habitants) [45].**

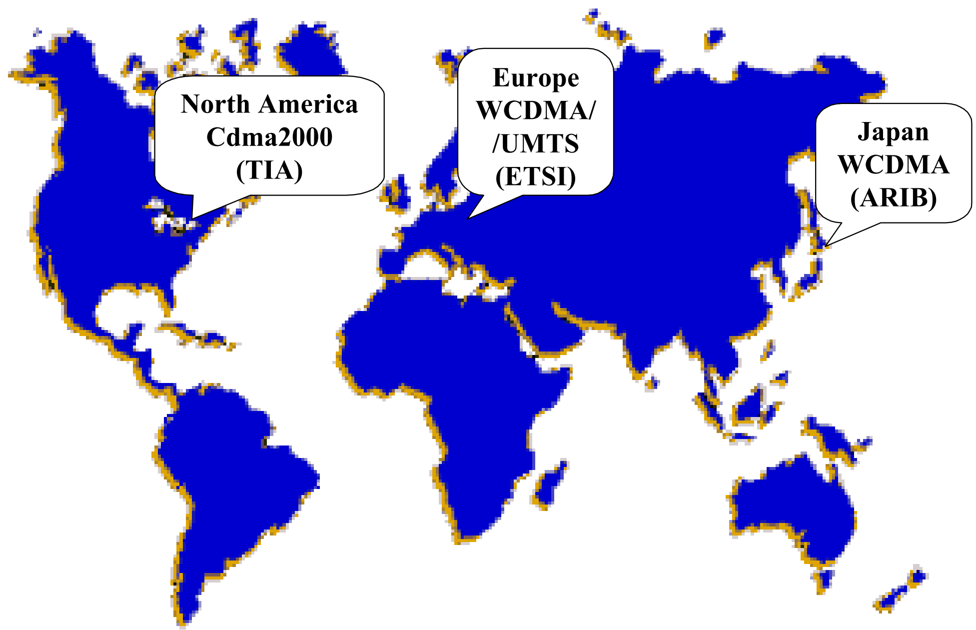


**Figure 23. World distribution of 3G standards [43].**

The migration to 3G requires building new networks. However, there are several intermediate standards called 2.5G that can delay the deployment of 3G networks. These standards allow the reuse of 2G wireless infrastructure through hardware and/or software modifications, saving the cost of replacing it. Intermediate 2.5G standards supply higher data rates than 2G systems but lower than 3G networks. Operators plan to use these enhanced rates to start offering initial versions of data services before deploying 3G networks. Migration scenarios for converting from 2G to 3G differ by country and for each of the standards. Figure 24 explains the migration paths to 3G for the most important 2G standards. The subsection dedicated to network operators, Section 4.2.2, discusses the consequences of these migrations paths and their degree of adoption.

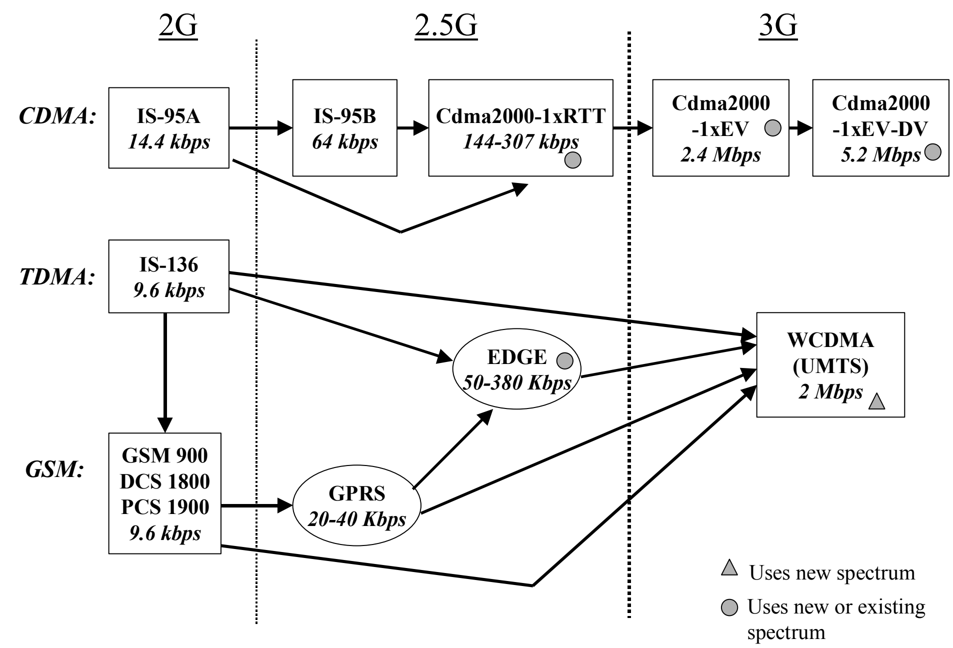


**Figure 24. Migration paths and data rates to 3G.**

### 4.2.2 The traditional value chain

Before analyzing the changes that SR technology may induce on the value chain for cellular communications, this section discusses the current industry structure, summarized in Figure 25. The use of incompatible standards defines today's value chain. When a new cellular standard reaches the market, the whole chain is affected. SR technology allows the reutilization of the same hardware platform to operate over multiple standards and therefore, it may relax the dependence on standards of the cellular industry. The impacts of such relaxation are analyzed in Section 4.2.3. The traditional sector is also strongly dependent on government spectrum policies, which might be deeply affected by the adoption of software radios. This section reviews the main points of this dependence while 0 fully discusses current regulation and the impact of SR. Section 4.2.2 follows a bottom to top approach, i.e. from semiconductor manufacturers (at the bottom of the diagram) to final consumers (at the top), that focuses on the relationships among and the goals of the various value chain participants.

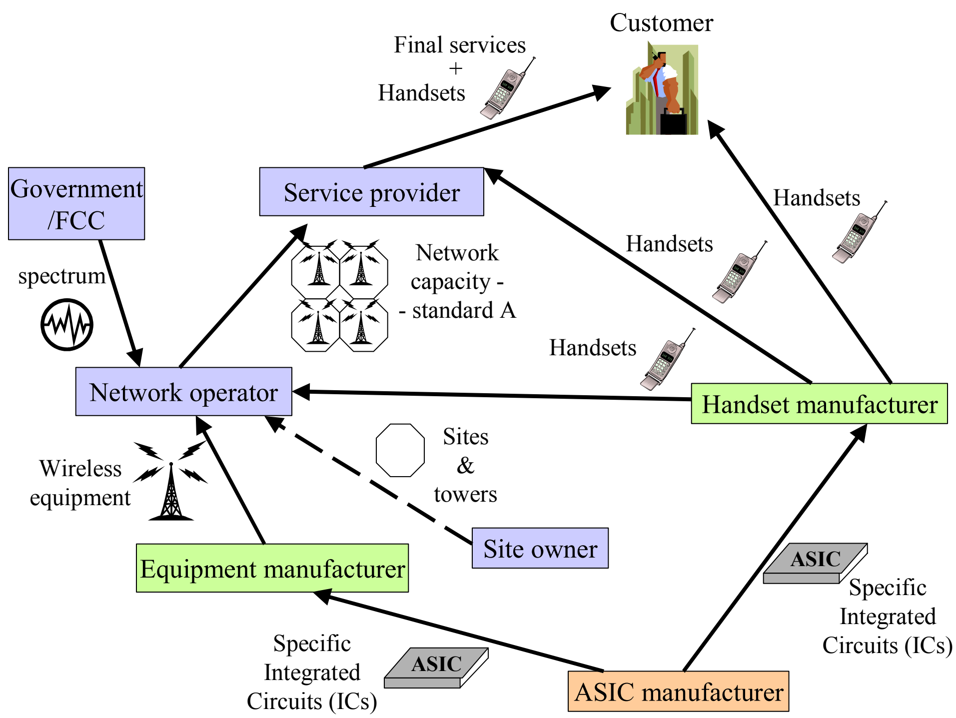


**Figure 25. Traditional value chain for the cellular communications industry.**

## ASIC manufacturers

Dedicated integrated circuits (ICs) are indispensable pieces of traditional hardware-based wireless infrastructure and handsets (see Chapter 2). ASICs implement standard specific protocols and signal-processing treatments. When wireless standards change, new ASICs must be produced. ASIC design is costly in time and money. The cycle of designing and manufacturing an ASIC takes about a year and a half. Manufacturing accounts for just the last three months of this time.[16] Only mass production reduces cost. Early adopters of new wireless standards, therefore, must bear the high costs of expensive ASICs until demand grows sufficiently that the chips become commodities. Consequently, ASICs manufacturers seek to maximize the sales of each single chip to benefit from scale economies and low production costs and to recover the design investment.

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[16] ASIC designers provided these timeline estimates during private conversations.

The ASIC market is a growing market (growth of $2 billion from 1999 to 2000) that accounted for more than $10 billions in 2000 (see Figure 27). This market is highly competitive with at least five mayor competitors (IBM, Lucent/Agere, LSI Logic, NEC and Fujitsu) and multiple smaller companies (see Figure 26). As explained in Section 2.4, ASICs are in competition with DSPs and FPGAs. The DSP and the FPGA markets experienced a comparable growth to the ASIC market from 1999 to 2000 (see Figure 27). Only Lucent/Agere competes in the three markets with substantial market share (see Figure 26). The rest of the players concentrate on one of the markets and therefore, have incentives to push their concerning market further than the others.

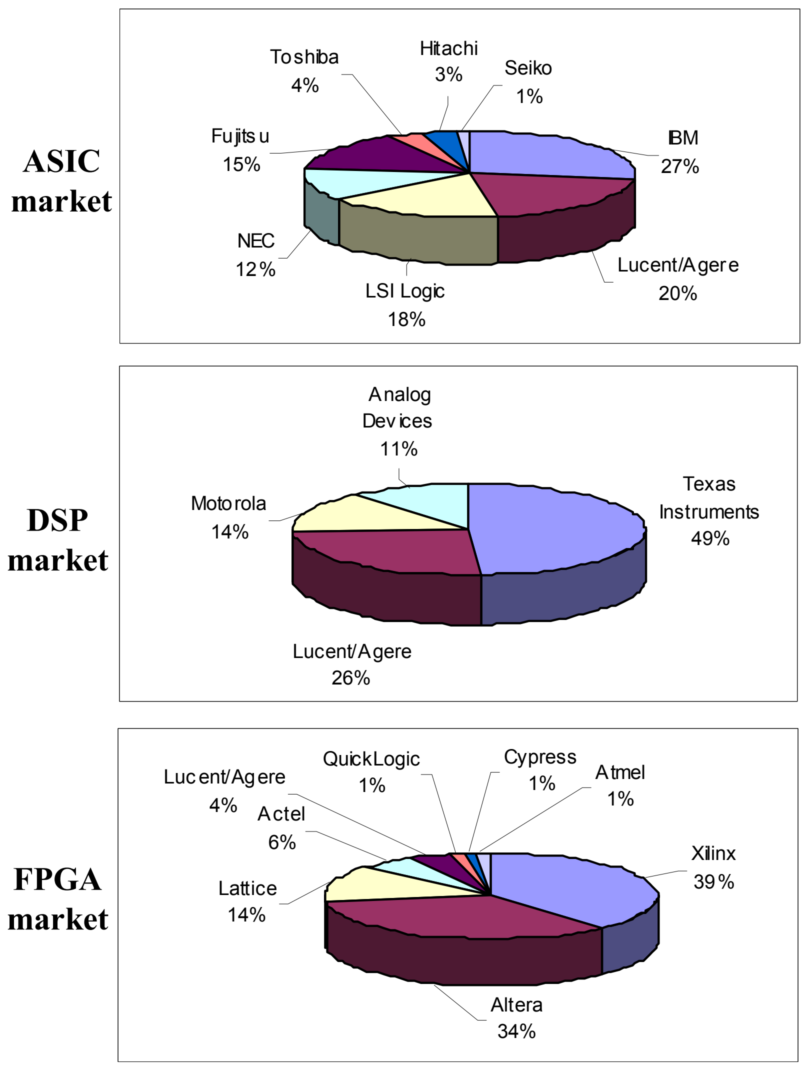


**Figure 26. Worldwide largest ASIC, DSP and FPGA manufacturers in 2000 [19].**

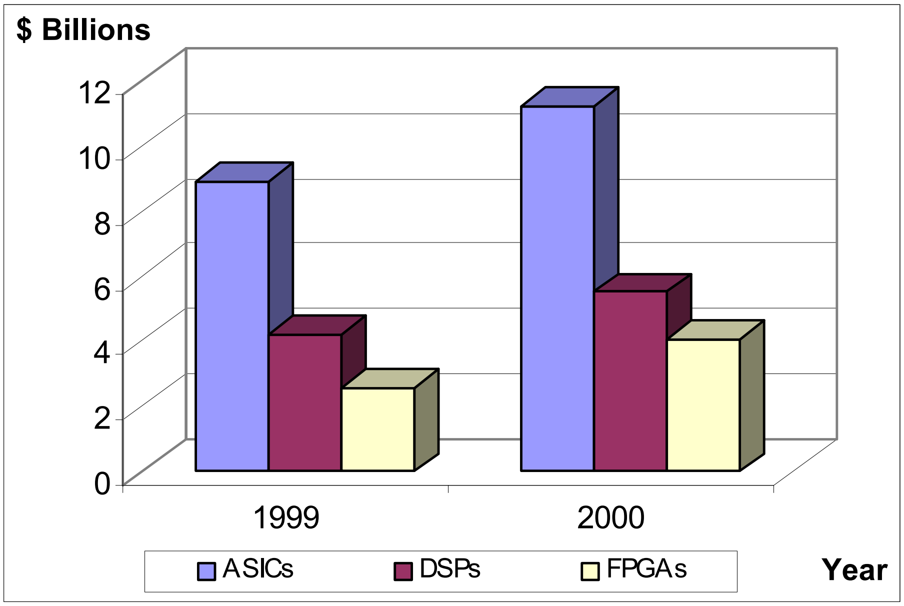


**Figure 27. Worldwide ASIC, DSP and FPGA market [19].**

Equipment manufacturers

Equipment manufacturers build wireless infrastructure for the deployment of cellular networks. The worldwide cellular infrastructure market has grown rapidly in recent years and is expected to be $35 billion in 2002 (see Figure 28).

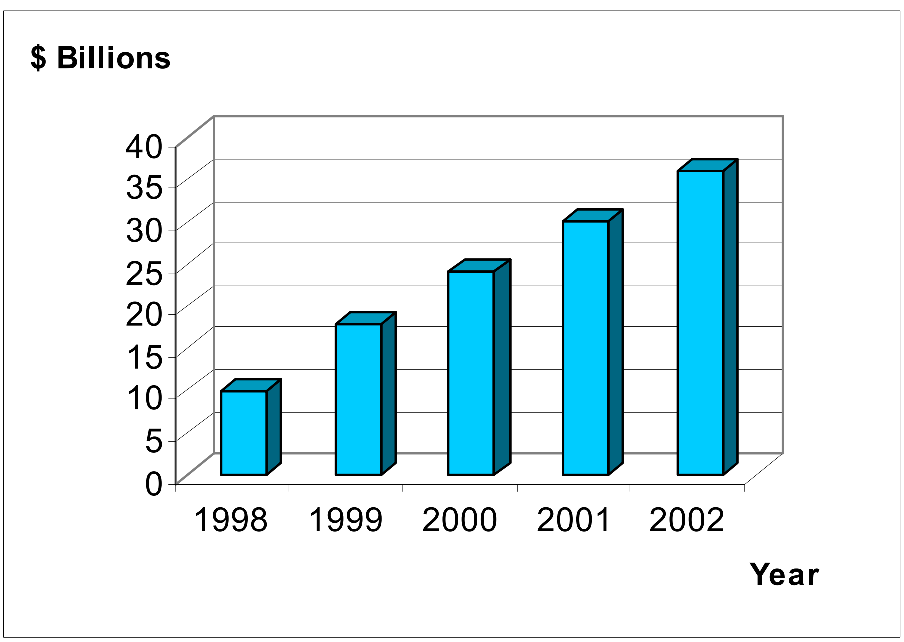


**Figure 28. Worldwide wireless infrastructure market [35].**

Wireless infrastructure is standard specific, i.e. it is built to operate in a particular standard and cannot be reused to operate over other standards without major and expensive hardware modifications.[17] Using the ASICs provided by semiconductor manufacturers, equipment vendors implement the protocols and signal-processing treatments detailed in the standards as well as proprietary features to create product differentiation. Manufacturers exploit incomplete standards or variability in the options allowed to differentiate their products, which often results in incompatibility problems. For example, the European standard GSM missed to fully specify the interface between the Base Station (BTS) and the Base Stations Controller (BSC) (see Figure 37). Vendors took advantage to create proprietary solutions. Consequently, BTSs and BSCs from different providers are incompatible and cannot communicate. GSM network operators are therefore obligated to buy both pieces of equipment from the same vendor. The market for network equipment is not quite competitive, with the largest firm accounting for only 30% of total sales (see Figure 29).

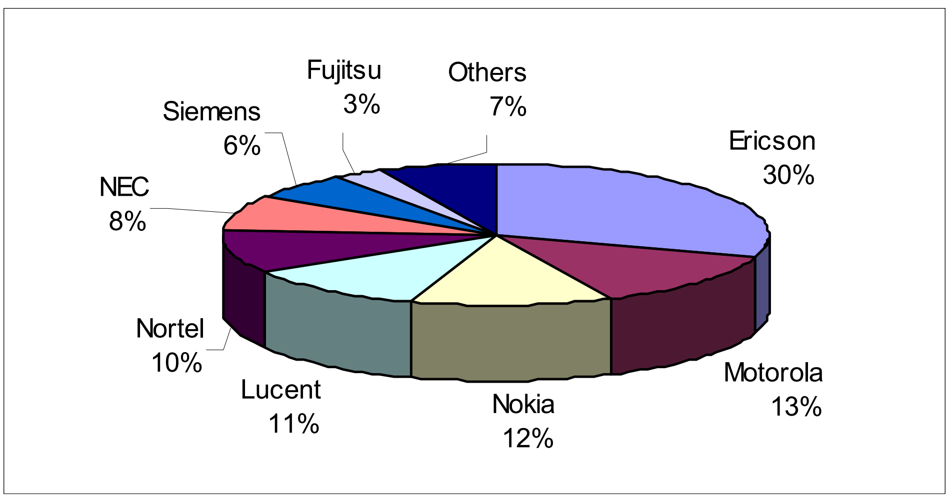


**Figure 29. Market share for wireless infrastructure manufacturers in 2001 [96].**

[17] An exception to this statement is 2.5G migratory steps (see introduction to Section 4.2), where small and relatively inexpensive hardware and/or software modifications allow the reuse of the wireless equipment operating over the 2G version of the standard. This approach is similar to SR in the sense that it upgrades a piece of equipment to operate in a new version of the standard. However, it is limited to a family of 2G and 2.5G standards, GSM and GPRS or TDMA and GPRS for example (see Figure 24). The pieces of equipment cannot be upgraded to any other wireless standard, cellular or not, like in SR.

The development and production of wireless equipment require long lead times and incurs high costs.[18] When new standards reach the market, new equipment must be developed and produced. Profits are only realized on high volume sales. Standardization makes vendor differentiation more difficult but also creates larger markets and therefore, more opportunity for mass production. The optimum for equipment vendors is to create differentiated products and sell the maximum number of units of each design.

### Network operators

Network operators deploy and operate wireless networks. The wireless networks are comprised of three main parts: the Radio Access Network (RAN), the Core Network (CN) and the Application Layer (see Figure 37). The RAN deals with the air interface. The CN takes care of fixed communications and links to other networks. The application layer carries out management functions like equipment surveillance and billing.[19] RAN deployment includes site construction as well as base station installation and accounts for approximately 70% of the total deployment costs [95]. Base station costs account for 60 to 70% of the expenditures on RAN equipment [97].

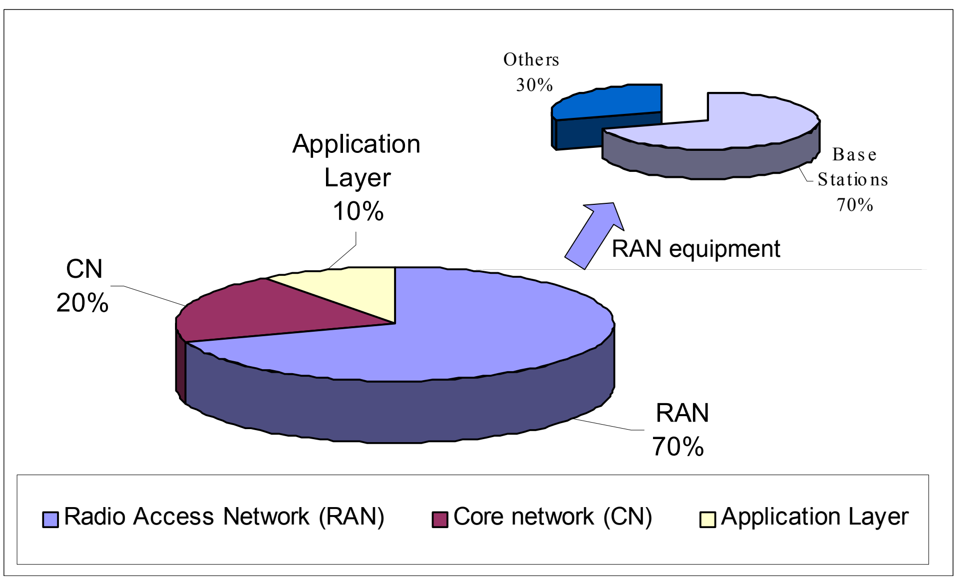


**Figure 30. Cost distribution in the deployment of cellular networks.**

[18] Just as an example, only the testing stage of a new base station takes more than one year.

[19] Section 4.2.5 gives a deeper explanation of these concepts and quantifies RAN expenditures for a particular case.

The cost of spectrum used to be a small part of the network cost because European and Asian regulators used to establish low fix prices and, in North America, low expectations of future profits did not induce operators to bid high for the licenses. This situation has changed with the third generation of cellular communications (3G). Most European 3G licenses were auctioned and the auction prices paid reached exorbitant levels because operators expected high profits. Thus, currently, the price of spectrum for 3G networks represents a significant share of the total investment (see Table 3). The delay in the deployment of 3G networks caused by the lack of operational equipment and the uncertainty about 3G demand have induced operators to reconsider their profit forecasts. Profits seem to be lower and therefore, the prices paid for the licenses, too high.

**Table 3. Costs of 3G licenses [7], [34].**

| Country | Date | Licensing policy | Price/license | $US/adult | Nb licenses |
|---|---|---|---|---|---|
| Spain | March 13, 2000 | Beauty contest & fixed fee | $111 mil | $13 | 4 |
| Finland | March 18, 2000 | Beauty contest | $0 | $0 | 4 |
| UK | April 26, 2000 | Highest bid | $6.3-9.4 bil | $576 | 5 |
| Japan | June 2, 2000 | - | $0 | $0 | 3 |
| Netherlands | July 6, 2000 | Highest bid | $369-666.8 mil | $194 | 5 |
| New Zealand | July 10, 2000 | Highest bid | $10.3-16.7 mil | $17 | 4 |
| Switzerland | July 6, 2000 | Highest bid | $29 mil | $19 | 4 |
| Germany | July 31, 2000 | Highest bid | $7.62-7.7 bil | $657 | 6 |
| Italy | Oct. 19, 2000 | Hybrid | $2-2.03 bil | $203 | 5 |
| Austria | Nov. 2, 2000 | Highest bid | $ 98-105 mil | $90 | 6 |
| Norway | Nov. 29, 2000 | Beauty contest | $11.2 mil | $12 | 4 |
| Portugal | Dec. 6, 2000 | Beauty contest & fixed fee | $90 mil | $43 | 4 |
| Poland | Dec. 6, 2000 | Highest bid | $570 mil | $18 | 3 |
| Sweden | Dec. 18, 2000 | Beauty contest & 0.15% annual revenue | $10,700 | $0.006 | 4 |
| South Korea | 4th quarter 2000 | Beauty contest & fixed fee | $1.1 mil | $59 | 3 - 2 applied |
| Canada | January 2001 | Highest bid | $7.16-452.7 mil | $18 | 5 |
| Belgium | Feb. 27, 2001 | Highest bid | $139.6 mil | $49 | 3 |
| Australia | March 15, 2001 | Highest bid | $ 4.6-148 mil | $23 | 6 |
| France | May 2001 | Beauty contest & fixed fee | $570 mil | - | 4 - 2 applied |
| Greece | July 11, 2001 | Highest bid | 125.6 mil | $65.29 | 4 – 3 applied |
| Hong Kong | Sept. 19, 2001 | Revenue share | fixed payment $6.4 mil/year | Variable | 4 |
| Denmark | Sept. 20, 2001 | Sealed bid | $ 118 mil | $108 | 4 |
| Czech Repub | Nov. 30, 2001 | Highest bid | non bider | Tba | non applied |

As shown in Figure 31, in the United Kingdom and the Netherlands, license costs are larger than deployment costs. In Germany and France, both costs are similar while in Spain and Italy license costs are around the half of deployment costs. The United

Kingdom, the Netherlands and Germany are between the largest European markets and were among the first to be auctioned. Largest European operators wanted to assure these markets and bided extremely high. The French 3G allocation took place very late, when the largest European operators had already heavily invested in other countries like the UK, the Netherlands and Germany and had contracted high debt. Moreover, the French government imposed a high fixed fee of $570 millions per license (see Table 3). In consequence, only two operators, which were holding 2G licenses in France (France Telecom and SFR), applied for four licenses. Spain was the first country to allocate its 3G licenses and the government established a moderated fixed fee of $111 millions per license, which avoided the exorbitant prices reached in other European auctions. Operators considered that 3G services would have difficulties to success in Italy since 2G penetration was already 73.73% in 2000.[20] Moreover, as in the French case, the largest operators had already heavily invested in the other European markets.

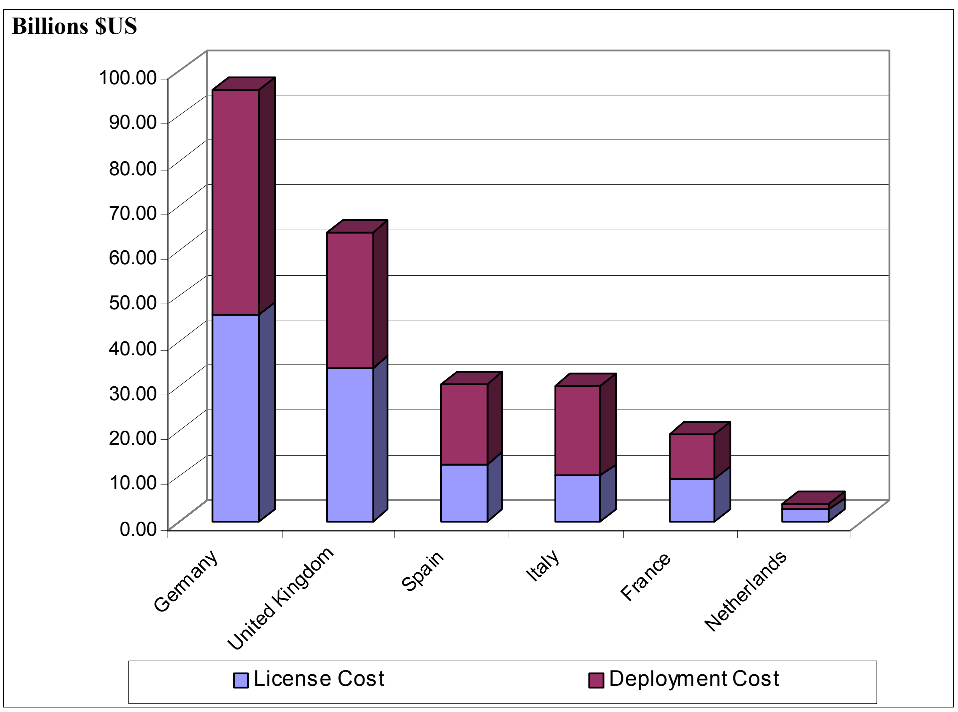


**Figure 31. Cost comparison between deployment and licensing costs for the six largest 3G markets in Europe [95].**

[20] Italy is the country with highest penetration in the world: 83.94% in 2001 (see Figure 21 and Figure 22).

Because wireless infrastructure is standard specific, offering services in new standards requires the deployment of new networks. As explained before, the cellular market is moving toward the third generation of wireless communications. Given the enormous costs of 3G deployment, the delay in 3G infrastructure and the expenditures incurred in spectrum licenses, most operators are adopting 2.5G standards as an intermediate step between 2G and 3G networks. As explained in the introduction of this section, migratory steps depend on different factors, principally the 2G technology and the cost of upgrades.

**Table 4. Migration costs [34].**

| Migration path[21] | Cost/POP [22] | Total cost/No BTS [23] | Cost/BTS [24] |
|---|---|---|---|
| GSM/GPRS | $1-2 | $27,000 | 19% |
| TDMA/EDGE | $3-4 | - | 50% |
| WCDMA | $8-12 | $170,000 | 70% |
| Cdma2000-1xEV | $10-13 | - | 70% |

Most GSM operators plan to follow the same migratory path. They will first adopt GPRS, which requires software changes and avoids hardware replacements. Therefore, GPRS results in only a small incremental cost in the RAN (see Table 4). The further evolution of GSM, EDGE, offers higher data rates but is more expensive than GPRS and requires RAN hardware replacements. Most GSM countries, especially in Europe, plan to skip this stage and migrate from GPRS directly to WCDMA in its European version.

[21] The migrations from GSM to GPRS and TDMA to EDGE use the old radio infrastructure (Radio Access Network (RAN)). In the GSM/GPRS, new software is installed on the radio infrastructure. In the TDMA/EDGE example, both software and hardware changes are necessary. This is the reason for the price difference. In both cases, a new Core Network (CN) is necessary.

For WCDMA and Cdma2000-1xEV, the whole network has to be replaced (RAN and CN).

[22] The term **POPs** is commonly used in wireless communications literature. It refers to the number of people covered by a network or license. One POP is one person. In general, the number of POPs is higher than the number of subscribers.

**Cost/POP =** Total cost of upgrading the network (Radio Access Network (RAN) and Core Network (CN)) divided by the number of POPs.

[23] **Total cost/No BTSs =** Total cost of upgrading the network (Radio Access Network (RAN) and Core Network (CN)) divided by the number of base stations (BTSs) in the system.

[24] **Cost / BTS** = % of the **Total cost/No BTSs** that is really spent in upgrade each base station (BTS).

EDGE upgrade is available for TDMA systems at a higher cost than its migration from GPRS (see Table 4). Analysts forecasted EDGE as the natural migration path for TDMA networks. However, AT&T, the third largest American operator in number of subscribers after Verizon Wireless and Cingular, announced its intention to develop a GSM/GPRS network overlapping the 80% of its TDMA infrastructure. Other North American operators such as Cingular appear likely to follow the same path. Infrastructure vendors like Nokia are exerting pressure over North and South American service providers to migrate to GSM networks. Four Latin American operators and one Canadian have already overlaid or replaced their TDMA networks with GSM infrastructure. Three new GSM networks have been or will be opened in Latin America in 2001 and 2002. The migration of a large number of operators from TDMA to GSM will mainly affect Motorola and Lucent, which are the TDMA leaders in the American market, and will especially benefit GSM-oriented vendors like Ericsson and Nokia.

While GSM and TDMA will likely converge, CDMA follows a totally separate migration path. The largest North American CDMA operators plan to upgrade their networks with the natural evolutions of CDMA (see Figure 24). Table 5 summarizes the migratory strategies of the North America operators.

**Table 5. North American operators' migration paths [49].**

| | Verizon Wireless | Sprint PCS | Nextel | AT&T Wireless | Cingular | VoiceStream |
|---|---|---|---|---|---|---|
| **Subscriber Base (thousands)** | 27,122 | 10,714 | 7,250 | 15,748 | 20,535 | 3,343 |
| **1G Technology** | AMPS | AMPS | AMPS | AMPS | AMPS | AMPS |
| **2G Technology** | CDMA-IS95A | CDMA-IS95A | iDEN | TDMA | GSM & TDMA | GSM |
| **Next migration** | 1xRTT | 1xRTT | 1xRTT | GSM-GPRS | GPRS & EDGE | GPRS |
| **Launch date** | 1H02 | 1H02 | N/A | AQ01/1Q02 | 1H02 | 4Q01 |
| **Vendor selected** | NT, LU | NT, LU, MOT | MOT | NT, LU, ERIC, NOK | NOK, ERIC, NT | ERIC, NOK |
| **Second migration** | 1xEV | 1xEV | 1xEV | EDGE | EDGE | EDGE |
| **Launch date** | 2H02/1H03 | N/A | 2H02/1H03 | 4Q02 | 2H02 | N/A |
| **Further upgrade** | N/A | N/A | N/A | WCDMA | WCDMA | WCDMA |
| **Launch date** | 2003-2005 | 2003-2005 | N/A | 1H03 | N/A | N/A |

Traditionally, cellular services have been vertically integrated with the network operators, both owning and operating the wireless network and marketing the retail services provided over the network. This trend is changing. Operators are increasingly focusing on network management and starting to sell capacity to intermediaries that will provide the final retail services to end-users. The goal of network operators is to maximize network capacity at the lowest costs to supply the highest number of users and/or intermediaries.

The market of cellular services is intensely competitive. At least three operators share each country. The third generation will increase competition even more since the number of licenses has increased by at least one or two per country (see Table 3). In Europe, traditional national monopolies like France Telecom, Deutsche Telecom, Telecom Italia, British Telecom and Telefónica have licenses in their own countries and have extended to other markets. Each of these major operators has around the 10% of the largest European markets: Italy, United Kingdom, Netherlands, Germany, Spain and France (see Figure 32).

In the USA, licenses do not cover the whole country. Consequently, the number of operators varies across regions. Furthermore, the use of incompatible 2G standards in the U.S. causes roaming problems. Since operators can choose the standard to provide 2G services, a user with GSM service in her state, for example, may find that when traveling to another state, only IS-95 networks are available and therefore, she cannot use her cell phone. In Japan, NTT DoCoMo is the largest operator and the first to provide 3G service in the world. NTT DoCoMo focuses on innovative data services that have great success among the Japanese.

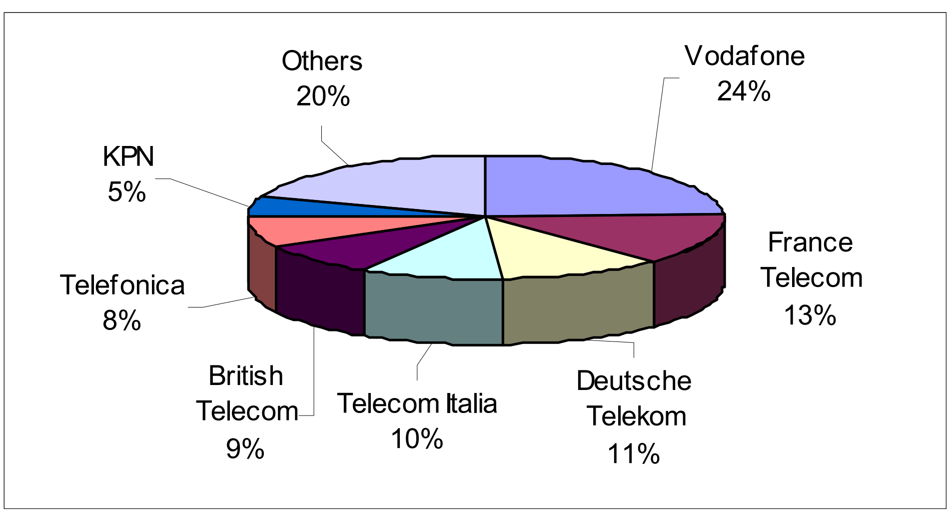


**Figure 32. Network operators market share in the six largest European markets: Italy, United Kingdom, Netherlands, Germany, Spain and France (2000) [34].**

### Service providers

Service providers build commercial services on top of network capacity and market those services to final clients. As explained in the previous subsection, network operation and final service provision have been traditionally integrated but, recently, vertically disintegrated business models are emerging. Virtual Mobile Network Operators (VMNOs) like Virgin do not own physical networks but buy wireless capacity from network operators and use it to supply final services.

As technology progress, products reach the market at faster pace. Most of these products are not successful. When a service reaches some triumph, competitors rapidly copy it and take away market share. Service providers need continuous innovation to compete in the market. Another problem is distribution. The market is crowded with new services and advertising, and hence, attracting customer attention is increasingly difficult. The goal of service providers is to build innovative products in the fastest and cheapest way with which to target consumers efficiently.

### Site owners

Site owners are companies that build and own towers. They rent them as radio sites for antenna and equipment installation to different types of wireless operators such as TV and radio broadcasting or cellular operation. This figure is frequent in the United States and other American countries. Companies like American Tower own and rent 14,000 sites in the United States, Mexico and Brazil. These companies are not common in countries dominated by GSM, where network operators build and own their sites. GSM operators occasionally hire site owner companies as consultants for site deployment.

Currently, site owners' products are limited to tower infrastructure and consulting services but some of these companies are planning to expand their business and offer transmission capacity. This possibility is being reinforced by the high cost of covering rural areas and the arrival of VMNOs (Virtual Mobile Network Operators). In the United States, coverage is an important competitive factor. The cost of covering remote areas is high. Service providers will likely rent capacity to avoid construction and infrastructure investments in these less strategic zones. Site owners could not only provide capacity to network operators but also to VMNOs. However, traditional technology obligates site owners to install a base station for each operator and each standard they want to serve, which is not cost-effective.

### Handset manufacturers

The handset market is highly competitive (see principal players and market share in Figure 33). Handset manufacturers face similar constraints and goals to the network equipment manufacturers. Handsets are standard specific, use ASICs as basic elements and require high development and production investment, i.e. there are large upfront (subsequently sunk) and recurring fixed costs. Hence there are large-scale economies – that is, average costs decline with volume and for therefore, providers must sell ht highest possible volume of service or product. Handset manufacturers sell direct to end-users as well as network operators and service providers. Service providers frequently buy high quantities of handsets at discount prices to be used in service promotions.

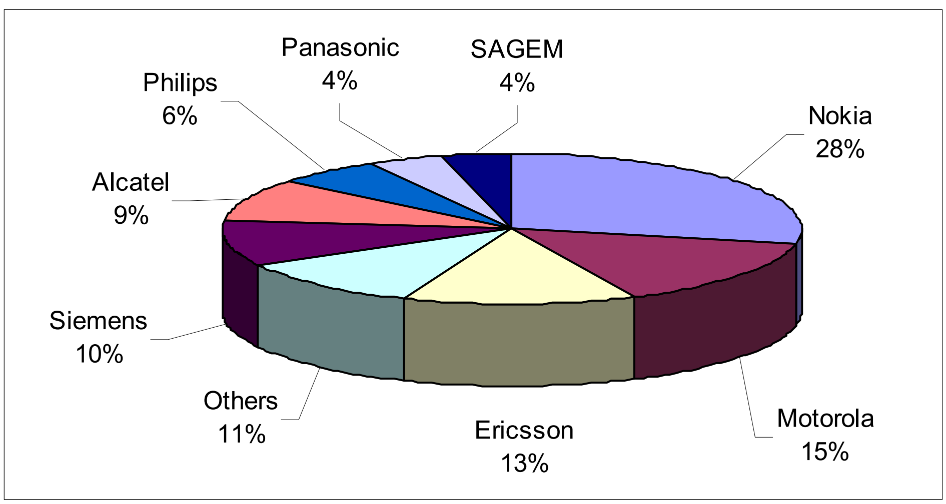


**Figure 33. Worldwide handset market in 1999 [98].**

### Customers

The demand for wireless communications has grown spectacularly in the last decade. The explosion of voice and data services, improved quality, and lower prices have attracted a mass consumer market to cellular service. As technology evolves, users continually demand higher performance and data-oriented cellular services as well as seamless operation at the lowest prices.

Government/FCC

Wireless applications and particularly the cellular industry are constrained by spectrum policies. Only operators provided with FCC licenses can provide service over a specific band[25]. The increasing demand for wireless services has generated a scarcity of spectrum that makes difficult the issuing of new licenses. This situation has special impact in the cellular industry, where demand grows at a faster pace than in other wireless services. The problem is particularly extreme in the United States where military and governmental organizations occupy most of the 2GHz band needed by the third generation of wireless communications (3G). The Clinton administration started negotiations to liberate 3G spectrum. However, the dialogues have been stopped under the current administration, raising concerns that the U.S. will lag behind Europe and some Asian countries in the deployment of next generation cellular services.

### 4.2.3 The SR value chain

SR makes the cellular value chain less susceptible to standard changes. When new standards reach the market, these can be addressed by a software upgrade instead of by replacing the hardware. The cellular sector will suffer an analogous transformation to the one presented in Section 4.1: first, *general-purpose processors* will gain market share from *dedicated semiconductors* and, second, *general-purpose platforms vendors*, *operating systems designers* and *software programmers* will begin to replace traditional *equipment* and *device manufacturers*. Figure 34 summarizes these changes and gives some examples of players. Thus, ASIC manufacturers like Lucent and Motorola (see Figure 26) may compete against Morphics, Chameleon and other SR oriented processors (see Section 2.4.3), DSP vendors like Texas Instruments (see Figure 26) and, probably, new entrants in the wireless industry like Intel. Traditional vendors such as Ericsson and Nortel (see Figure 28) may race with two different players: new hardware entrants like

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[25] There are some exceptions to this statement like Part 15 devices. Refer to 0 and Appendix C for a detailed explanation of licensing rules.

Compaq and software designers like Radioscape and Vanu (see Section 2.4.3). These changes will have an important impact on the upper layers of the value chain: reduced deployment cost per standard, development of the market for VMNOs, implementation of new business models for site owners and improved cellular services. SR also has major effects on regulation. Given the importance of this topic, 0 is dedicated to regulatory discussion.

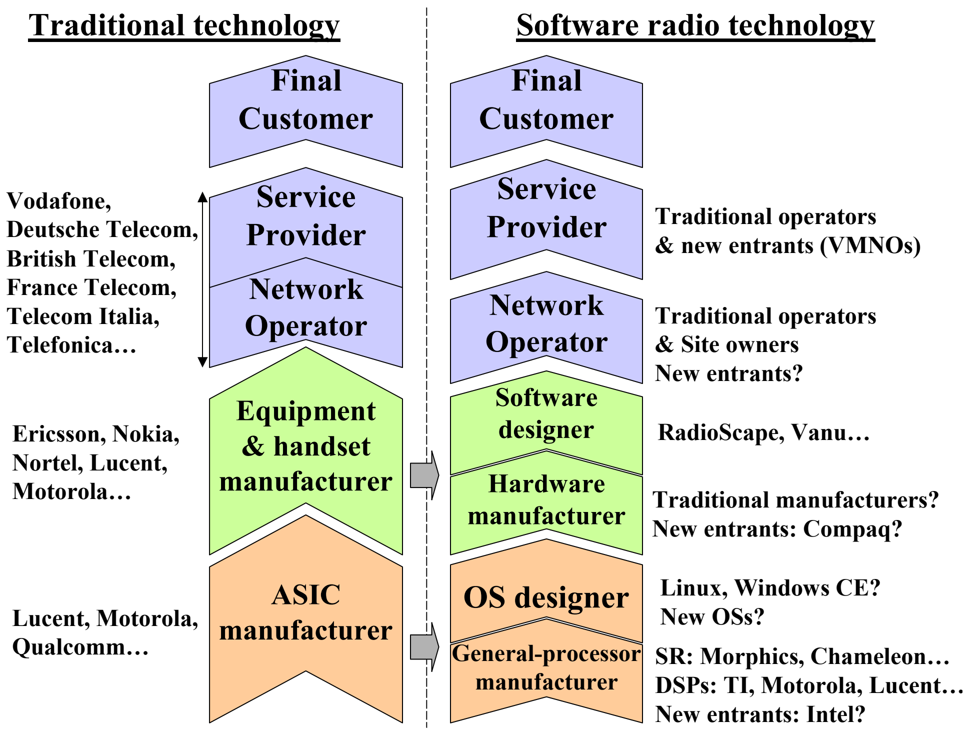


**Figure 34. Value chain evolution under SR technology.**

This section reviews the likely consequences of the new industry structure on each of the key classes of participants. Figure 35 provides a more detailed view of the SR impact on the cellular value chain presented in Figure 34 and previous paragraphs, which can easily be compared to Figure 25 (the traditional value chain).

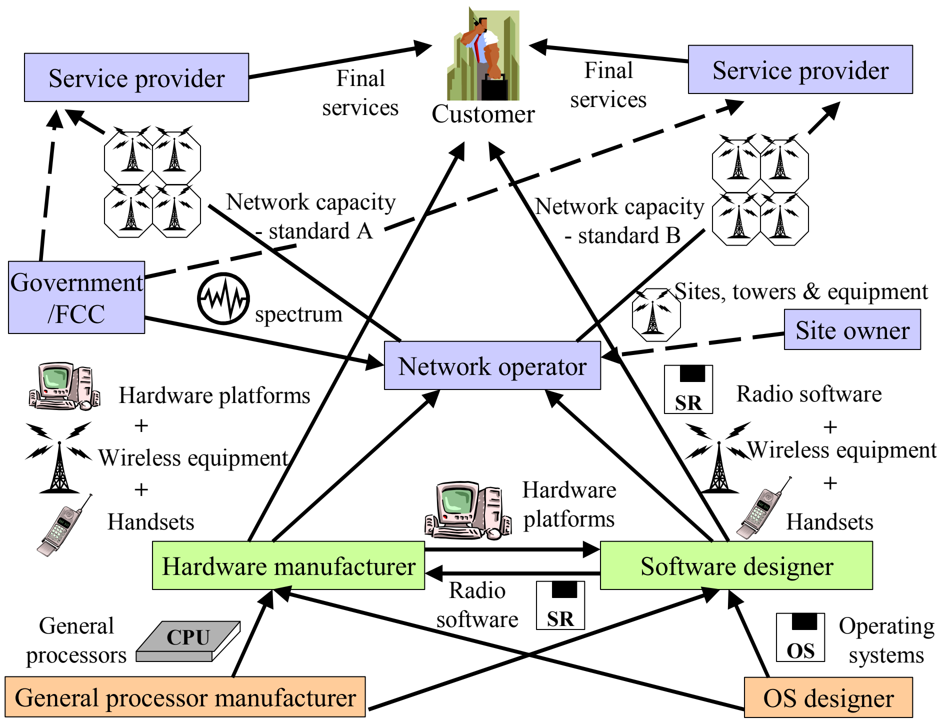


**Figure 35. SR value chain for the cellular communications industry**

## Semiconductor, equipment and handset manufacturing

After the adoption of SR technology, general-purpose processors will be able to replace dedicated integrated circuits. On the one hand, wireless ASICs producers like Qualcomm will be forced to restructure their cellular oriented business or focus on other markets where flexibility is less important. As explained in Section 4.1, flexibility usually comes at performance trade-off so dedicated semiconductors will likely retain market opportunities in highly demanding and specialized products (see page 55). Traditional equipment and handset vendors frequently manufacture semiconductors for internal use and external sales. This is the case for Motorola, which fabricates ASICs for domestic production and outside vending. SR adoption will take away this important source of revenue from vendors. On the other hand, communications-oriented processors with some degree of programmability like DSPs or flexible ASICs (see Chapter 2) will gain some market share over dedicated ASICs. However, general-oriented and totally programmable processors like Intel products will be likely winners in the long-term.

Signal processing software running over general-purpose processors needs as any other software from suitable operating systems (OSs). Operating system designers become new players in the cellular industry. OSs are particularly important in software radios since the system's performance depends on their efficacy. Efficient operating systems, i.e. which require a low number of instructions to perform a task, save processing capacity that can be used by the signal processing software. In order to attain such efficacy, some SR companies such as Vanu, Inc. [91] use publicly available and highly performing OSs like Linux. OSs become more critical in handset design since devices have strongest battery and capacity constraints (see Section 2.5). Especial operating systems, Real Time Operating Systems (RTOS), such as Windriver, Vertex and Windows CE have reached the market to serve the needs of traditional technology devices. The adoption of SR may enhance the competition between these systems in order to provide efficient platforms for software radios. The complexity of the OS market makes of OS interaction with SR technology an interesting and wide subject that could be addressed in further research.

SR technology divides infrastructure and device production into two functions: hardware platform manufacturing and software design. The traditional model where large vendors like Nortel, Motorola and Lucent supply network operators, service providers and final customers with standard-specific equipment like base stations and handsets may be disrupted. Hardware manufacturers will be induced to market platforms that are capable of supporting software from any designer. The economies of scale for hardware manufacturing and the platform manufacturers' need for differentiation may induce hardware and software companies to form alliances to market complete products as well as selling hardware and software independently. In the first stages of SR adoption, the most likely scenario is the evolution of traditional manufacturers towards hardware manufacturing and their alliance with software programmers. Nevertheless, as SR is more widely adopted, software and hardware companies may become independent entities and competition will increase.

Traditional manufacturers strongly oppose the adoption of SR technology because it threatens their current business model. Network operators may have some resistance to adopt software-based infrastructure since software is perceived as less robust than hardware-oriented products. Equipment vendors could take advantage of their long-established relationship with network operators to reinforce such mistrust and to block the adoption of SR technology. However, software radios offer important benefits for network operators, the largest vendors' clients. Equipment manufacturers may decide to change their strategy and to start manufacturing software radios to better serve operators' needs. The situation created by 3G standards might provide some equipment manufacturers with further incentives to adopt software radio products. The migration toward 3G has served to increase the differences between Western manufacturers: Ericsson and Nokia have widened the distance that separates them from their competitors. Nortel and Siemens have increased its European market share. Motorola, Lucent and Alcatel have lost most 3G contracts and are far away from Ericsson and Nokia (see market shares in Figure 29). The worst positioned operators may look to SR technology as a way to recuperate market share. Market leaders could also adopt SR to avoid losing their dominant position when software radios win market share.

Such changes are related to the number of contracts that the different manufacturers won in the European market, the second after Japan to introduce 2.5G and 3G services. As explained in the previous section, the largest network deployment cost corresponds to the Radio Access Networks (RAN). Moreover, the radio interface is the most sensible part of 2.5G and 3G networks. The operators with best RAN offers and most complete end-to-end solutions have won most GPRS and UMTS European contracts and have increased their market share. The comparison of Table 6 and Figure 36 support this assessment. The only exception is Siemens. Even if its RAN performances are not as relevant as Ericsson's or Nokia's, its alliance with NEC, who has provided NTTDoCoMo with equipment for the first 3G network in the world, has allowed the company to benefit from the Japanese experience and share costs. Alcatel has tried to follow a similar strategy through its alliance with Fujitsu, the other NTTDoCoMo 3G provider. The movement took place too late and Alcatel skills were too weak for the company to react in time.

**Table 6. Manufacturers' 3G skills in 2001 [94].**

| Manufacturer | Radio Access Network (RAN) | Core Network (CN) | Applications & Services | Terminals |
|---|---|---|---|---|
| **Ericsson** | +++ | ++ | ++ | ++ |
| **Nokia** | +++ | + | +++ | +++ |
| **Siemens** | + | +++ | ++ | +++ |
| **Nortel** | ++ | +++ | +++ | + |
| **Alcatel** | + | ++ | + | ++ |
| **Lucent** | ++ | ++ | ++ | + |
| **Motorola** | + | +++ | ++ | ++ |

+++ Very Good, ++ Good, + Average

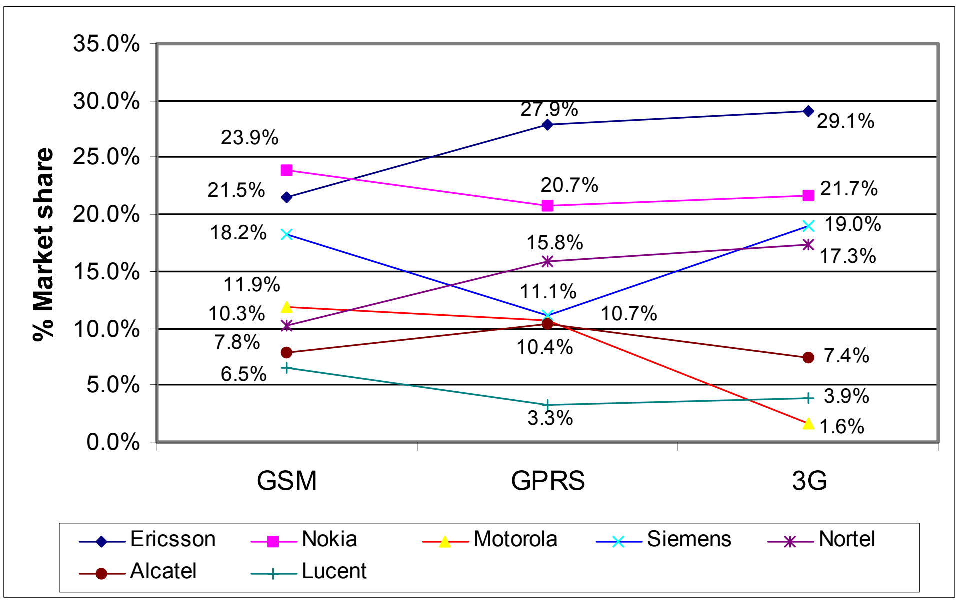


**Figure 36. Market share by standard for wireless infrastructure manufacturers in 2001 [94].**

Hardware and software separation has important consequences in base stations production and capabilities. **On the production side**, homogeneous hardware platforms will implement all types of base stations. Consequently, *less expensive production resources* will be required. Cheaper general assembling lines will replace more expensive and specialized ones. The requirements of wireless infrastructure vary substantially with particular operating conditions. For example, equipment for rural areas has more relaxed constraints than equipment for densely urban infrastructure. Software radio improves *product scalability* to meet operational conditions without developing different products.

Since most products will share the same basic hardware, *production planning will be less critical* and *economies of scale will be larger*. Nevertheless, the capability of software to make compatible different platforms will make *more difficult product differentiation*. Network operators and final consumers could buy from different providers, *increasing competition*.

Hardware manufacturers must track the continuous improvement of wireless standards. Dedicated committees review these standards and add new features. A good example is the two hundred modifications that the 3G European UMTS standard has suffered in the last two years. Upgrading traditional hardware-based products to follow standardization changes requires high investments in time and cost. However, standards cannot be improved infinitely to meet the evolving needs of the industry. Therefore, even more higher-performance standards are designed continuously. This is the case of the transition from GSM to UMTS in Europe. When a new standard reaches the market, new equipment must be built. In both cases, traditional manufacturers face high development times and costs. SR has *lower standardization upgrades* and *smaller standard migration times and costs:* with SR infrastructure, hardware replacement is not necessary and redesign is mostly limited to software writing.

**On the capabilities side**, SR will expand the ability to support *multi-band, multi-standard and multi-application base stations*. This capability is particularly important in the United States, where incompatible systems cover the country. Tri-mode GSM, TDMA and IS-95 base stations might provide three standards over the same network to improve seamless operation. This advantage may extent the cellular market to other services such as fix wireless: Not only standards offering the same service can share SR infrastructure, also standards for different services. For example, in developing countries like Colombia, wireless systems are being used to provide basic telephone service. At the same time, the first cellular networks are being implemented. SR infrastructure could integrate both services on the same equipment.

Additionally, *infrastructure sharing* has arisen as a new need in Europe, where operators have spent enormous sums on 3G licenses. To palliate the effects over their investment capacity, operators are seeking to share 3G networks.[26] Even if this practice may adversely impact prospects for competition, some regulators have already given their permission.[27] Today, only Nokia offers a product with sharing capacities (the Multi-Operator Radio Access Network solution). However, this equipment is limited to the 3G European standard and cannot allocate resources dynamically between the operators sharing the equipment. SR infrastructure provides a flexible way to develop multiple operation products that dynamically allocate frequencies and processing capacity. If, for example, numerous AT&T users are present in a commercial center at a given moment but only a few of Verizon wireless, SR base stations may allocate more frequencies to AT&T users. When the user proportions change, SR base stations will reallocate the necessary resources.

Other attractive capabilities of SR base stations are the ability for *in field* and *remote upgrade*. Hardware replacements and/or modifications are cumbersome and costly. Pieces of equipment must be retired from the field to perform these operations. SR infrastructure facilitates upgrading. The new software can be directly installed on the field. Upgrades of wireless equipment could be done remotely through the Internet or the radio interface without having to physically access the piece of equipment.

Finally, SR facilitates the *interaction with innovative technologies* such as adaptive antennas.[28] The future performance of wireless infrastructure is closely linked to other

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[26] Estimates forecast savings of 10 to 20% in the initial investment when sharing construction costs. 60% of this initial investment corresponds to base station equipment (BTS) and site installation. Operators will save 3 to 10% of the BTS operational costs and 1 to 2.5% of the site operation costs when sharing the network.

In June 2001, British Telecom and Deutch Telecom signed an accord to share network-building costs between BTCell and One2One in the UK and D1 and ViagIntercom in Germany. British Telecom announced building savings of 18% with this accord. Network sharing is becoming an important trend in the cellular market.

[27] The German Regulatory Authority for Telecommunications and Posts (RegTP) announced in 2001 a decision allowing operators to share power supply sources, sites, masts, towers, shelters, radio links, leased lines, base stations (BTSs), base station controllers (BSCs), radiating systems and other elements such as combiners, cables and antennas. In The Netherlands, the government regulators have allowed 3G licensees to share networks. They will be forbidden to share the core network and the frequencies.

[28] The beam of this kind of antennas may reconfigure to adapt to relevant changes in the environment. Such adaptability allows less interference in transmission and reception. For an introduction to adaptive antennas and their application to cellular systems, see [37].

technologies such as adaptive antennas. These technologies are not mature yet and need from intelligent software interfaces with the pieces of infrastructure. SR facilitates building those interfaces and provides equipment flexible enough to meet adaptive antennas future requirements without hardware modifications.

#### Network operators

Network operators will benefit from the new base stations capabilities and increased market competition among equipment vendors described in the previous subsection. Operators adopting SR equipment will also face *reduced deployment costs* and *increased network capacity*. Such features create incentives for operators to push manufacturers to market SR products.

Spectrum, site construction and equipment costs are the largest parts of network investment. Estimations for SR base stations show that the cost per piece of equipment is currently similar for traditional and SR technology [59]. However, SR base stations can operate over multiple standards, substantially *reducing the cost per standard* (see Section 4.2.5 for a case study on cost reduction for SR technology). Planning is an essential phase of network deployment. Operators have to estimate the traffic and particular propagation conditions for each area to cover and plan the type and quantity of infrastructure to deploy. Numerous assumptions are made in these studies, which consequently, are not highly accurate. Further adjustments are necessary when network operation begins. Adjustments are expensive and may affect network performance.[29] SR infrastructure is homogeneous and may be in field customized for each particular situation. *Network planning gains from increased flexibility* and *becomes less expensive* with SR.

Similar to equipment manufacturers, network operators also must track the upgrade and migration of wireless standards, which involve expensive equipment modifications and replacements. When standard changes reach the market, operators must choose between affording these upgrades or offering less performing network capacities and

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[29] For example, if the traffic in a spot is much higher than forecasted, new frequencies has to be added to the base station. In order to add frequencies, new hardware cards must be installed and the frequency plan of the area containing the base station should be redesigned.

compete in worse conditions. SR base stations *reduce the cost of standard upgrade* and *migration.* Developing full-country networks is a costly strategy, especially in extended countries. In order to offer more complete coverage to their users at lower costs, operators try to roam users over local networks when they lack coverage (roaming). This solution works perfectly in areas with uniform standards like Europe. However, this is much more difficult in countries like the United States where multiple standards share the space. Providing multiple standards at low costs over SR networks *favors roaming*.

SR enhances the business model of network operators but threatens the business model of equipment manufacturers. Consequently, operators have more incentives than manufacturers to adopt software radios and may need to push back on vendors. Large operators like Vodafone and Verizon Wireless buy large quantity of equipment from manufacturers and therefore, have buyer power to push vendors to the development of particular products. If equipment manufacturers resist adopting SR, operators may form alliances with SR developers like Vanu and hardware manufacturers outside the cellular market like Compaq to develop their own SR products. Such strategy will obligate traditional manufacturers to joint the SR market or to risk losing a large part of market share.

Service providers

Service providers will benefit from the cost reduction and added capabilities experienced by network operators. SR capacities to offer multiple standards and support several operators over the same network promote the proliferation of VMNOs. Service providers will also take advantage of remote and over the air download to *save distribution* and *advertising costs* and push their services to their clients (see Section 3.2.1).

Site owners

SR technology allows site owners to extent their business from site renting to network capacity sale. SR base stations can support different standards and dynamically allocate resources between service providers as needed. Consequently, *infrastructure investments become cost effective*.

Customers

Final customers will benefit from a general improvement of cellular services derived of the changes presented along this section. In particular, *general-purpose handsets*, *seamless operation* and *downloadable applications* and services.

### 4.2.4 Initial SR drawbacks

As presented in the previous section, SR provides lots of advantages but may also have some problems, especially in the first stages of adoption. Operators and regulators are mostly concern about secure operation. First, software is much more difficult to test than hardware and therefore, unexpected bugs may cause operation in not desired conditions. Second, third parties could manipulate software radios more easily than hardware equipment to originate unauthorized operation. The Federal Communications Commission has addressed both concerns in its process about software radios (see 0).

As explained in Section 4.2.2, equipment vendors take advantage from unspecified aspects of wireless standards to differentiate their products, which results in incompatibility between different manufacturers. Network operators deploying SR infrastructure, especially base stations, may find problems to run their SR pieces of equipment with other manufacturers systems. This is an important point that regulators and standardization bodies have to address.

Today, Qualcomm holds key patents for CDMA technology, which is the base of the most important 3G standards and some 2G networks (see Figure 24). All systems implementing CDMA systems need a license from Qualcomm, including software radios. Qualcomm interests in the ASIC market may induce the company to deny such licenses to SR companies or to establish high prices that may increase software radio costs.

Cost could be one of the main drawbacks of SR products. Some sources price SR base stations at the same cost than traditional ones (see [74]) but it is likely that SR costs will be higher in the early stages of adoption. This is a problem only if one standard is to be deployed per network but can be easily overcome if two or more standards operate over the same network (see Section 4.2.5).

Finally, financing is an important issue in the cellular industry. Traditionally, equipment manufacturers have financed network operators. Startup SR companies lack the capacity to finance large operators like British Telecom or Verizon Wireless. In consequence, they have low probability to be chosen as equipment vendors. This was the case of Airnet [2], a small infrastructure company that, in 1996, started offering base stations that could migrate from GSM to GPRS and EDGE with simple software upgrades. However, the product has not been able to gain important market share. Airnet's customers are limited to some North American independent wireless operators, Marconi (based on UK) and China's Great Dragon Telecom (GDT). Airnet it is almost unknown in Europe. The principal reason of its lack of success is Airnet's incapacity to finance European operators and interconnect with most manufacturers switches due to compatibility reasons. SR companies need from strong financing alliances to enter the cellular market.

### 4.2.5 Case study: Deployment and operation costs for traditional and SR cellular networks in Massachusetts

Cost may be one of the main drivers for the adoption of SR technology in the cellular industry. The objective of this section is to evaluate cost savings when deploying cellular networks with SR base stations. A cost model is applied to estimate deployment and operation costs for cellular networks using traditional and SR base stations in the state of Massachusetts.[30] Such analysis shows that, for two or more standards, deployment costs are reduced in at least 44% per standard and operation costs drop to at least 47% per year and standard.

First, this section describes a simplified model of the architecture of cellular networks, which is used to evaluate deployment and operation costs. Second, using this model, the thesis sets three network configurations to be evaluated: traditional base stations (Architecture 1), SR base stations with different core networks (Architecture 2)

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[30] The cost model used in this section is based on the model developed for the following paper:

Aldana, S., Brucker, X., Manuel, V., Merino Artalejo, M. F. and Pinczuk, G., "*Cost Model for a Mobile Network Based on Software Radio Technology*", Tufts-MIT class "Telecommunications Modeling and Policy Analysis" (DHP P232 – ESD.127), May 4, 2001.

and SR base stations with a common core network (Architecture 3). In third place, the section presents the cost model structure, its data and parameters and explains why Massachusetts has been selected as case study. Finally, this section analyses the results of the cost model. The paragraphs of this subsection provide high-level explanations of the data and assumptions but not actual numbers. Appendix B provides the specific values used to run the model.

## Cellular networks architecture

As explained in the previous sections, multiple cellular standards supply cellular services around the world. Even if these standards are frequently incompatible, they share a common network architecture, which is summarized in Figure 37. Three main subsystems integrate cellular networks: the *Radio Access Network* (RAN), the *Core Network* (CN) and the *Application Layer*.[31]

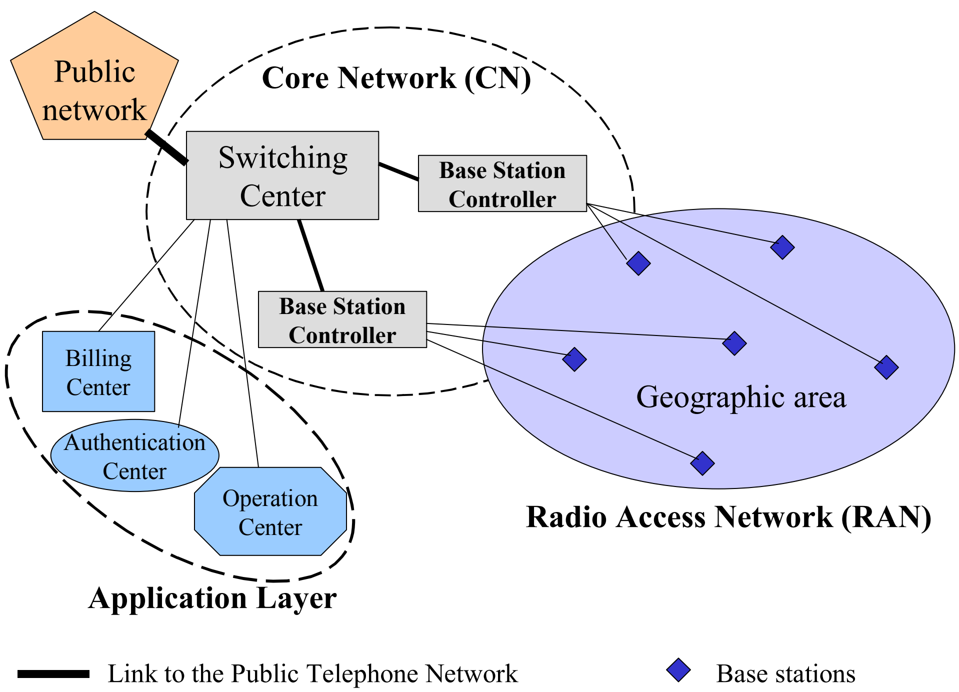



**Figure 37. Cellular networks architecture.**

[31] The notation for similar parts of the network may vary from standard to standard. For example, in GSM, the RAN is called Base Station Subsystem (BSS) and, in UMTS, a base station is called a Node B.

The RAN is composed of the base stations (BTSs) and deals with the communications radio. The BTSs cover a geographic area and provide communication between the network and the mobile stations (user's cell phones) via the air interface. The CN concentrates the traffic and routes it to its destination. Traffic destination can be another mobile user in the same network or another fixed or mobile network (see Public Telephone Network in Figure 37). The CN is usually composed of two levels of traffic concentration: *Base Station Controllers (BSCs)*[32] and *Switching Centers*. The BSCs link the base stations together and are each responsible for the operation of approximately ten BTSs. The switching centers route communications between the BSCs and other networks. They are also connected to the Application Layer.

This Application Layer carries out network management functions. The *Authentication Center* contains information about each user, such as the type of contract, the bills paid and other personal information. This center is called each time a user tries to register, to verify that the user is a genuine customer. The *Billing Center* keeps record of each user's bill. Finally, the *Operation Center* deals with all questions regarding operation and maintenance of the network. This center surveys the network to detect any problem and makes statistics about traffic concentration, busiest hours and other parameters available for use by both marketing and strategic planning departments.

### Scenarios

The deployment of cellular networks using SR base stations will allow different standards to share the same RAN. Moreover, the use of a common RAN permits sharing also the CN. Such possibilities may reduce deployment and operation costs per standard. The objective of this section is to analyze such costs for three different architectures.

Architecture 1 (Figure 38) is deployed with traditional base stations. In consequence, totally independent networks have to be built to cover the same geographic area, the state of Massachusetts for example. In Architecture 2 (Figure 39), SR base stations are used. The same RAN could supply multiple standards, GSM and IS-95 for example, over the same geographic area. Independent CNs are deployed for each radio standard. Finally, in

[32] In some standards, the BSCs may be considered part of the RAN.

Architecture 3 (Figure 40), not only SR base stations are installed, but also the same CN serves all standards. In all the architectures, each standard has its own Application Layer to allow independent exploitation by different service providers.

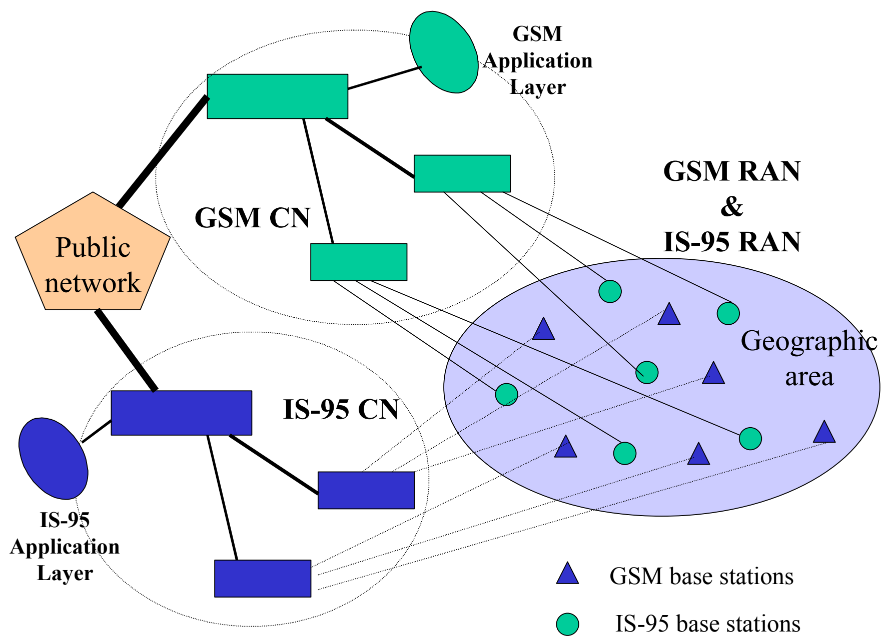



**Figure 38. Architecture 1: Traditional base stations and independent CNs.**

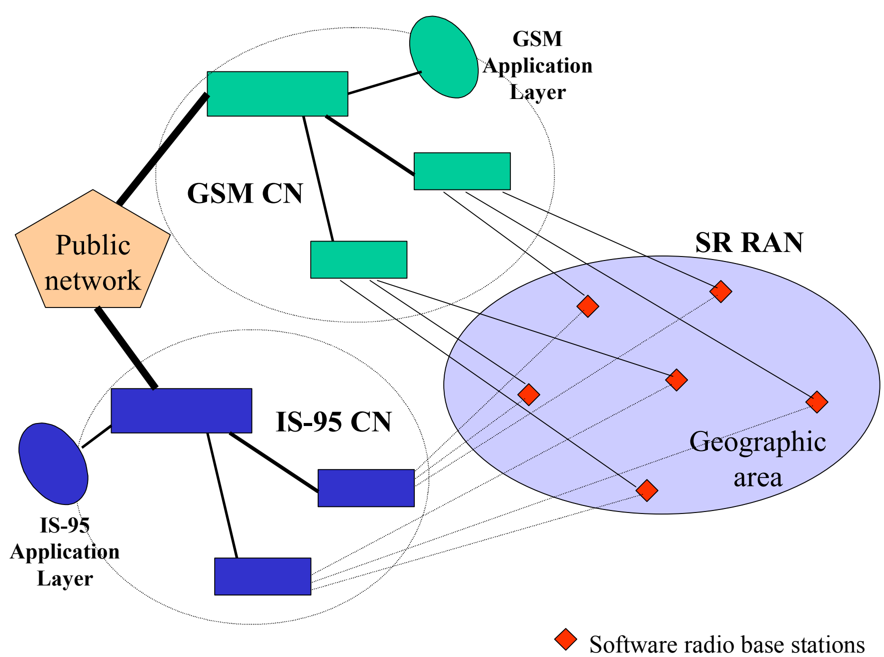



**Figure 39. Architecture 2: SR base stations and independent CNs.**

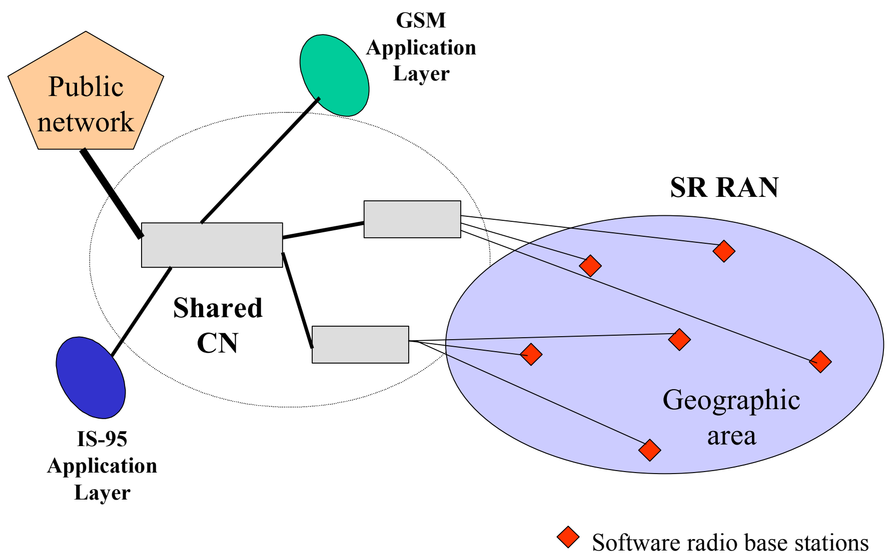



**Figure 40. Architecture 3: SR base stations and shared CN.**

## The cost model

Deployment and operation cost calculations are done with the model presented in Figure 41. Such model is similar to those used by real-life network operators. The model carries out a dimensioning of the area to be covered based on geographic and demographic data, general assumptions and the chosen quality of service. This dimensioning is checked out through a traffic calculation. If traffic constraints invalidate the previous dimensioning, the process is repeated. When the dimensioning process is finished, the number of sites and equipment data are used to calculate the pieces of equipment required to deploy the network. The cost calculation, based on equipment prices and operation charges, is the last step. The following paragraphs provide a high-level description of the model. For further details and actual data, refer to Appendix B.

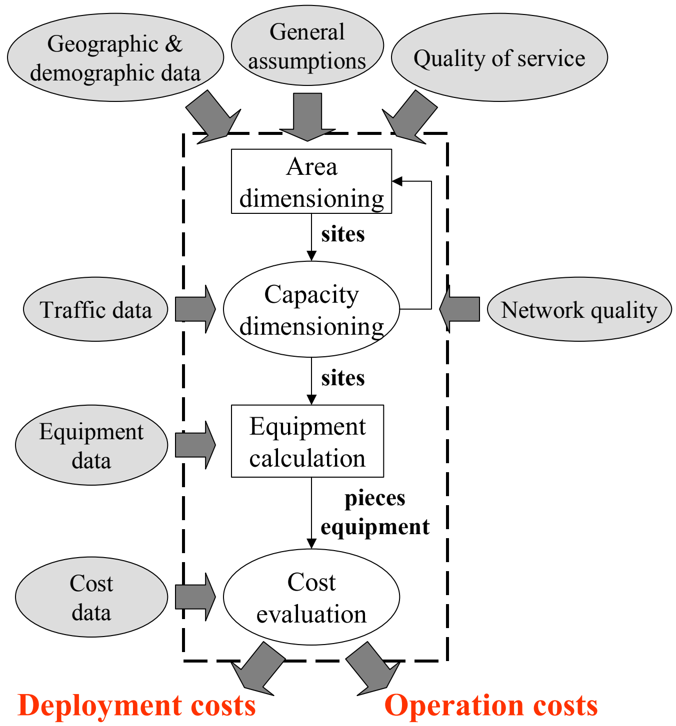



**Figure 41. Cost model structure.**

a) <u>Area dimensioning</u>

The objective of the area dimensioning is to calculate the number of cells required to cover the targeted area. Each cell contains a site with a base station and a set of antennas. The inputs to this step are the following:

- <u>General assumptions</u>

In a real case, the standard to be deployed is already defined, GSM or IS-95 for example. In this case study, SR base stations could operate over several standards. The RAN should be dimensioned for the most restrictive standard to guarantee operation in all systems. RAN dimensioning depends on the size of the cell, which is a function of the frequency band and the traffic.

Usually, 2G cellular communications take place in the 800-900 MHz and 1.8-1.9 GHz bands. Because high frequencies attenuate faster than low frequencies, cells should be small enough to assure coverage in highest bands. Smaller cells imply larger number of sites and equipment and therefore, higher cost. This study case focuses on 2G services and uses the 1.9 GHz band to do the dimensioning.[33]

The size of a cell also depends on the traffic contained in the cell since a number of frequencies can only handle a limited amount of traffic. In general, smaller cells contain fewer users and therefore, less traffic.[34] The traffic handled per band may vary with the multiplexing technique used by the standard. In theory, TDMA systems can handle less traffic than CDMA systems. Therefore, following the strategy of dimensioning by the most restrictive case, the dimensioning calculations of this model are based on TDMA systems.

Finally, the traffic contained in a cell changes over the day. The burden of traffic concentrates in business hours. The network has to be dimensioned for the hour of most occupation, the busy hour.

- Geographic and demographic data

The size and population of the zone to cover are necessary to calculate the number of sites. On the one hand, operators do not offer full coverage over a whole country or state. Investments for covering the total area would be enormous while returns in rural areas with low population density would be insignificant. Operators restrict networks to high-density areas and highways. They also reserve some sites to small towns in rural areas, most of them with tourist or strategic value. The classification of areas by number of users and building density receives the name of morphology. A typical morphology is contained in Table 7.

**Table 7. Typical morphological classification.**

| Name | Characteristics |
|---|---|
| Dense Urban | High density of tall buildings, usually downtown business and commercial areas |
| Urban | Three to four-story buildings in the center of the city |
| Suburban | Residential areas with open spaces |
| Rural | Small villages and country side |

[33] If the same model is applied to 3G systems, the highest frequency band will change as a function of the studied standards.

[34] This statement could not be true if comparing cells of highly populated areas and cells of rural regions. In highly populated areas, the density of cellular communications is much higher.

On the other hand, penetration rates are also different per morphology. Users concentrate in dense areas. Moreover, part of customers live in suburban areas but, concentrate in downtown working centers during the most busy hours of the day.

- Quality of service

Not all the areas are covered with the same quality of service. Table 8 summarizes the most important kind of services. Cellular operators define different levels of service for different morphological levels. For example, in areas with high concentration of business and commercial centers, Urban Dense (see Table 7), operators offer Indoor Deep services. However, in rural areas, service is limited to Outdoor coverage.[35]

**Table 8. Mobile services by coverage.**

| Service | Characteristics |
|---|---|
| Indoor Deep | A cell phone can be used inside rooms without windows |
| Indoor Daylight | A cell phone can be used inside rooms with windows |
| Indoor Window | A cell phone can be used inside rooms near the windows |
| Outdoor | A cell phone can be used outside buildings |
| Incar | A cell phone can be used inside a car |

### b) Capacity dimensioning

Area dimensioning must be checked in capacity, i.e. the number of sites has to be enough to handle the traffic generated in the area. Given the number of users, the traffic provided by each of them and their distribution over the morphologies, the model uses the Erlang law to calculate the number of frequencies per site. Assuming tri-sector sites (three directive antennas per site), twelve frequencies per site, four frequencies per sector, is the maximum that a site can have.[36] Only those sites situated on roads have two sectors (bi-sector sites). In such cases, eight frequencies per site, four frequencies per sector, are the operational maximum. If the number of frequencies of any site, calculated with the

[35] Note that this is the minimal service that is guaranteed in the whole cell. Close to the base station, the service may be of higher quality (Indoor Daylight or Indoor Deep, for example).

[36] More than four frequencies per sector complicate frequency allocation because they increase the level of interferences. In consequence, higher values reduce network quality and make more difficult capacity upgrade over time.

size of the cell from the previous step, is higher than four per sector, the dimensioning process has to be repeated for smaller cells until four or less frequencies per sector can handle the total traffic.

- Traffic data

  Not all the users generate the same amount of traffic, especially at the busy hour. Users can be divided into two categories: business and residential users.[37] Business users are those that establish communications as a part of their professional activity. Residential users refer to those that restrict themselves to private communications. In general, business users generate more traffic and are concentrated in dense urban areas.

- Network quality

  The quality of a network is measured by the blocking probability, i.e. the probability that a call will be blocked because all the network resources are allocated (Erlang law). A blocking probability of 0.02, for example, means that two calls out of one hundred are lost. Network quality is inversely proportional to the blocking probability and directly proportional to cost.

#### c) Equipment calculation

After calculating the number of sites to cover the area, this step accounts for the pieces of equipment to build the RAN and CN networks to handle the total traffic.

- Equipment data

  Equipment capacity may change for different manufacturers. In this thesis uses average numbers across manufacturers. Refer to Appendix B for actual values.

#### d) Cost evaluation

The cost evaluation step calculates deployment and operation costs based on number of sites and pieces of equipment. The model does not take into account the cost of the

[37] Further segmentations, based on accurate demographic data, are done in real networks calculations to better assess the traffic.

links between network elements. In effect, these costs will be roughly similar for different architectures. Nevertheless, if there is a difference, costs will be lower for those architectures based on software radio because more network elements are shared.

- Cost data

Not only equipment costs may highly vary across manufacturers but also with the size of the purchase. Large operators covering wide areas usually have more negotiation power and may obtain better deals from manufacturers. The cost data used in this section are averages of samples obtained from operators of different sizes.

One of the most sensitive cost data corresponds to the base station. Base stations account for the largest share of equipment costs (see Figure 30). The average cost for a traditional 2G base station is $68,000. SR base stations could cost more than traditional base stations, especially for the first commercial versions. After taking into account the prices provided by different sources like Telefónica and Lehman Brothers [49], the cost model uses a price of $108,000 for SR base stations, which accounts for 1.5 times the price of a traditional base station. This assumption is quite conservative since it allows evaluating SR benefits in a situation where SR base stations are more expensive than traditional equipment. After presenting the main results obtained under such assumptions, this section makes a sensitivity study to evaluate the variation of deployment and operation savings with changes in SR base station costs.

### Massachusetts

The cost model presented in the previous section has been applied to calculate the network scenarios of Figure 38, Figure 39 and Figure 40 in the state of Massachusetts. Massachusetts was chosen because it represents a good compromise between highly populated states such as New York, with a population of nearly 18 million people, and more sparsely populated states such as Nebraska, with a population of under 1.5 million people. Massachusetts has high morphological diversity: dense downtowns, but not as extreme as New York, followed by suburban areas, rural areas and important highways.

This variety allows appreciating SR impact in representative low and high-density areas. Demographic and geographic data for the state of Massachusetts are detailed in Appendix B.

### Results

The use of SR base stations in cellular networks causes reductions of at least 33% in deployment costs per standard and 47% in operation costs per year and standard for two or more standards.[38] Actual savings depends on the number of standards developed in the same network and the kind of architecture. The number of standards is inversely proportional to the total cost (see Figure 42 and Figure 43) and the cost per standard (see Figure 44 and Figure 45). With one standard, traditional deployment costs are lower than SR deployment costs. The reason is that SR base stations are more expensive than traditional base stations (1.5 times more) and therefore, deploying a network for only one standard is more expensive with SR base stations. Operation costs are similar for traditional and SR base stations and therefore, for one standard, operation costs are similar.

For two standards and Architecture 2 (see Figure 39), deployment costs per standard drop to 66.7% of the traditional costs because both standards share the same set of base stations and because a SR base station costs less than two traditional base stations. Operation costs per year and standard drop to 52.7% of traditional costs since two standards share the maintenance of the set of base stations. Costs diminish as the number of standards increase and become 43.5% and 29% for deployment and operation of four standards in Architecture 2 (Figure 39).

Cost decreases even more when not only SR base stations are used but also the CN is shared. For Architecture 3 (see Figure 40) and four standards, costs drop to 32% in deployment and 25% in operations. However, the largest cost impact corresponds to SR base stations (Architecture 2) and not to CN sharing (Architecture 3): for two standards,

[38] Remember that the results presented in this section correspond to the scenario in which SR base stations are 1.5 times more expensive than traditional base stations. Refer to the next subsection for sensitivity analysis on SR base station costs.

SR base stations are responsible for 33.3% reduction in deployment costs (from 100% to 66.7%) and 47.3% reduction in operation costs (from 100% to 52.7%); CN sharing reduces deployment costs in only 7.7% (from 66.7% to 59%) and operation costs in 2.7% (from 52.7% to 50.0%). The same pattern is followed as the number of standards increases (see Table 11 and Table 12).

This analysis has important implications for network operators and the adoption of SR technology. Operators will likely push for SR technology when (i) they need to provide service over two or more standards and (ii) network sharing is technologically and regulatory possible.

**Table 9. Deployment cost per standard referred to Architecture 1.**

| No standards | Architecture 1 | Architecture 2 | Architecture 3 |
|---|---|---|---|
| 1 | 100% | 114.1% | 114.1% |
| 2 | 100% | 66.7% | 59.0% |
| 3 | 100% | 51.1% | 40.9% |
| 4 | 100% | 43.5% | 32.0% |

**Table 10. Operation costs per standard and year referred to Architecture 1.**

| No standards | Architecture 1 | Architecture 2 | Architecture 3 |
|---|---|---|---|
| 1 | 100% | 100.0% | 100.0% |
| 2 | 100% | 52.7% | 50.0% |
| 3 | 100% | 36.9% | 33.3% |
| 4 | 100% | 29.0% | 25.0% |

**Table 11. Deployment cost reductions due to SR base stations and CN sharing.**

| No standards | SR base stations deployment cost reduction | CN sharing deployment cost reduction |
|---|---|---|
| 1 | - | - |
| 2 | 33.3% | 7.7% |
| 3 | 48.9% | 10.2% |
| 4 | 56.5% | 11.5% |

**Table 12. Operation cost reductions due to SR base stations and CN sharing.**

| No standards | SR base stations operation cost reduction | CN sharing operation cost reduction |
|---|---|---|
| 1 | - | - |
| 2 | 47.3% | 2.7% |
| 3 | 63.1% | 3.6% |
| 4 | 71% | 4% |

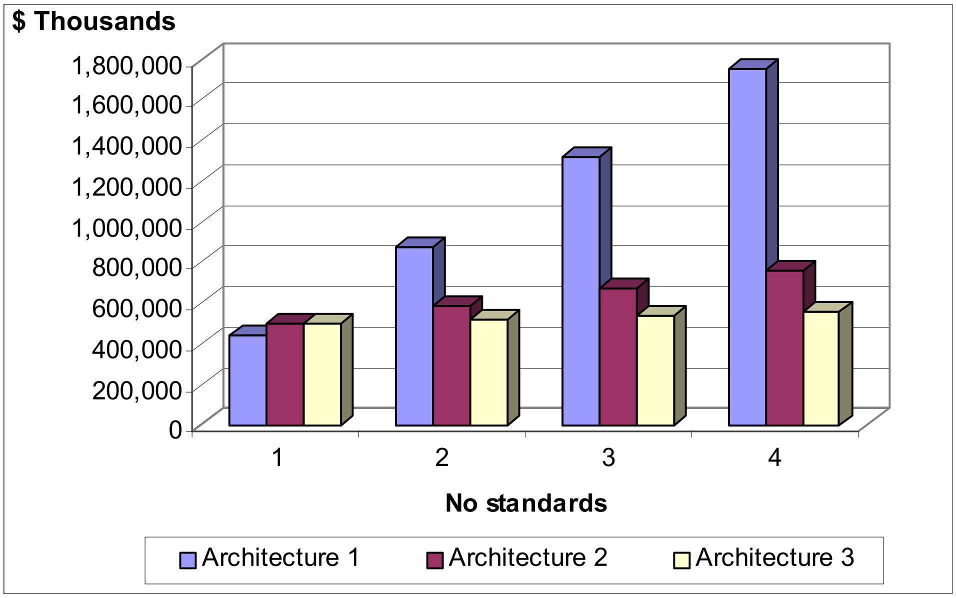



**Figure 42. Total deployment costs.**

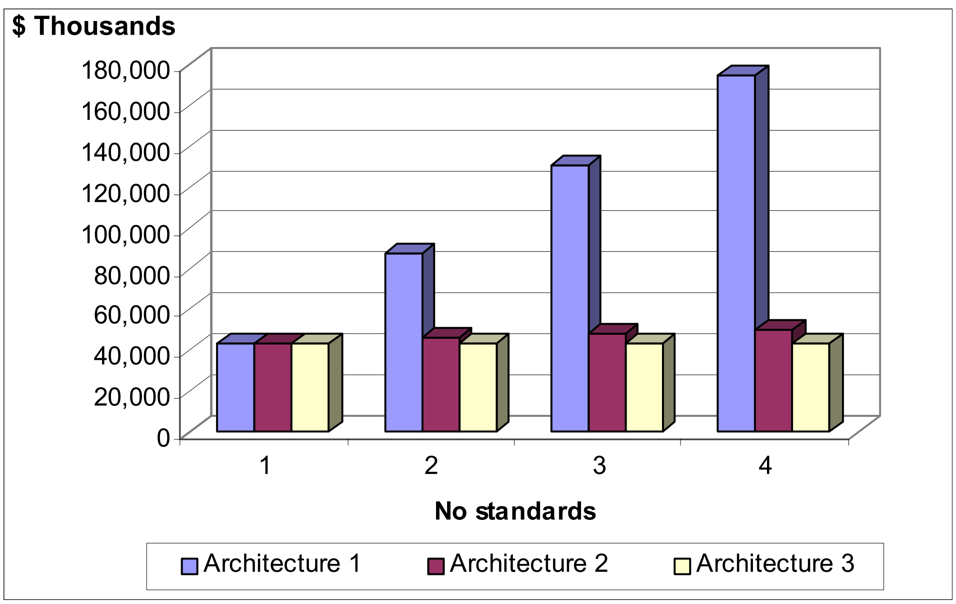



**Figure 43. Total operation costs per year.**

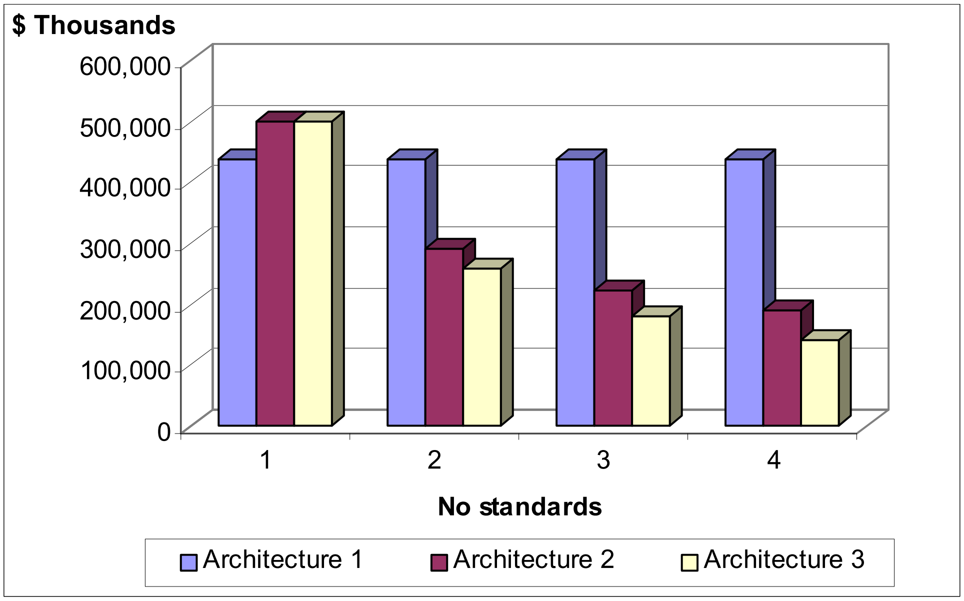



**Figure 44. Deployment costs per standard.**

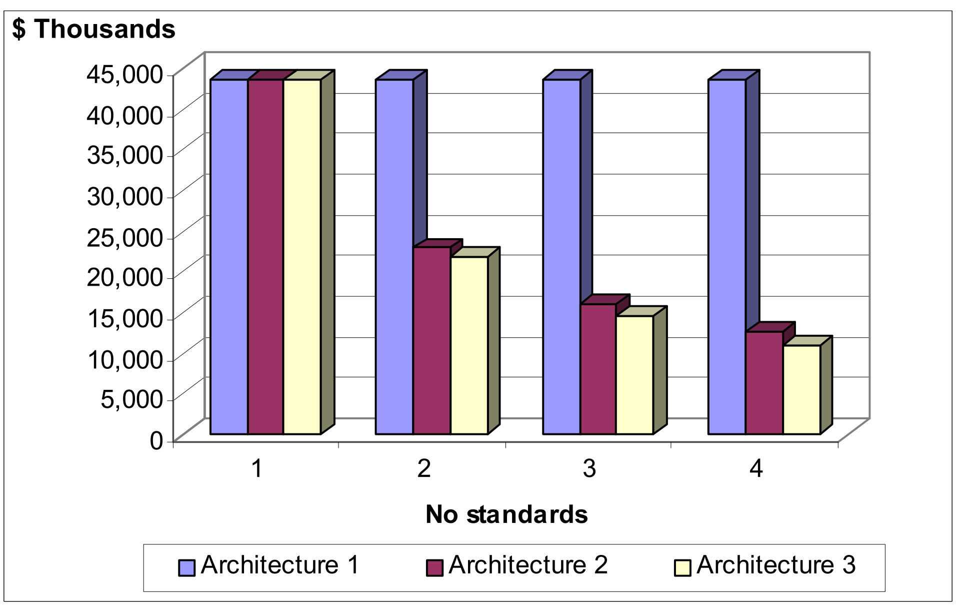



**Figure 45. Operation costs per standard and year.**

Sensitivity analysis on SR base station cost

This study calculates network costs for SR base stations prices ranging from half to three times the cost of traditional base stations. Operation costs per year are assumed to be the same for traditional and SR base stations and therefore, network operation costs are not affected. Even in the worst scenario calculated, SR base stations being three times more costly than traditional base stations and operating over only two standards, SR technology allows deployment savings of 14% for Architecture 2 (see Figure 46) and 22% for Architecture 3 (see Figure 47). Benefits increase as SR costs become closer to traditional prices. Thus, in the best case studied, SR base stations costs being half of traditional base station prices and operating over four standards, deployment savings account for 63% for Architecture 2 (see Figure 46) and 75% for Architecture 3 (see Figure 47). In summary, the sensitivity analysis shows that, even in the worst case, the benefit of SR in terms of deployment costs outweighs the effect of more expensive base stations.

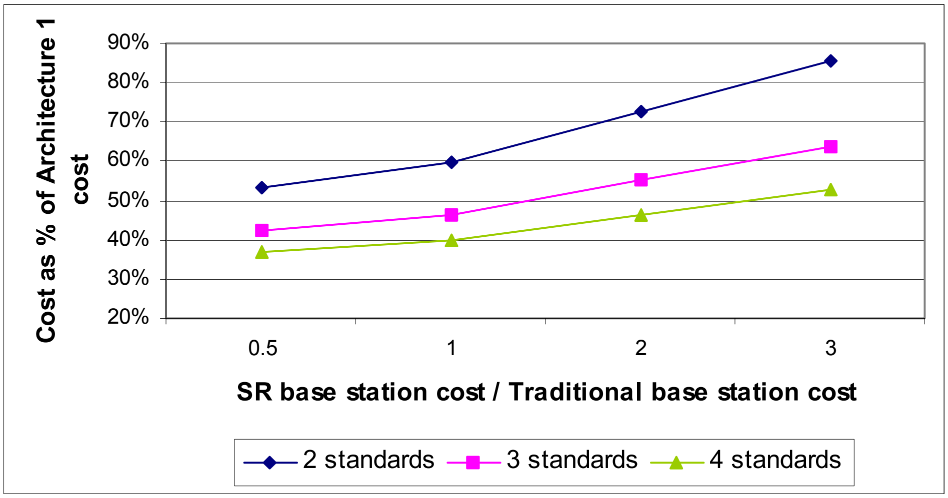



**Figure 46. Deployment costs per standard for Architecture 2 as a function of SR base station costs.**

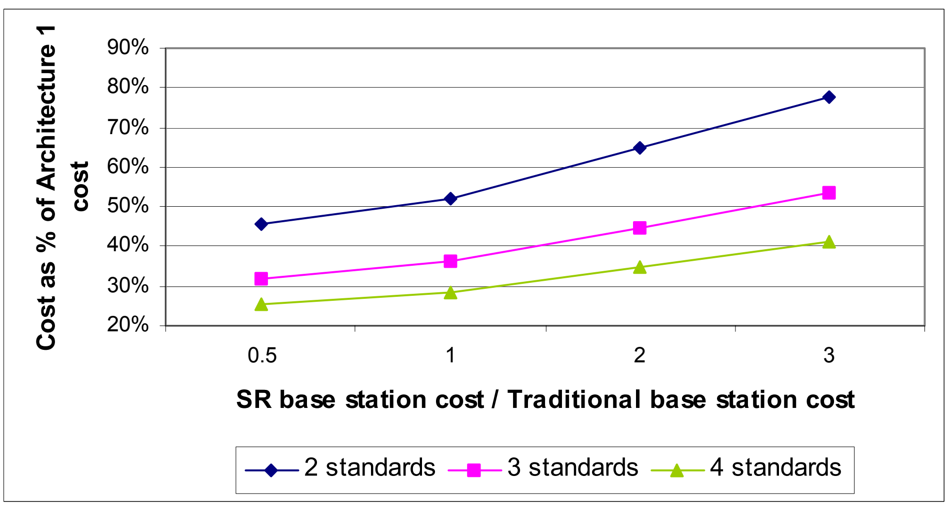



**Figure 47. Deployment costs per standard for Architecture 3 as a function of SR base station costs.**

# Chapter 5. Policy issues on SR

SR not only has impact on the industry structure but also affects governmental policies, particularly certification, standardization and spectrum management. SR effects have a variety of time scales that depend on the degree of technical development. In the short term, SR concerns certification rules. Certification issues might extend into the future as a barrier to market competition. In the long term, SR has the potential to deeply affect standardization and spectrum management policies. Sort and long-term effects are analyzed in Sections 5.2 and 5.3. To study how SR may affect governmental policies, it is necessary to understand the regulatory structure, its powers and obligations. Section 5.1 provides the necessary regulatory background and reviews the spectrum management models generated by current wireless policies.

## 5.1 Regulatory framework

Before analyzing how SR may affect governmental policies, this section reviews the current regulatory framework. The section focuses on the United States, the only country that has carried out a formal regulatory process to address SR technology. The Japanese regulator MPHPT (Ministry of Public management, Home affairs and Posts and Telecommunications) [53] has done some studies and has recognized the importance of SR technology and the need for further attention [79]. References to other nations are made in this section when differences with the United States may affect SR development and adoption.

Aware of the potential of SR technology, the Federal Communications Commission (FCC), the US telecommunications regulatory organization, has carried out since May 1999 a process to assess the state of the art of SR technology and how it may affect the Commission policies. The documents related to this process can be found under the ET Docket 00-47 on the FCC web site [29]. Appendix D contains a detailed explanation of the Docket steps and the resulting norms. Section 5.1.1 provides an overview of the FCC. Section 5.1.2 describes FCC licensing policies and the spectrum management models created by these policies, the present services and the current state of the art of wireless technologies

### 5.1.1 The USA spectrum authority: the FCC

The Congress nationalized electromagnetic spectrum through the National Radio Act of 1927. Congress declared electromagnetic spectrum a public good and assumed the responsibility of serving the public interest by making this resource as widely available as possible to public and industry. The responsibility of issuing licenses was delegated on the National Radio Commission. The 1934 Communications Act created the Federal Communications Commission (FCC), which replaced the National Radio Commission. The Communications Act grants the FCC authority for licensing private sector and non-federal-government use of the radio spectrum. The FCC has the responsibility of employing this authority in optimizing the use of spectrum to serve the public interest at the federal level.

The Commission is an independent regulatory agency, i.e. it is not part of the executive branch. The authority of assigning spectrum for federal government use corresponds to the president. The president delegates this responsibility to the administrator of the National Telecommunications and Information Administration (NTIA), an executive agency dependent on the U.S. Department of Commerce. The Interdepartmental Radio Advisory Committee (IRAC) advises NTIA. Decisions by one agency usually affect the other agency. In consequence, FCC and NTIA work together to assure efficient spectrum management. Frequently, NTIA procedures and decisions are kept secret because affecting national security issues. Public and politic sectors have criticized this enclosure.

### 5.1.2 Spectrum management models

Since its creation, the FCC has relied on licensing and equipment certification to fulfill its responsibility of optimizing the use of spectrum to best serve the public interest. Licenses specify operation rights and technical rules to transmit over a given band. The objectives of licenses are avoiding interferences, promoting spectrum reuse and protecting the public from health effects. The combination of operation rights and wireless technologies have generated different schemes of spectrum management that can be classified in a four-category model presented in this section. The FCC also certifies the wireless equipment to make sure that it operates in the conditions imposed by licensing. SR technology may affect both licensing and certification. In order to understand the impact of SR on FCC spectrum policies, this section describes the licensing process and the spectrum management models created by this policy.

The FCC bases its spectrum management policy on three steps *allocations*, *allotments* and *assignments*. The entire spectrum is divided into blocks called allocations. The FCC determines the use of each allocation, for example land mobile radio, broadcasting or amateur radio. Usually, each allocation is further divided into allotments. An allotment corresponds to a particular service. In land mobile radio, different allocations are dedicated to public cellular mobile telephone, specialized mobile radio and public safety services. In the assignment phase, the FCC grants a party the right of operating (license) on a specific channel, the final division of the allotment. The grant of operation rights has important consequences:

- The licensee is allowed to operate a specific service over a particular portion of the spectrum. Contrary to other countries, USA licenses do not obligate to adopt a specific standard to supply the required service. For example, American cellular communications providers can use GSM, IS-95 or any other standard that operates in the licensed band. This is not the case in Europe, where operators are granted licensees for specific standards like GSM, DCS and UMTS. The liberty to choose standard has had important consequences in the USA mobile industry. Incompatible cellular standards have proliferated generating roaming problems along the national territory.

- The licensee has operation rights over her assigned portion of the spectrum. In most cases, these rights are exclusive. In others such as amateur radios or Part 15 devices, transmission rights are shared under certain rules or are only second-class rights (see Appendix C for details).

- The licensee is the guard of her spectrum. She monitors and reports to the FCC illegal interferences in her band of operation. Although this is also true in Europe, most European regulators exhibit monitoring functions. The French regulator, the Autorité de Régulation des Télécommunications (ART) [5], for example, carries out periodic measure campaigns to verify that emissions are kept in the band limits and to establish benchmarking between cellular operators.

The assignment of operation rights is not enough to avoid interferences, promote spectrum reuse and prevent health effects. The FCC includes on its licenses technical requirements to deal with these problems. The most important limitation, shared by all kinds of licenses and services, is maximum output power. First, limiting output power reduces interferences on adjacent bands. Transmissions in contiguous bands with much higher levels of power than the desired signal can produce masking effects that avoid information recovery. Second, power limitation allows physical reutilization. Licenses are not only restricted to particular bands and services but also to precise geographic areas. Power restrictions reduce the distance propagated by the signal and confine it to the licensed area. Finally, the FCC imposes safety power levels to reduce the probability of effects on human health caused by high-level radiation.

Operating rights and technical rules fully protect services that transmit a unique signal over a band and a geographic area, like broadcasting, from interference. Other services that have to carry different users' signals over the same band such as mobile communications need further strategies. The combination of current licensing policies (especially operating rights), the needs of the different services and the state of the art of wireless technologies generates several schemes of spectrum management that can be summarized as follows:

- Broadcast: Broadcast licenses have exclusive rights of utilization over a portion of spectrum and a geographic area. Only one licensee can operate on each channel. FCC limitations on transmitted power over main and adjacent bands avoid interferences between broadcasting services.

- Mobile communications: Mobile communications licenses grant utilization rights over a portion of spectrum and a geographic area. Similarly to the rest of wireless services, the FCC limits the maximum power that mobile equipment can radiate. This regulatory framework is enough to avoid interferences in broadcasting services but it is not the case for mobile communications. Base stations transmit several users' voice and data over the same portion of spectrum. Information overlaps at the receiver and is lost. The standards for mobile communications have adopted different multiplexing techniques to avoid this problem. The most popular standards follow two multiplexing strategies: FDMA/TDMA and CDMA.

- Amateur radio: Part of the spectrum is reserved for amateur radio operation. Amateur radio users need a license to operate their pieces of equipment. However, they are not assigned rights over any particular frequency. All licensees transmit over the same bands. Interference management is based on human control. Operators must coordinate to avoid interferences. Licensees are responsible for choosing non occupied frequencies and give priority to stations transmitting emergency communications.

- Part 15 devices: Part 15 devices can operate in almost any part of the spectrum without a license. Nevertheless, these devices have to accept the interferences caused by any other radiator. If a Part 15 device causes interferences, the operator is responsible for immediately correcting the problem and stopping the transmission if the FCC orders it.

Category titles correspond to the most relevant service of each group but any other wireless service can be classified under the model. The categories are ranged by their flexibility and efficiency in the use of spectrum. Broadcasting type services are totally rigid. Spectrum resources cannot be allocated to other uses or users. Mobile communication type services offer some flexibility because they allocate resources as users need them. Multiple amateur radios share the same band, making a high efficient use of spectrum. However, human control is burdensome and is not performing when the number of radios is high. Finally, Part 15 radios can share any part of the spectrum being the most efficient in spectrum use. Nevertheless, humans must also control Part 15 devices, resulting in the same problems as amateur radios. More detailed and technical explanations of each category can be found in Appendix C.

## 5.2 Short-term FCC policy: Certification

Certification has been the first issue addressed by the Commission in its process of rule making (see Appendix D). The FCC is responsible for certifying that the pieces of equipment can only operate under licensed conditions.

The FCC has bundled the hardware and software of SR equipment for certification purposes and has limited the rights of third parties to apply for certification of changes in software radios. The bundle of hardware and software adds time and costs to the design and implementation of new products and applications and may damage the development and adoption of the technology. Third parties certification rights might fit the current industry structure and the earliest stages of SR adoption. Nevertheless, these rules may impede the full adoption of SR and the development of market competition in the future. Section 5.2.1 discusses FCC concerns about SR effects. Section 5.2.2 addresses the effects of hardware and software bundle. Section 5.2.3 deals with third parties certification rights. Finally, Section 5.2.4 presents other alternatives for SR certification.

### 5.2.1 FCC concerns

The Commission certifies wireless equipment to guarantee its correct use in the allocated bands and to assure citizens' protection from radio emissions. Habitually, the FCC has rested on manufacturers' responsibility to attain these objectives. The party holding the grant of equipment authorization is responsible for ensuring that equipment complies with the rules (*47 C.F.R. §2.926*). Traditional hardware-based equipment can be easily tested and certified to operate under specified conditions. Only few and complicated manipulations are able to modify equipment behavior. Moreover, if misbehavior takes place, liable parties can be easily identified. Misbehavior is discouraged through a system of responsibilities.

SR threatens this system. Modifying the behavior of software radios only requires the installation of new software. Since equipment modification is made in software, the cost of manipulating a radio becomes much lower than in traditional radios. Third parties could write radio software because software is not linked to specific integrated circuits but to general-purpose processors. If measures are not taken, any software designer might hack and operate a wireless device under unauthorized conditions. The localization of hackers is difficult. Increased facility and lower cost of manipulating radio equipment reduces manufacturers' control. This new scenario deeply worries the FCC, whose responsibility is to certify that equipment only operates under licensed conditions.

### 5.2.2 Bundle of hardware and software

To deal with the concerns explained in the previous section, the Commission has imposed each combination of software and hardware be certified together in SR equipment (*47 C.F.R §2.932 (e)*). This long-established approach has not been burdensome for traditional equipment but may be for SR. In hardware-based infrastructure, a single piece of hardware is linked to a software package. Software modifications are rare and difficult to implement since they affect the firmware. However, this certification method may be highly troublesome for SR technology. In SR equipment, numerous applications may run over the same hardware platforms as well as multiple hardware platforms run the same piece of software. As pointed out by Vanu, Inc. [47], the number of bundles grows fast: SR technology running over N hardware platforms P possible software packages will generate N*P combinations. The Commission requires each of these combinations to be certified separately. If SR technology achieves some success, the burden of certification will enormously increase and discourage the use of SR technology

The separation of hardware and software reduces the barriers of entry in the market for cellular equipment. Software design requires small investments and promotes the entrance of new players. The use of homogeneous hardware platforms allows general-purpose processors manufacturers to take away market share. Certification of each hardware and software combination increases the time and cost for new products to reach the market and raises entry barriers. Independent radio communications software designers will have to fill separate certification procedures to install a piece of software over different manufacturers' platforms. A parallelism with traditional software designers can be used to understand the burden of this regulation. A similar rule in the computer world will require software designers of graphic applications for example, to fulfill long and costly certification applications before installing their software in their clients PCs, working stations or whatever kind of computers they could use. If independent software designers are discouraged, hardware platforms manufacturers lack the necessary complement to their products. In consequence, they could only convert themselves into traditional manufacturers or leave the market. This scenario favors the business model of traditional equipment manufacturers, which certify the complete pieces of equipment, and discourages competition.

The Commission has established a new certification procedure for software radios, the Class III permissive change ((*47 C.F.R. §2.1043 (a), 47 C.F.R. §2.1043 (b)(1), 47 C.F.R. §2.1043 (b)(2), 47 C.F.R. §2.1043 (b)(3)*). This permissive change applies to those software changes in software radios that affect frequency, power and modulation. The Class III permissive change uses a less burdensome filing process than the one for certification of new equipment. Even if the quantity of data to be presented has been reduced, Class III is not streamlined enough to prevent the effects presented in previous paragraphs. Class III changes require test data showing that the equipment complies with the rules for the new service and the RF exposure requirements. Once the change has been approved, the equipment could be upgraded in the field. All pieces of wireless equipment must exhibit a label with the number of their FCC certification procedure. If new certification procedures take place, the FCC grants a new number and a new label must replace the old one. In Class III permissive changes, the label will not change after the Commission approves the change. The FCC will keep record of all authorized changes under one licensing number. A piece of equipment with this label could operate in any of those modes. For being eligible for Class III changes, a device must previously be classified as a software radio (for FCC SDR definition see *47 C.F.R. §2.1 (c)* and Appendix D).

### 5.2.3 Third parties certification rights

The FCC not only seeks to assure that SR equipment operates under authorized conditions (bundle of hardware and software for certification purposes) but also to easily attribute responsibilities when unauthorized operations take place. The FCC has tried to perpetuate the system of responsibilities used for traditional equipment. The Commission has made equipment manufacturers liable for each operation mode of the equipment and reduced the certification rights of third parties like independent software designers. These rules may fit the industry structure in the early stages of SR adoption but might disrupt its full adoption and future market competition.

Under the last rules issued by the Commission, the manufacturer of a software radio has to apply for an identification number of SR equipment (SR defined as *47 C.F.R. §2.1 (c)*, see Appendix D). The grant of SR equipment authorization is responsible for ensuring that equipment correct operation (*47 C.F.R. §2.926*). The FCC does not impose a specific method to assure security or authentication but requires manufacturers to take adequate steps to prevent unauthorized changes to the software that drives their equipment (*47 C.F.R. §2.932 (e)*). Only the party holding the grant of equipment authorization for a software radio can file a Class III permissive change. There are two possibilities for a third party to file a SR permissive change. First, the original grantee may authorize a third party to file an application on its behalf as permitted now for other devices (*47 C.F.R. §2.911 (c)*). The original grantee would continue to be responsible for the continued compliance of the device**.** Second, a third party can obtain a new identification number for a device and become the party responsible for its compliance. The new number is displayed in the electronic label of the SR equipment.

These rules are sufficient for the early stages of SR adoption in the current industry structure (see Section 4.2.2). Today, equipment manufacturers hold the wireless equipment market and are the players that have the capacity to first adopt SR. In the earliest scenarios, large manufacturers like Motorola, Ericsson and Nokia might sign contracts with small SR designers such as Vanu and Radioscape to use their software and certify its proprietary SR equipment. This situation will favor the diffusion of SR technology and its advantages across the different levels of users, from network operators to final customers, who are currently used to hardware-based solutions and have confidence in well-known manufacturers.

However, as SR becomes more widely adopted, third parties restriction to certification may damage the full benefit of SR and the development of industry competition. SR not only allows manufacturers to separate hardware and software facilitating the development and diffusion of their new products and applications, but also permits the entrance of new market players to take care individually of hardware and software aspects. Hardware manufacturers may produce general-purpose, more performing and less expensive hardware platforms, able to run any software application. Software designers would write innovative software products portable across hardware platforms. Competition is improved. Under third parties rules, equipment manufacturers keep the power of filing Class III changes, making impossible for software designers to separately certify their products. The two ways for third parties to file Class III permissive changes, under the granted permission and obtaining a new identification number for a device, are unlikely to success. First, granted manufacturers will only authorize software certification under their control, impeding its certification with other hardware platforms. Second, software designers will require enormous resources to obtain a new identification number for each device and be out of the control of hardware manufacturers. Such leaves important entrant barriers and discourages the entrance of small software designers, common of other software industries. Third party measures will reduce competition and avoid changes in the wireless industry.

### 5.2.4 FCC alternatives

After presenting the FCC concerns in terms of software radio certification and the drawbacks of current regulation, this section reviews how other industries certify pieces of software. Such review is used to discuss alternatives that the FCC could adopt for SR certification.

The state of the art in software certification is quite limited today.[39] Four main approaches are currently used in the industry:

- <u>The aerospace industry approach:</u> This industry is the most critical in safety terms. In this kind of systems, there is an analysis of the different situations that can cause the failure of the whole system. For example, the pilot cannot control the rudder, so the airplane cannot maneuver and eventually crashes. The software is exhaustively tested to guarantee that the software cannot cause these situations

[39] The information contained in this section about the state of the art and the procedures used in software certification was obtained through private conversations with industry experts from MIT, the MITRE organization and the Spanish university UPM.

and to assure that, if there is a software failure, it is mitigate to not cause the system failure. Aerospace testing costs are extremely large.[40]

- The computer security industry approach: The code of security-related applications is submitted to numerous manual and automated analysis to ensure that it follows the security rules established for the system. For example, that only secret data can be written into a store certified as secret.
- Standards conformance: Pre-established test suites try to provide some degree of confidence about the lack of problems in the software. Passing the test suite does not mean that the application is without bugs but only that it passes this particular test.
- Formal methods: Formal methods like SPARK [80] try to prove properties. The proved parts of code do not need to be tested.

The most reliable method is the one used by the aerospace industry but it is also the most expensive. The FCC could use this method to guarantee the correct operation of software radios while tries to minimize the portion of software that has to be certified to avoid costs. In this sense, Vanu, Inc. presented an interesting proposition [47] that could allow exhaustive testing of a small portion of the software radio, reducing certification costs, and might suppress the need for certification of further upgrades. The following subsection presents such proposition and discusses its advantages in the context of SR certification and its impacts on the industry.

### Vanu, Inc.'s certification proposition

Vanu, Inc. filed a proposition to the FCC [47] to overcome the Commission's concerns about certification. This section describes such proposition focusing on the technical background that sustains the proposal and the regulatory changes necessary to support the new scheme.

[40] For the Boeing 777, software test costs were several billions of dollars.

a) Technical Background

The current state of the technology allows designing SR equipment following a two-layered approach (see Figure 48):

- SPU (Signal Processing Unit): The SPU layer takes the user information (voice and data) and transforms it through signal processing to provide the ITU (Independent Transmitter Unit) with a base band or low IF (Intermediate Frequency) version of the RF (Radio Frequency) signal. The SPU software deals with modulation, state machines, transmission timing, power control algorithms and other feature that characterized the communication standard.
- ITU (Independent Transmitter Unit): The ITU layer controls the RF physical parts of the radio. This layer is in charge of generating and amplifying the RF signal from the SPU data stream. ITU can assure the compliance to FCC rules. The layer has a list of the bands, services and power levels allowed by the Commission. When the SPU layer makes a request, the ITU checks that the demand is on the list and generates the RF signal. If the request is not included in the list, the ITU does not take the request into account or even turns off the radio.

Both layers and the hardware used by each of them are totally independent. Vanu, Inc. calls software radios following this approach ITRs (Independent-Transmitter Radios).

This approach presents important benefits for SR certification:

- Simpler certification: SPU software cannot affect RF transmissions. Therefore, only the ITU layer needs to be certified. ITU should be certified in combination with the hardware and the manufacturer will be responsible of the set.
- Higher reliability: The ITU is a small part of the SR software. In consequence, it is less vulnerable to errors and can be more rigorously tested. Many manufacturers may share the same ITU improving the testing across different equipment vendors.

- Higher flexibility: Relaying on ITU, developers can design new SPU layers to implement new services. Since SPU layers would not need certification, users can immediately download the new applications.

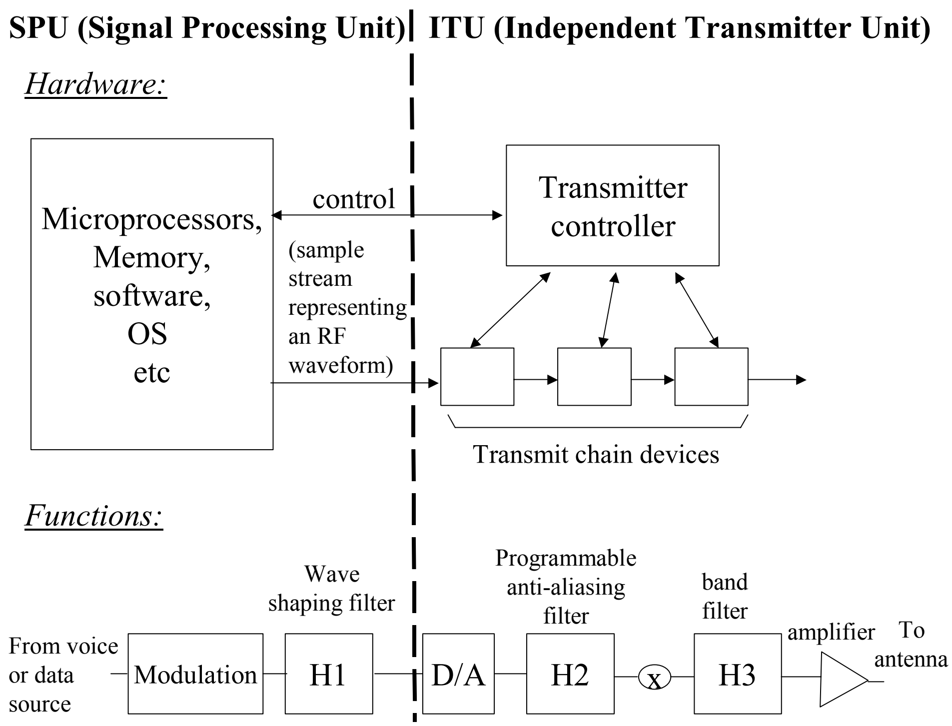



**Figure 48. Architecture and functions of Independent-Transmitter Radios [47].**

a)Regulatory changes

Vanu, Inc. proposes that manufacturers be permitted, not required, to design layered SDRs, where only the ITU layer must be certified.

The changes made on Section 2.1043 (a) by the Commission say:

> "*Changes to the software installed in a transmitter that* ***do not affect the radio frequency emissions*** *do not require a filing with the Commission and may be made by parties other than the holder of the grant of certification.*"

The First Report and Order explains these changes:[41]

> "*This rule is intended to clarify that any party may install* ***software applications*** *on a device that are* ***separate from the software that controls the radio frequency operating parameters****. For example, a wireless device may be designed to run software such as a web browser that does not affect the radio operating parameters*."

Vanu, Inc. considers that SPU software is included in these considerations: this piece of software cannot change RF parameters out of the FCC certification. However, the language is not clear since SPU controls radio frequency operating parameters. Vanu, Inc. proposes the following change to the language of Section 2.1043 (a) to fully include SPU layers:

> "*Changes to the software installed in a transmitter that do not affect* ***its compliance as to*** *the radio frequency emissions do not require a filing with the Commission and may be made by parties other than the holder of the grant of certification.*"

This modification will allow including SPU changes under Class I permissive changes, not requiring a filing to the Commission. Vanu, Inc. proposes an extension to Section 2.1043 (b) (1) (in **bold** and underlined) to fully clarify this point:

> "*A Class I permissive change includes those modifications in the equipment which do not degrade the characteristics reported by the manufacturer and accepted by the Commission when certification is granted. No filing with the Commission is required for a Class I permissive change.* ***An application for certification of a software defined radio may optionally identify software that does not affect the characteristics relied upon by the Commission, any changes to which will qualify as a Class I permissive change.***"

[41] First Report and Order, paragraph 20, note 42.

## 5.3 Long-term FCC policy: Standardization and Spectrum Management

In the long term, the full development of SR capabilities and the wide adoption of the technology will lead to new scenarios related to standardization and spectrum management. Current FCC policies may present barriers to the realization of such scenarios. This section looks into the future and analyzes how SR will affect standardization and spectrum management policies and what are the necessary regulatory changes.

### 5.3.1 Standardization

Standardization is a key issue in the industry for wireless communications. The success of a new service highly depends on the adoption of a common standard across the industry. However, standard selection depends on multiple factors such as performance, players' interests and market share. Countries adopt different regulatory policies to deal with standard selection. SR provides with means to guaranty operation across standards and may relax the need for standardization policies.

The adoption of a common standard across an industry supplies important benefits. First, customers can use the same device in different networks. Second, roaming accords provide seamless operation in the national territory or even in other countries. Third, manufacturers benefit from economies of scale. Fourth, network providers can use compatible equipment from different providers. Nevertheless, the selection and adoption of a common standard is a delicate issue. Controversy arises when trying to select the most performing standard. Manufacturers try to impose proprietary standards to gain market share and license usage rights. The largest vendors and operators use their influence to lobby in favor of particular standards.

Countries have adopted different solutions to deal with standard selection. The two extremes are the Unites States and Europe. On the one hand, the FCC gives the industry the freedom to choose standards. As explained in Section 5.1.2, licenses impose the type of service to be provided but not the standard. On the other hand, the European regulatory authorities impose the standard to be used with a particular license. The results of these policies have been significantly different. In the cellular market for example, while

Europe benefits from full roaming across countries, the United States have a web of networks that use different standards and have roaming problems.

The standardization problem becomes extremely important with the third generation (3G) of wireless communications. Three main versions of 3G have been developed (see Section 4.2.1 and Figure 23). The world interoperability of this powerful and expensive generation of wireless communications is in danger. In the international arena, no regulator has power to impose a standard. The different players recognize the benefits of adopting a common standard but do not want to lose the advantages of imposing their own version.

SR offers the capabilities to make standard selection unnecessary. Since the same piece of equipment may operate over different standards through software upgrades, a common standard is not needed any more. Manufacturers may develop different solutions without affecting the interoperability of the industry. The 3G discussion will not need to go on and each country will be free to develop its own 3G version.

### 5.3.2 Spectrum management

SR capacity to operate over new bands and standards through software upgrades allows a more flexible and efficient use of spectrum. Network deployment with SR technology demands lower deployment and operation costs per standard, reducing entry barriers (see results in Section 4.2.5). Such properties may have important consequences on spectrum management, discussed along this section. First, SR may *promote the use of spectrum by the most valuable services* and *affect current licensing procedures*. Second, software radios provide *means for the implementation of secondary markets for spectrum* and the *extension of the Amateur radio and Part 15 devices models to a broader set of services*.

#### Most valuable services and licensing procedures

As explained in Chapter 4, entry barriers are reduced when using SR technology. Spectrum becomes a more flexible resource because operators can more easily and less expensively offer different services. For example, a professional network using SR infrastructure, like a taxi company, holding a license for a particular band and having excess of capacity, could inexpensively upgrade its network through software to offer services to other professional groups. Thus, a medical care unit operating over a different standard in the same band and having a deficit of capacity could buy service from the taxi company. This scenario promotes efficient use of spectrum since the taxi company spectrum is less likely to rest unused for long times when serving the medical care unit. Lower entry barriers induce operators to move to the most demanded services, and therefore, the most valuable. The taxi company will be willing to migrate its spectrum from medical care standards to more demanded services like enforcement units communications if higher prices are paid.

These new scenarios will be possible only if licensing policies change. As explained in Section 5.1.2, current US licenses specify the type of service to be provided. More restricted are European licenses that require particular standards. Licenses should give enough freedom to their grantees to move to other services as demand change.

Licensing problems also arise from the separation that is taking place between network operation and service provision, discussed in Section 4.2.3. Network operators rent capacity to service providers (VMNOs), which sell final services to customers. Competition in service provision is improved. SR encourages this scenario and makes possible for operators to offer capacity in different bands and standards over the same physical network (see Chapter 4). Under the current licensing system, operators must hold a license to supply network capacity in a particular band and are obligated to deploy infrastructure to cover a percentage of the surface and people included in the license before a certain deadline. With SR infrastructure, they do not need to deploy new infrastructure to extend their business to other portions of the spectrum but they have to buy a license per new band.

Buying several licenses may create problems. First, the price of a license may be high (see Table 3 for 3G licenses prices). The need of buying multiple licenses could discourage operators from adopting this model and decrease competition in service provision. Second, this scenario favors market power since substantial parts of spectrum are concentrated in a single player, the network operator. The option of licensing the service provider instead of the network operator could solve both problems. The grant of service providers reduces spectrum investment to a fewer number of licenses per player and decreases the concentration of spectrum. Nevertheless, this option is not available under current licensing since the grantee must deploy its own infrastructure.

Secondary markets

SR provides the means for the implementation of secondary markets for spectrum. Secondary markets allow the original licensee to sell spectrum to third parties. Even more, the original licensee could rent spectrum to third parties for space of days, months or years. Legally, the regulatory ban to sell spectrum have avoided the creation of these markets. In practice, the time and cost required to deploy a new network with traditional technology have made impossible the implementation of secondary markets. A traditional operator requiring extra capacity during one month for an sportive event, for example, is not likely willing to rent additional spectrum in other bands since it has to deploy new sites at high cost and time. With SR technology, the operator can use its own sites and upgrade them through software to run over the new bands. SR allows spectrum to be more fungible, which increases market liquidity.

Spectrum management models

SR capabilities favor the expansion of less restrictive spectrum management models like “Amateur Radio” and “Part 15 devices” (see Section 5.1.2 and Appendix C). The main limitation to extend these models today to wider applications is the human control that they require. Operators are responsible for monitoring the band and stopping transmission if causing interferences. SR provides the means for automatic control. Future software radios generations are expected to monitor the environment and select the most appropriate service at a given moment. If the radio detects interferences, it can rapidly move to other bands and standards to assure the communication. These functions permit a more accurate control of interferences and the co-operation of multiple systems.

# Chapter 6. Conclusions

This thesis studied the impact of SR technology on wireless communications. This chapter summarizes the conclusions of such study and provides directions for further research.

## 6.1 Summary

Traditional radios present important drawbacks that slowdown the development of wireless technologies. Their hardware-oriented approach causes low flexibility to adapt to new services and standards, long times and high costs for the development and manufacturing of new products and limits the number of services that can be provided over the same radio. SR proposes a software-oriented approach that may remove most of these problems.

### 6.1.1 New capabilities

In software radios, signal-processing software running over general-purpose processors carries out all the radio functions. This new architecture provides highly attractive capabilities like:

- multi-operation over different standards and services,
- dynamic adaptation to the environment,
- lower development and manufacturing times and costs,
- reduced risk of obsolescence and
- improved marketing channels through in field upgrade and remote and over the air download.

### 6.1.2 Applications

SR was born as a military technology and, still today, the military is the fist adopter and driver. Nevertheless, SR capabilities fulfill the needs of numerous wireless segments and may find applications in such heterogeneous fields like:

- the military,
- the automobile industry,
- law enforcement,
- the wireless infrastructure segment,
- emergency forces,
- mass-market communication devices,
- other transportation industries and
- mass-market electronics.

The realization of such scenarios will depend on the degree of development of SR (see Figure 17). After the military, the automobile industry and law enforcement groups are the most likely early adopters. In the near future, SR might find application in the wireless infrastructure industry and among emergency forces. Further in time, mass-market communication devices and other transportation industries may adopt software radios. Mass-market consumer electronics might be a sector of application for SR in the far future.

### 6.1.3 Technical limitations to SR

SR is a still young technology in face of development. Today, SR presents limitations originated by the state of the art of other technologies, mainly analog to digital converters (A/D) and semiconductors. Even if RF digitalization stands as the most beneficial approach, A/D limits in speed and resolution obligate SR designers to adopt an intermediate architecture, IF digitalization, at cost of flexibility. On the semiconductor side, programmable ASICs and DSPs are being developed to fulfill the high computational requirements of software radios. These new processors may implement some of the first SR designs. However, future software radios are likely to make increasing use of general-purpose processors like the CPUs used in PCs. Other limitations arise from linear amplification over wide bands and cost for three of fewer standards. SR devices are further limited by battery life.

### 6.1.4 Industry impact

SR may not only modify radios' capabilities and applications but also change the industry structure. SR will disrupt the traditional relationship between semiconductor producers and radio equipment/handset manufacturers, the lowest layers of the value chain. First, general-purpose processors will capture market share from dedicated semiconductors. Second, traditional radio equipment and device manufacturers will find themselves increasingly competing against general-purpose platforms vendors, operating system designers and software programmers.

Such changes may deeply affect the upper layers of the different wireless segments. In the case of the cellular industry, SR might reduce deployment costs in at least 33% per standard and operation costs in at least 47% per standard and year, promote the separation of network operation and service provision, modify the business model of players like site owners and improve national and international roaming. In the long-term, competition will increase, in the benefit of final consumers. In the short-term, SR will induce a migration of market power from semiconductor and equipment manufacturers towards network providers and final consumers.

### 6.1.5 Regulation

SR threatens the business model of traditional vendors, who could exercise high pressure to stop SR adoption. In this context, regulators become fundamental players whose role should be to promote the development and adoption of SR technology through their policies. In the short-term, current FCC certification rules (bundle of hardware and software and third parties certification rights) may damage the adoption and development of software radios. In the long-term, SR will guarantee operation across standards and may relax the need for standardization policies. Also in the long-term, software radios may affect spectrum management policies. First, SR may promote the use of spectrum by the most valuable services and allow lightening up licensing procedures in terms of provided service. Second, software radios supply resources for the implementation of secondary markets for spectrum and the extension of the Amateur radio and Part 15 devices models to broader sets of services.

## 6.2 Further research

Several SR related issues have not been discussed with extreme detail due to the scope of this work. This section lists such topics and provides directions for further research.

### 6.2.1 SR likely players

As explained in Chapter 4, SR will modify the wireless industry structure and promote the entrance of new players, mainly general-purpose processor manufacturers, OS designers, software programmers and hardware platforms vendors. This thesis provided some examples of new entrants. However, further research may try to identify likely SR players through an analysis of how existing companies such as Intel or Compaq could adapt their business models to fit the SR industry structure.

### 6.2.2 SR impact on spectrum management models

Chapter 5explained how, in software radios, control might be transferred from humans to radios and interference management become more efficient. Such transfer may allow the extension of flexible spectrum management models like Amateur Radios and Part 15 devices to a wider set of services. Further work should imagine specific scenarios to take advantage of such new capability.

### 6.2.3 Software certification

Chapter 5 makes a high level revision of the software certification techniques currently used in other industries. Further research should be done on this matter in order to evaluate the degree of certainty that can be achieved in software certification and its costs. Such study will allow better assessing propositions like the one filed by Vanu, Inc. (see Section 5.2.4) and designing specific policies in the matter of SR certification.

# Appendix A. Radio principles.

The objective of this appendix is to give a more detailed view of the elements and functions of a traditional radio chain (see Figure 2), explained in Section 2.1. The first section gives a high level overview of modulation principles. The second section explains the most extended scheme of traditional radios, the superheterodyne transceiver, and uses the straightforward example of an AM superheterodyne receiver to illustrate basic radio concepts like modulation and intermediate frequency (IF). Finally, the third section reproduces the schemes of the two SR architectures (RF and IF digitalization) presented in Section 2.3 for the particular case of an AM receiver.

### I. Modulation principles

Wireless communication signals are radio waves, usually in the MHz and more recently GHz bands, in which information has been inserted through the modification of one or several of the following wave parameters: amplitude (AM modulation), frequency (FM modulation) and/or phase. This process is called modulation. The opposite operation, extracting the inserted information, is named demodulation.

Figure 49 exhibits an example of the simplest type of modulation, the amplitude modulation (AM). A voice signal, situated at frequency zero (baseband), and a carrier of frequency $f_{RF}$ are multiplied. Such multiplication has two effects. In the time domain, the amplitude of the carrier changes with the information signal. At reception, the changes in the amplitude of the carrier will be detected and information recovered. In the frequency domain, the information signal moves from baseband to the carrier frequency ($f_{RF}$). This effect allows transmitting radio waves over longer distances because high frequencies have less propagation attenuation than low frequencies. Figure 49 shows the original signals and the modulation effects in the time domain and in the frequency domain.

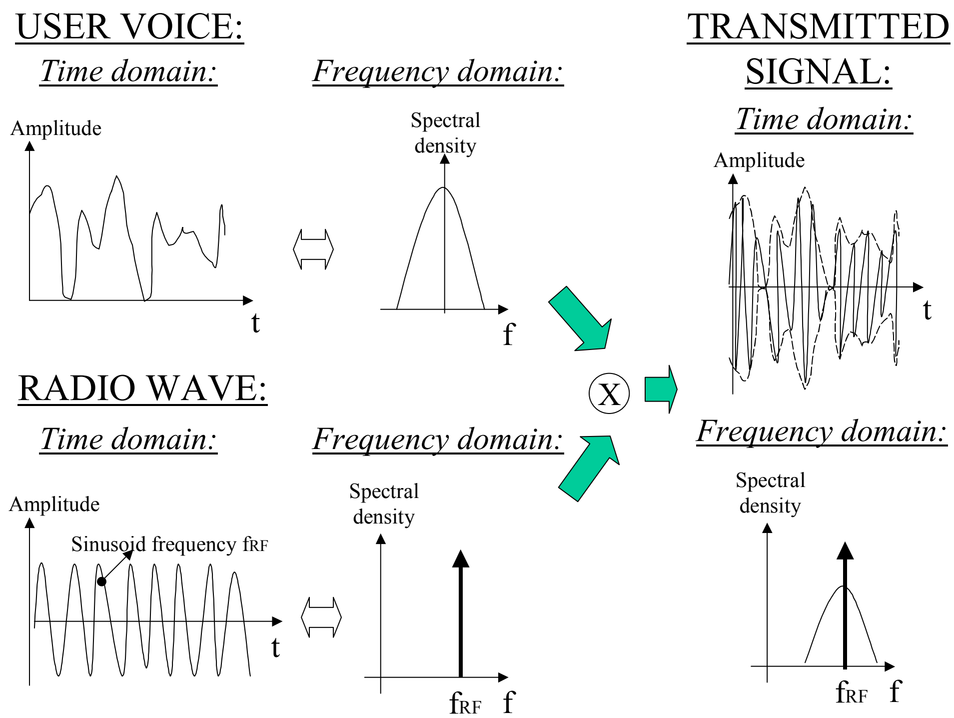



**Figure 49. Radio principles: Amplitude Modulation (AM).**

### II. The superheterodyne receiver

The transmitted signal is detected at the receiver and the information is extracted. Most traditional radio systems use a superheterodyne receiver to carry out this operation. Figure 50 describes this process for the case of an AM receptor. Figure 2 already illustrated how demodulation takes place in traditional radios but Figure 36 details the elements inside the functional boxes of Figure 2 and the signal treatment carried out along the hardware chain.

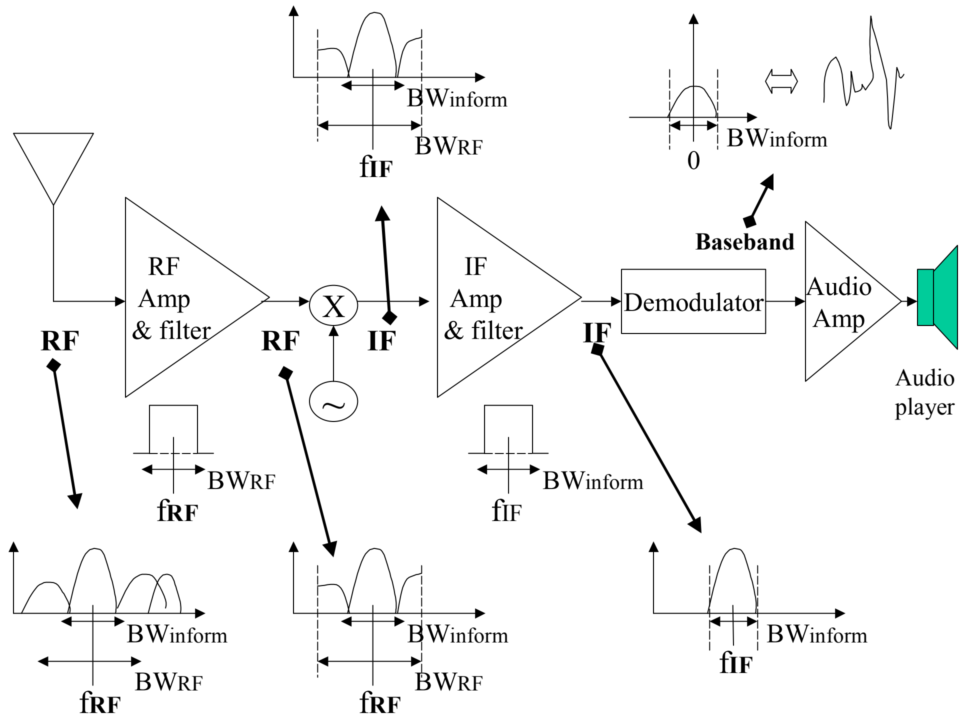


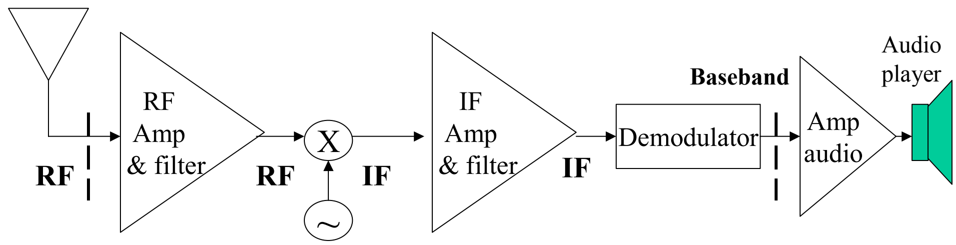

**Figure 50. Traditional superheterodyne receptor.**

As explained for Figure 2, the antenna collects the RF signal, which is amplified and roughly limited in bandwidth by an RF amplifier (see Section 2.1). The signal is filtered to eliminate interferences but building accurate tunable filters is difficult and expensive. In consequence, the signal is moved to an intermediate frequency (IF), where high-quality inexpensive filters are available. Finally, the user information is demodulated to recover the original signal (see previous section), amplified and sent to an audio player.

## III. SR architectures for an AM receiver

The figures of this subsection apply the SR architectures presented in Figure 6 (SR receiver with RF digitalization) and Figure 7 (SR receiver with IF digitalization) for the example of an AM receiver. Actual components replace in this example the functional blocks.

## Traditional superheterodyne receiver




## SR receiver: RF digitalization

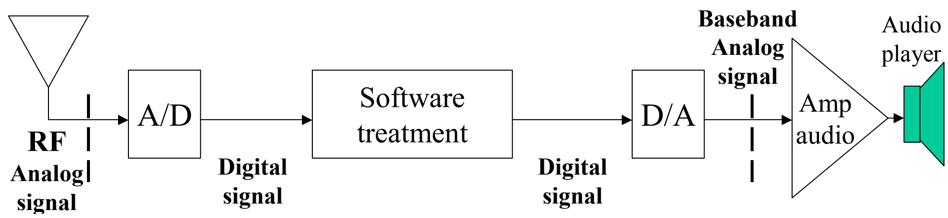
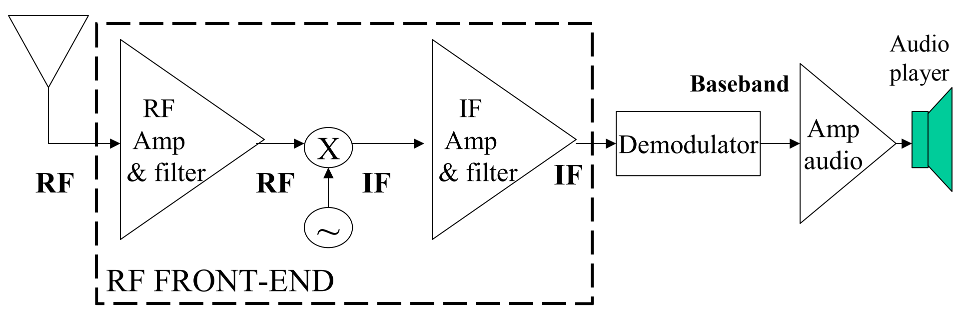



**Figure 51. Traditional superheterodyne AM receiver versus SR receiver with RF digitalization.**

## Traditional superheterodyne receiver




## SR receiver: IF digitalization

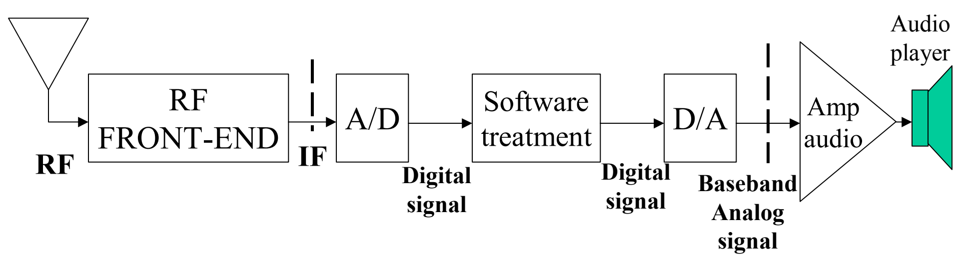



**Figure 52. Traditional superheterodyne AM receiver versus SR receiver with IF digitalization.**

# Appendix B. Cost model

This appendix summarizes the data used to run the cost model (see I and II) and provides an example of dimensioning, equipment and cost evaluation for four standards (see III). The sources of these data are personal relations and experience in the industry. Changing the cost model data entries will change absolute deployment and operation costs (Figure 42, Figure 43, Figure 44 and Figure 45) but may only slightly affect the comparison between the three architectures (Table 9 and Table 10).

### I. Dimensioning data

This section covers the data used in both dimensioning process, by area and capacity. The data contained in this section provides from public sources [81] and personal contacts in the industry. The following paragraphs review each of the data types:

- General assumptions

As explained in Section 4.2.5, the cell size depends on the frequency of propagation. Assuming the cells are perfect hexagons, the distance inter-site fixes the size of the cell. However, the distance inter-site is also dependant on the type of service to provide in the area. Table 13 covers the distance inter-site for the most common combinations of morphology and coverage service at 900 MHz and 1900 MHz.

**Table 13. Inter-site distance in meters.**

| Morphology | Coverage Service | 900 MHz | 1900 MHz |
|---|---|---|---|
| Dense Urban | Deep Indoor | 800 | 500 |
| Urban | Indoor Daylight | 1600 | 1100 |
| Suburban | Indoor Window | 5000 | 2100 |
| Flat rural | Outdoor | 14000 | 10000 |
| Hilly rural | Outdoor | 5000 | 7000 |
| Roads | Incar | 140000 | 10000 |

- Geographic and demographic data

Geographic and demographic data refer to three kinds of information: population, morphology and penetration rates (see Section 4.2.5). Given population and surface information about Massachusetts' counties (see Table 14), the US Census bureau criteria [90] have been followed to define morphologic levels:

- Dense Urban: Any area with a density of at least 10,000 people per square mile.
- Urban: Any area with a density between 1,000 and 10,000 people per square mile.
- Rural: Any area with a density less than 1,000 people per square mile.

**Table 14. Area, density and population in Massachusetts counties.**

| Area Name (in 1990) | Land Area ($Mi^2$) | Density ($Pop/Mi^2$) | Population (4/1/90) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Total | Urbanized Area | Other Urban | Rural | % Rural |
| | | | | | | | |
| **Massachusetts** | 7838,0 | 767,6 | 6 016 425 | 4 730 382 | 339 221 | 946 822 | 15,7% |
| | | | | | | | |
| **Barnstable County** | 395,8 | 471,5 | 186 605 | 66 713 | 48 234 | 71 658 | 38,4% |
| **Berkshire County** | 931,4 | 149,6 | 139 352 | 55 047 | 30 754 | 53 551 | 38,4% |
| **Bristol County** | 556,0 | 910,6 | 506 325 | 424 151 | - | 82 174 | 16,2% |
| **Dukes County** | 103,8 | 112,1 | 11 639 | - | - | 11 639 | 100,0% |
| **Essex County** | 498,1 | 1345,4 | 670 080 | 565 747 | 38 998 | 65 335 | 9,8% |
| **Franklin County** | 702,1 | 99,8 | 70 092 | - | 22 538 | 47 554 | 67,8% |
| **Hampden County** | 618,5 | 737,7 | 456 310 | 401 817 | 10 427 | 44 066 | 9,7% |
| **Hampshire County** | 529,0 | 277,1 | 146 568 | 62 885 | 35 649 | 48 034 | 32,8% |
| **Middlesex County** | 823,5 | 1698,1 | 1 398 468 | 1 282 066 | 7 062 | 109 340 | 7,8% |
| **Nantucket County** | 47,8 | 125,8 | 6 012 | - | 3 069 | 2 943 | 49,0% |
| **Norfolk County** | 399,6 | 1541,7 | 616 087 | 573 356 | 4 535 | 38 196 | 6,2% |
| **Plymouth County** | 660,6 | 658,9 | 435 276 | 226 610 | 39 435 | 169 231 | 38,9% |
| **Suffolk County** | 58,5 | **11345,2** | 663 906 | 663 906 | - | - | 0,0% |
| **Worcester County** | 1513,2 | 469,0 | 709 705 | 408 084 | 98 520 | 203 101 | 28,6% |
| | | | | | | | |
| **Densely Urban:** | 58,5 | 11345,2 | 663 906 | | | | |
| **Urban:** | 3051,0 | 1444,0 | 4 405 697 | | | | |
| **Rural** | 4787,0 | 197,8 | 946 822 | | | | |
| | | | | | | | |
| | | | | | | | |
| **Dimensioning Data Definitions** | | | | | | | |
| Dense Urban: greater than 10,000 people per square mile. | | | | | | | |
| Urban: greater than 1,000 people per square mile. | | | | | | | |
| Rural: less than 1,00 people per square mile. | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| **Massachusetts** | | | | | | | |
| **Roads** | **Total Miles** | **Urban** | **Rural** | | | | |
| | 35 254 | 23 061 | 12 193 | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| *http://www.stateline.org/fact.cfm?FactID=722 | | | | | | | |

Under these criteria, Massachusetts has counties which are 100% rural such as Dukes County and counties which are 100% urban, Suffolk County - moreover, Suffolk County is not just urban but densely urban with a population density of over 10,000 people per square mile. Massachusetts' towns follow a similar pattern: downtown with business centers and shopping areas surrounded by residential areas, mainly composed by small houses. Propagation conditions can be easily approximated to dense urban for downtown areas and suburban for residential areas.

As already explained, operators do not cover the whole area but only zones with higher density. Table 15 summarizes the morphological levels and the percentage covered in the cost model scenario.

**Table 15. Area distribution and covered area in Massachusetts.**

| Morphology | Total area (Km2) | % Covered area | Covered area (Km2) |
|---|---|---|---|
| Densely Urban | 151 | 90% | 136 |
| Urban | 7,902 | 32% | 2,528 |
| Rural | 12,398 | 5% | 619 |
| Road | 56,406 | 4% | 2,256 |

Penetration rates accounts the percentage of the population that has a cellular phone in the covered area. Population numbers include children, old people and other people not using cellular phones. Table 16 shows the assumptions for the Massachusetts scenario.

**Table 16. Penetration rates per morphology.**

| Morphology | Penetration rate (%) |
|---|---|
| Densely Urban | 38% |
| Urban | 8% |
| Rural | 1% |

- Quality of service

The quality of service chosen for each morphological area is summarized in Table 17.

**Table 17. Quality of service for Massachusetts.**

| Morphology | Coverage Service |
|---|---|
| Dense Urban | Deep Indoor |
| SubUrban | Indoor Window |
| Flat rural | Outdoor |
| Roads | Incar |

- <u>Traffic data</u>

Business and residential users generate different amount of traffic are differently distributed across regions. Table 18 and shows traffic values while Table 19 summarizes their geographic distribution.

**Table 18. Traffic generated per user.**

| User type | Traffic per user (mErlangs at the busy hour) |
|---|---|
| Business | 25 |
| Residential | 15 |

**Table 19. User segmentation per morphology in Massachusetts.**

| Morphology | Business % | Residential % |
|---|---|---|
| Dense Urban | 20% | 80% |
| Urban | 1% | 99% |
| Flat rural | 0% | 100% |

- <u>Network quality</u>

The cost model has been run with a blocking probability of 0.02, which is a value commonly used in real cellular networks.

## II. Equipment and cost data

Equipment and cost data contained in this section were mainly obtained through personal contacts in the cellular industry and the reference [36]. Table 20 summarizes the values used to run the cost model.

**Table 20. Equipment and cost data.**

**EQUIPMENT AND COST DATA**

**Deployment costs:**

***RA (US$/unit)***

| | Traditional Tecnology | Software Radio |
|---|---|---|
| Site | $143,000 | $143,000 |
| Base Station (BTS)* | $56,000 | $60,000 |
| 1 pair of frequences (TRX) | $1,000 | $4,000 |
| 1 Antenna | $2,500 | $2,500 |

** A traditional BTS with 12 TRXs costs $68,000*
** A SR BTS with 12 TRXs could cost $108,000 (source Lehman Brothers &Telefonica)*

***CN (US$/unit)***

| | Traditional Tecnology |
|---|---|
| 120 TRX Base Station Controller | $3,000,000 |
| 2500 Erlangs Switching Center | $318,000 |
| Authentication center | $500,000 |
| Operation center | $500,000 |
| Billing center | $500,000 |

**Operation costs:**

***Technical maintenance (US$/year)***

| | Traditional Tecnology | Software Radio** |
|---|---|---|
| Total Maintenance | $23,200,826 | $23,200,826 |

| | % Total Network Maintenance |
|---|---|
| RA Maintenance | 90 |
| CN Maintenance | 10 |

*** RA maintenance costs could be reduced with SR technology but, for simplicity, they are assumed the same*

***Rent (US$/year)***

| | Traditional Tecnology |
|---|---|
| Site | $12,000 |

## III. Cost model

This section covers an example of dimensioning, equipment calculation and cost evaluation for the case of four different standards in each of the three architectures presented in Section 4.2.5.

### III. 1. Area and capacity dimensioning

Table 21 shows the dimensioning worksheet for the cellular network. The shaded cells correspond to data. The white cells are calculated automatically from the entry data. A macro carries out the Erlang Law to check the capacity dimensioning.

**Table 21. Area and capacity dimensioning.**

**DIMENSIONING**

**AREA DIMENSIONING**

| Morphology | Coverage Service | Inter-site distance (m) | Site Area (km²) |
|---|---|---|---|
| Dense Urban | Deep Indoor | **490** | 0.208 |
| SubUrban | Indoor Window | **1900** | 3.126 |
| Flat rural | Outdoor | **8000** | 55.426 |
| | | | **Site distance (km)** |
| Roads | Incar | **10000** | 10.000 |

| Morphology | Area (km²) | Number of tri-sector sites |
|---|---|---|
| Dense Urban | 136.4067 | 657 |
| SubUrban | 2528.6688 | 809 |
| Flat rural | 619.9165 | 12 |
| | **Distance (km)** | **Number of Bi-sector sites** |
| Roads | 2256.26 | 226 |

| | |
|---|---|
| Total tri-sector sites: | **1478** |
| Total bi-sector sites: | **226** |
| **TOTAL SITES:** | ***1704*** |

**CAPACITY DIMENSIONING**

| | |
|---|---|
| MARKET | 614209 |
| SIMULTANEOUS USERS | 0.95 |

| Users segmentation | Business | Residential | Business % | Residential % | Market % |
|---|---|---|---|---|---|
| Dense Urban | 47934.0132 | 191736.0528 | 20 | 80 | 41.1 |
| SubUrban | 3348.32972 | 331484.6423 | 1 | 99 | 57.4 |
| Flat rural | 0 | 8995.512 | 0 | 100 | 1.54 |
| | | | | | 100 |
| Roads | 67 | 6630 | | | |

| Traffic/user (Erlang at busy hour) | Business | Regular |
|---|---|---|
| Dense Urban | 0.025 | 0.015 |
| SubUrban | 0.025 | 0.015 |
| Flat rural | 0.025 | 0.015 |

| Total traffic (Erlang) | |
|---|---|
| Dense Urban | 4074.4 |
| SubUrban | 5056.0 |
| Flat rural | 134.9 |
| Roads | 101.1 |

| | Traffic/site (Erlang) | Nb frequencies |
|---|---|---|
| Dense Urban | 6.20 | **12** |
| SubUrban | 6.25 | **12** |
| Flat rural | 11.24 | **8** |
| Roads | 0.45 | **3** |

| | |
|---|---|
| BLOCKING PROBABILITY: | 0.02 |

### III. 2. Equipment calculation and cost evaluation

The following set of three worksheets cover equipment calculation and cost evaluation for the three architectures and four standards.

## ARCHITECTURE 1: TRADITIONAL BASE STATIONS AND INDEPENDENT CNs

### COSTS

| | |
|---|---|
| NUMBER OF STANDARDS | 4 |

| | Total cost (US $) | Cost/standard (US $) |
|---|---|---|
| Deployment costs | $1,756,728,000 | $439,182,000 |
| Operation costs (per year) | $174,595,305 | $43,648,826 |

### NETWORK DEPLOYMENT COSTS

**I. RAN (Radio Access Network)***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Site | 1704 | 143,000 | 243,672,000 |
| Base Station | 1704 | 56,000 | 95,424,000 |
| 1 pair of frequences (TRX) | 18366 | 1,000 | 18,366,000 |
| Antennas (1 set of 3 antennas) | 5112 | 2,500 | 12,780,000 |
| | | Total: | **370,242,000** |

**II. CN (Core Network)***

**II.1. Base Station Controller**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 120 TRX Base Station Controller | 154 | 360,000 | 55,440,000 |
| | | Total: | **55,440,000** |

**II.2. Switching Center - Gateway function**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 2500 Erlangs Switching Center | 4 | 3,000,000 | 12,000,000 |
| | | Total: | **12,000,000** |

**II. Application layer***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Authentication center | 1 | 500,000 | 500,000 |
| Operation center | 1 | 500,000 | 500,000 |
| Billing center | 1 | 500,000 | 500,000 |
| | | Total: | **1,500,000** |

| | |
|---|---|
| **DEPLOYMENT COST (US$):** | **439,182,000** |

** Prices include software licenses.*

### RAN OPERATION COSTS (per year)

**I. TECHNICAL MAINTENANCE**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Network Maintenance | 1 | 20,880,744 | 20,880,744 |
| | | Total: | **20,880,744** |

**II. RENTS**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Sites | 1704 | 12,000 | 20,448,000 |
| | | Total: | **20,448,000** |

| | |
|---|---|
| **RAN OPERATION COST (US$/year):** | **41,328,744** |

### CN OPERATION COSTS (per year)

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| CN Maintenance | 1 | 2,320,083 | 2,320,083 |
| | | Total: | **2,320,083** |

| | |
|---|---|
| **CN OPERATION COST (US$/year):** | **2,320,083** |

## ARCHITECTURE 2: SR BASE STATIONS AND INDEPENDENT CNs

### COSTS

| | |
|---|---|
| NUMBER OF STANDARDS | 4 |

| | Total cost (US $) | Cost/standard (US $) |
|---|---|---|
| Deployment costs | $764,256,000 | $191,064,000 |
| Operation costs (per year) | $50,609,074 | $12,652,269 |

### NETWORK DEPLOYMENT COSTS

**I. RAN (Radio Access Network)***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Site | 1704 | 143,000 | 243,672,000 |
| Software Radio Base Station Hardware | 1704 | 60,000 | 102,240,000 |
| 1 pair of frequences (TRX) | 18366 | 4,000 | 73,464,000 |
| Antennas (1 set of 3 antennas per standard) | 20448 | 2,500 | 51,120,000 |
| | | **Total:** | **470,496,000** |

| | |
|---|---|
| **RAN DEPLOYMENT COST (US$):** | **470,496,000** |

**II. CN (Core Network)***

**II.1. Base Station Controller**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 120 TRX Base Station Controller | 154 | 360,000 | 55,440,000 |
| | | **Total:** | **55,440,000** |

**II.2. Switching Center - Gateway function**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 2500 Erlangs Switching Center | 4 | 3,000,000 | 12,000,000 |
| | | **Total:** | **12,000,000** |

| | |
|---|---|
| **CN DEPLOYMENT COST (US$):** | **269,760,000** |

**II. Application layer***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Authentication center | 4 | 500,000 | 2,000,000 |
| Operation center | 4 | 500,000 | 2,000,000 |
| Billing center | 4 | 500,000 | 2,000,000 |
| | | **Total:** | **6,000,000** |

| | |
|---|---|
| **APPLICATION LAYER DEPLOYMENT COST (US$):** | **24,000,000** |

** Prices include software licenses.*

### RAN OPERATION COSTS (per year)

**I. TECHNICAL MAINTENANCE**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Base Station Subsystem Maintenance | 1 | 20,880,744 | 20,880,744 |
| | | **Total:** | **20,880,744** |

**II. RENTS**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Sites | 1704 | 12,000 | 20,448,000 |
| | | **Total:** | **20,448,000** |

| | |
|---|---|
| **RAN OPERATION COST (US$):** | **41,328,744** |

### CN OPERATION COSTS (per year)

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| CN Maintenance | 1 | 2,320,083 | 2,320,083 |

## ARCHITECTURE 3: SR BASE STATIONS AND SHARED CN

### COSTS

| NUMBER OF STANDARDS | 4 |
|---|---|

| | Total cost (US$) | Cost/standard (US$) |
|---|---|---|
| Deployment costs | $561,936,000 | $140,484,000 |
| Operation costs (per year) | $43,648,826 | $10,912,207 |

## NETWORK DEPLOYMENT COSTS

**I. RAN (Radio Access Network)***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Site | 1704 | 143,000 | 243,672,000 |
| Software Radio Base Station Hardware | 1704 | 60,000 | 102,240,000 |
| 1 pair of frequences (TRX) | 18366 | 4,000 | 73,464,000 |
| Antennas (1 set of 3 antennas per standard) | 20448 | 2,500 | 51,120,000 |
| | | **Total:** | **470,496,000** |

| RAN DEPLOYMENT COST (US$): | 470,496,000 |
|---|---|

**II. CN (Core Network)***

**II.1. Base Station Controller**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 120 TRX Base Station Controller | 154 | 360,000 | 55,440,000 |
| | | **Total:** | **55,440,000** |

**II.2. Switching Center - Gateway function**

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| 2500 Erlangs Switching Center | 4 | 3,000,000 | 12,000,000 |
| | | **Total:** | **12,000,000** |

| CN DEPLOYMENT COST (US$): | 67,440,000 |
|---|---|

**II. Application layer***

| | Number of Units | Price per unit (US $) | Total (US $) |
|---|---|---|---|
| Authentication center | 4 | 500,000 | 2,000,000 |
| Operation center | 4 | 500,000 | 2,000,000 |
| Billing center | 4 | 500,000 | 2,000,000 |
| | | **Total:** | **6,000,000** |

| APPLICATION LAYER DEPLOYMENT COST (US$): | 24,000,000 |
|---|---|

** Prices include software licenses.*

## RAN OPERATION COSTS (per year)

**I. TECHNICAL MAINTENANCE**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Base Station Subsystem Maintenance | 1 | 20,880,744 | 20,880,744 |
| | | **Total:** | **20,880,744** |

**II. RENTS**

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| Sites | 1704 | 12,000 | 20,448,000 |
| | | **Total:** | **20,448,000** |

| RAN OPERATION COST (US$): | 41,328,744 |
|---|---|

## CN OPERATION COSTS (per year)

| | Number of Units | Price per unit (US $/year) | Total (US $/year) |
|---|---|---|---|
| CN Maintenance | 1 | 2,320,083 | 2,320,083 |

# Appendix C. Spectrum management schemes

This appendix describes a four-category classification that summarizes the spectrum management schemes result of (1) current FCC policies and (2) the state of the art of wireless technology. The four categories are broadcast, mobile communications, amateur radio and Part 15 devices. These titles correspond to the most relevant service of each category but any other wireless service can be classified under the model.

## I. Broadcast

Broadcast licenses have exclusive rights of utilization over a portion of spectrum and a geographic area. Only one licensee can operate on each channel. FCC limitations on transmitted power over main and adjacent bands avoid interferences between broadcast services. Even unlicensed devices (see Subsection IV) are forbidden to operate on these bands.

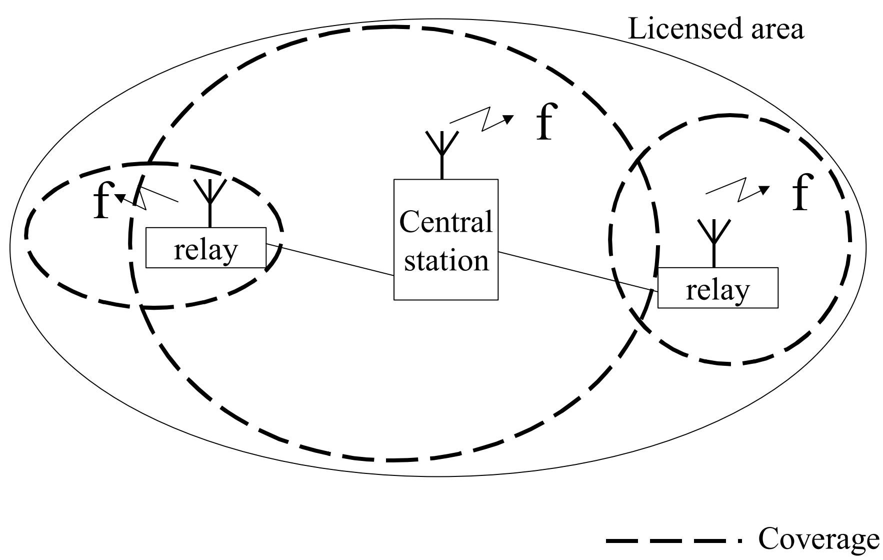



**Figure 53. Broadcast interference management model.**

The management interference model resulting from this policy is simple. The radio stations of broadcast licensees transmit at the maximum power level permitted by the FCC. Operation at maximum levels requires fewer radio stations and therefore, lower costs. On borders with other licensed areas, power may be reduced to avoid interferences with radio stations operating in the same or adjacent bands. In general, radio stations are divided in a main emission center and several relays dedicated to areas of difficult coverage such as zones masked by mountains. Since all radio stations broadcast the same signal, coverage overlapping is not a problem (see Figure 53).

## II. Mobile Communications

Mobile communications licenses grant utilization rights over a portion of spectrum and a geographic area. Similarly to the rest of wireless services, the FCC limits the maximum power that mobile equipment can radiate. As seen in the previous section, this regulatory framework is enough to avoid interferences in broadcasting services. This is not the case for mobile communications. Base stations transmit several users' voice and data over the same portion of spectrum. Information overlaps at the receiver and is lost. The standards for mobile communications have adopted different solutions to avoid this problem. The most popular standards follow two strategies: FDMA/TDMA and CDMA multiplexing techniques.

### FDMA/TDMA

FDMA/TDMA systems are widely extended. The European GSM and the American D-AMPS standards belong to this group. The licensed band is divided in smaller channels. The geographic area is separated in portions called cells. Each cell contains a base station. Base stations power is lowered to confine emissions to the size of the cell. Channels are reused in separated cells. In this way, a base station or a user handset never receives different information over the same channel (see Figure 54). When TDMA techniques are superposed to FDMA multiplexing, a user does not transmit continuously but during specific intervals of time.

Two parameters determine receivers' capacity (radio stations and mobile stations) to correctly recover information. First, the signal (C) must have a minimum level. This level is called *sensibility* of the receiver (S). Second, the signal C must be stronger than the sum of noise and interferences (No + I) at the reception point. This parameter is called *signal to interference* (C/I) relationship. In general, noise (No) is a less limiting factor than interferences on FDMA/TDMA systems. Usually, No is not taken into account on calculations. The most limiting condition is C/I. This parameter is especially critical on the edge of the cell. In this area, the interferences (I) are more important and the base station signal is less strong. In consequence, the C/I value is very low and reception quality degrades.

FDMA/TDMA systems are designed for the worst case. Assumed full operation, i.e., all frequencies and cells are operating simultaneously, engineers design the network to present at least minimum C/I and S levels in every point of the network. Because the edge limiting conditions explaining in the above paragraph, this design is reduced to guaranty C/I and S conditions on the edge of the cells. Typical values of C/I for GSM are between 9 and 12 dB.

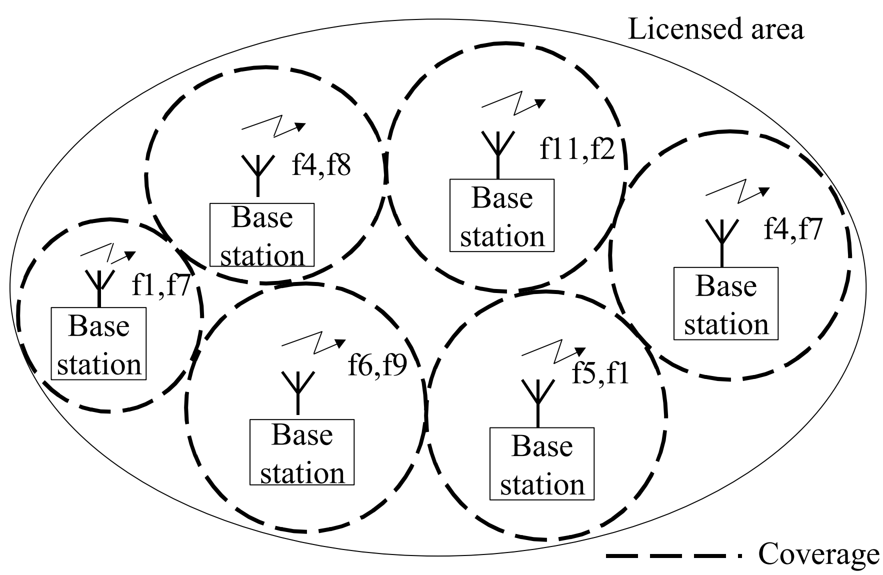



**Figure 54. FDMA/TDMA interference management model.**

<u>CDMA</u>

CDMA systems are broadly implemented in America. The most extended standard is IS-95. CDMA techniques are also being used for the development of the third generation of mobile communications (3G). A geographic area is divided in cells. Each cell contains a base station. Base stations power is lowered to confine emissions to the size of the cell.

Every cell and user operates over the same frequency. A user's signal is multiplied by a sequence of small pulses called chips. This operation has the property of expanding the energy of the signal over a wider band. The signal is spread. The resulting signal has lower spectral density (energy per unit of spectrum) and can be confused with noise. When the same code is applied again, the signal recovers its original appearance and can be easily received. The signal is despread. Chips sequences correspond to mathematical codes with special properties. The most important property is orthogonality. Thanks to this property, two signals spread with different codes over the same band can be recovered at reception. Codes are spatially reused along cells (see Figure 55).

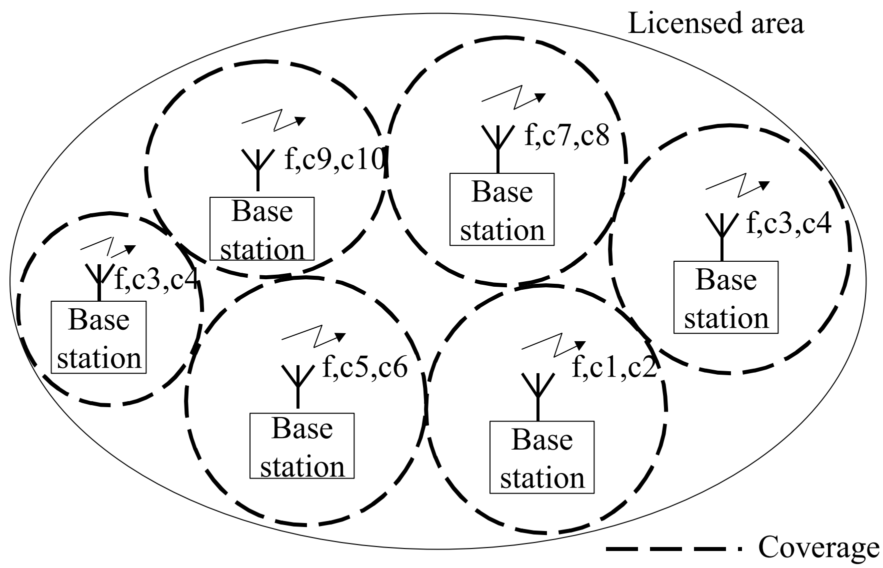



**Figure 55. CDMA interference management model.**

As explained, in CDMA systems, users are continuously interfering over the same frequency and information is recovered with despreading techniques. Nevertheless, there are limitations. The C/I relationship of the signal (see FDMA/TDMA) can be lower than in FDMA systems but there is a minimum limit. This value depends on the bandwidth and the type of information (voice, video or text). To give some idea, in CDMA systems of third generation, where the bandwidth is 5 MHz, voice signal can be 20 dB under noise and interferences, i.e., the minimum C/I is –20dB. Compare it with the 9 to 12 dB of GSM systems.

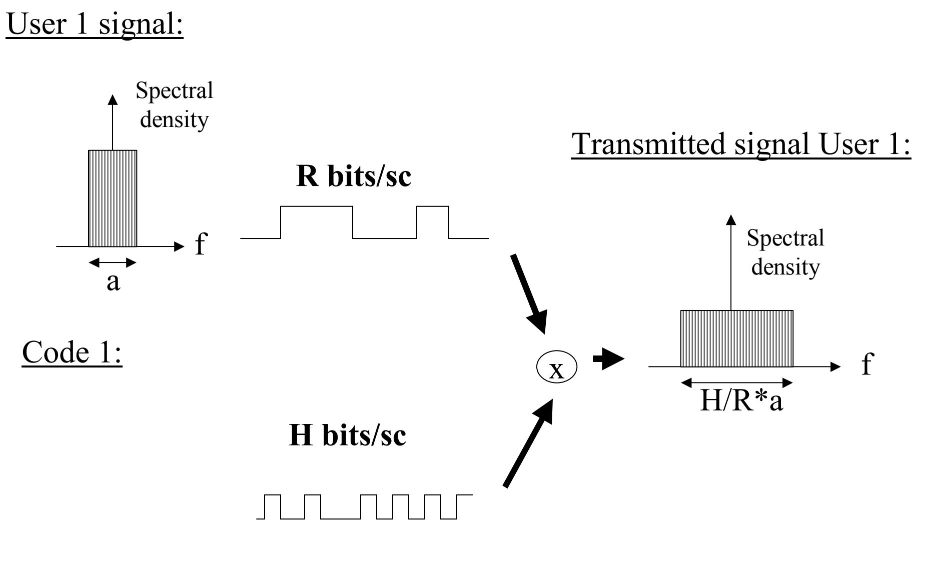



**Figure 56. Spreading technique.**

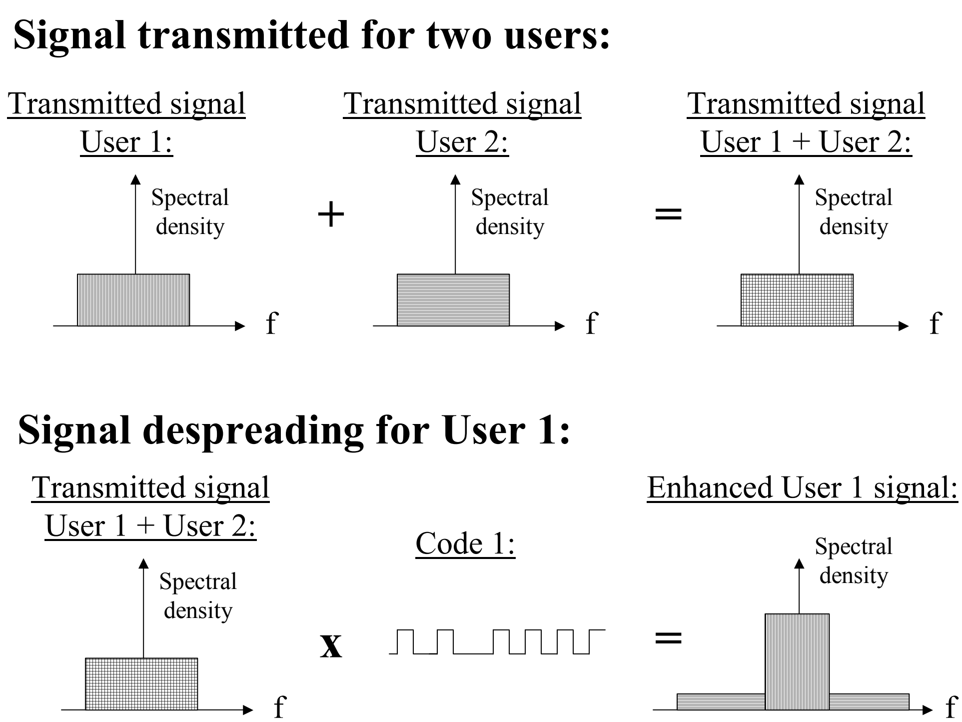



**Figure 57. Reception with interfering signals (despreading technique).**

To maintain C/I at appropriate levels, CDMA systems dynamically control the power of base stations and mobiles. Signals must be received at similar levels for despreading techniques to be efficient, i.e., to keep C/I levels in appropriate ranges. Interferences are dynamically managed through power control. As in FDMA/TDMA systems, networks are designed for the worst case (maximum traffic charge) or a standard case (50% of traffic charge) to guaranty C/I levels at any physical location.

### III. Amateur radio

Amateur radio equipment is regulated under Part 97 rules of the FCC. The regulatory framework for this type of equipment differs from classic frequency assignment. Part of the spectrum is reserved for amateurs radio operation. Amateur radio users need a license to operate their pieces of equipment. However, under rules 97, licensees are not assigned rights over any particular frequency (*§ 97.101*). All licensees transmit over the same bands.

The FCC imposes maximum transmission levels over amateur radio equipment to protect human health. Nevertheless, power limits cannot avoid interferences. The interference management model for amateur radios is based on human control. Operators must coordinate to avoid interferences. Licensees are responsible for choosing non occupied frequencies and give priority to stations transmitting emergency communications.

### IV. Part 15 devices

The FCC regulates many electrical and electronic devices under the Part 15 of the Title 47 of the Code of Federal Regulations. Part 15 rules cover low power devices that radiate RF energy intentionally, unintentionally or incidentally. An **intentional radiator** is "*a device that intentionally generates and emits radio frequency energy by radiation or induction*" (*§ 15.3 (o)*). They may transmit voice, data, video or other information and include cordless telephones, wireless data networks such as Bluetooth and IEEE 802.11 and baby monitors. An **unintentional radiators** is a device "*that intentionally generates radio frequency energy for use within the device, or that sends radio frequency signals by conduction to associated equipment via connecting wiring, but which is not intended to* *emit RF energy by radiation or induction*" (*§ 15.3 (z)*). FM receivers and televisions are typical examples of unintentional radiators. Finally, an **incidental radiator** "*generates radio frequency energy during the course of its operation although the device is not intentionally designed to generate or emit radio frequency energy*" (*§ 15.3 (n)*). Motors and mechanical light switches belong to this category.

The FCC must certify part 15 devices before its commercialization. Low power devices can operate in almost any part of the spectrum from 9 KHz to 38.6 GHz without a license. They share spectrum with licensed services like cellular communications and Amateur Radios. Part 15 devices are not allowed to operate in safety-related bands like those of aeronautical services, in bands especially sensitive to interferences such as radio astronomy spectrum nor in bands for television broadcasting (*§ 15.205*, see Table 22). Higher power Part 15 devices are frequently assigned to specific bands. After FCC certification, they can operate over the assigned spectrum without a license. Frequently, they share bands like the Industrial, Scientific and Medical (ISM) band[42] with other unlicensed devices. Bluetooth, 802.11 and 802.11b are examples of Part 15 devices operating over the ISM 2400-2483.5 and 5725-5850 MHz bands. Cordless telephones are restricted to the ISM 902-928 MHz band.

Part 15 device are not allowed to cause interferences on any other device. Under the rules, if a Part 15 device causes interference, the operator is responsible for immediately correcting the problem or turning off the transmitter. However, Part 15 devices have to accept the interferences caused by any licensed station, intentional (including ISM equipment), unintentional or incidental radiator.

---

[42] Industrial, Scientific and Medical equipment (ISM) refer to products that are designed to generate or use RF energy, *excluding applications for telecommunications and information technology*. Examples of ISM equipment are microwave ovens, RF lighting devices, RF welding equipment and magnetic resonance equipment. ISM equipment is regulated under the Part 18 of the Title 47 of the Code of Federal Regulation. After being certified by the FCC, this kind of equipment can operate over ISM bands without a license. The ISM bands cover the 902-928 MHz, 2400-2483.5 MHz and 5725-5850 MHz frequencies.

**Table 22. Restricted bands for Part 15 devices (*§ 15.205*).**

| | | |
|---|---|---|
| 490 - 495 KHz | 960 – 1000 MHz | 4.5 – 5.25 GHz |
| 495 - 505 KHz | 1 – 1.24 GHz | 5.35 – 5.46 GHz |
| 505 - 510 KHz | 1.3 – 1.427 GHz | 7.25 – 7.75 GHz |
| 37.5 – 38.25 MHz | 1.435 – 1.6265 GHz | 8.025 – 8.5 GHz |
| 73 – 74.6 MHz | 1.6455 – 1.6465 GHz | 9 – 9.2 GHz |
| 74.8 – 75.2 MHz | 1.66 – 1.71 GHz | 9.3 – 9.5 GHz |
| 108 –121.94 MHz | 1.7188 – 1.7222 GHz | 10.6 – 12.7 GHz |
| 123 – 138 MHz | 2.2 – 2.3 GHz | 13.25 – 13.4 GHz |
| 149.9 – 150.05 MHz | 2.31 – 2.39 GHz | 14.47 – 14.5 GHz |
| 156.52475 – 156.52525 MHz | 2.4835 – 2.5 GHz | 15.35 – 16.2 GHz |
| 156.7 – 156.9 MHz | 2.655 – 2.9 GHz | 17.7 – 21.4 GHz |
| 162.0125 – 167.17 MHz | 2.655 – 2.9 GHz | 22.01 –23.12 GHz |
| 167.72 – 173.2 MHz | 3.26 – 3.267 GHz | 23.6 – 24 GHz |
| 240 – 285 MHz | 3.332 – 3.339 GHz | 31.2 – 31.8 GHz |
| 322 – 335.4 MHz | 3.3458 – 3.358 GHz | 36.43 – 36.5 GHz |
| 399.9 – 410 MHz | 3.6 – 4.4 GHz | Above 38.6 GHz |
| 608 – 614 MHz | 4.5 – 5.25 GHz | - |

Part 15 devices have strict technical requirements (*§ 15.15*) to avoid harming humans and causing interferences. Fundamentally, devices are limited in output power.[43] The general rules can be summarized as follows:

- Transmitted power should be limited as much as possible in the manufacturing process. In no case, output power can exceed the regulatory limits. Specific power levels are indicated for each type of device. Special limitations concern specifications for devices operating in ISM bands for example (*§ 15.215 to 15.255*).
- In intentional or unintentional radiators, controls accessible to the user cannot allow to violate regulation. For example, if the user can control output power, the maximum transmission level must not exceed FCC restrictions.
- The FCC recognizes that its regulations are not able to prevent interferences in all situations (see Footnote 43). Given that operators of Part 15 devices must stop

[43] A maximum output power guaranties an attenuation distance. Devices situated further than such distance will not interfere. (Some exceptions may arise in especial propagation conditions like when reflections arrive in phase and are summed at the receiver.) Devices situated at shorter distances will cause interferences to each other. Thus, if a garage door opener becomes too closer to a TV receptor, it will cause interferences on the television (and the television on the garage door opener).

transmission when causing interferences, the Commission recommends manufacturers to attenuate undesired emissions more than signaled in the specifications.

The strategy for interference management in Part 15 equipment is therefore limited to bound transmitted power and to assure human control of the interferences. In practice, given their low power and the density of devices, interferences occur with low probability. As the density of devices increased, so does the probability of interferences.

# Appendix D. FCC regulatory process on SDRs

Aware of the potential of SR technology, the FCC has carried out in the last two years a process to assess the state of the art of SR technology and how it may affect the Commission policies for spectrum management. The FCC has invited the SR players to this procedure that has culminated with the first regulations about SR technology. This appendix reviews the process, the FCC assessment on SR technology and the final rules.

## I. The FCC regulatory process

The SDR regulatory process started in May 1999 under the FCC ET Docket 00-47 and culminated with the first regulations in September 2001. This was the shortest technology proceeding in the FCC history [79]. The documents related to the procedure can be found under the ET Docket 00-47 on the FCC web site [29]. The process took several steps, summarized in Figure 58:

### May 1999: FCC request for TAC report on SR technology [27]

The Commission requested the Technological Advisory Council (TAC) a report on the state of the art of software radio technology, a forecast for the future development of the technology and an analysis about ways in which software radios may affect FCC policies on spectrum management.

### August 1999: Delivery of TAC report [78]

The TAC presented its report to the FCC. In this report, the TAC recognizes the potential of SR technology to improve spectrum management techniques. The document distinguishes between the current generation of software radios, able to operate like multiple legacy systems, and the future software radios, which will operate in new ways and monitor the environment to choose the most appropriate channel and communication protocol. The TAC recommends the Commission to carry out a regulatory process to draft new rules regarding SR technology and to keep close relationships with the industry players and standardization groups involved in SR issues.

March 2000: FCC "Notice of Inquiry" [25]

The FCC followed TAC's advice and opened a process of inquiry to assess the benefits of SR technology and encumbers' opinions. In a "Notice of Inquiry," the Commission recognized the potential importance of SR on issues such as spectrum allocation, spectrum assignment and equipment approval and solicited actors involved in software radio technology comments about:

- State of the technology
- Improving interoperability between radio services
- Improving spectrum efficiency and spectrum sharing
- Equipment approval process

The FCC received 24 submissions after a 75-days comment period. During the 30-day reply period, 9 comments were filled.

December 2000: "Notice of Proposed Rule Making" [26]

In its "Notice of Proposed Rule Making", the FCC recognized the potential of software radios to improve spectrum management and other issues such as interoperability between radio services. The Commission stated that modify regulation to facilitate further development of SR technology is one of its duties. In the report, the FCC announced its belief that software radio technology is on the first steps of development and only few new rules are required at this moment. The "Notice of Proposed Rule Making" listed a set of new regulations and required SR players additional comments. Section II reviews FCC assessment on SR technology and the proposed regulations. During the 75-day comment period, 14 submissions were done. In the following 60-day reply period, 8 comments were filled.

September 2001: "First Report and Order" document [24]

After reviewing the comments on the proposed rules, the FCC amended Part 1 and Part 2 rules to create a new class of equipment for software radios and rules affecting the new category. These rules are detailed in Section III.

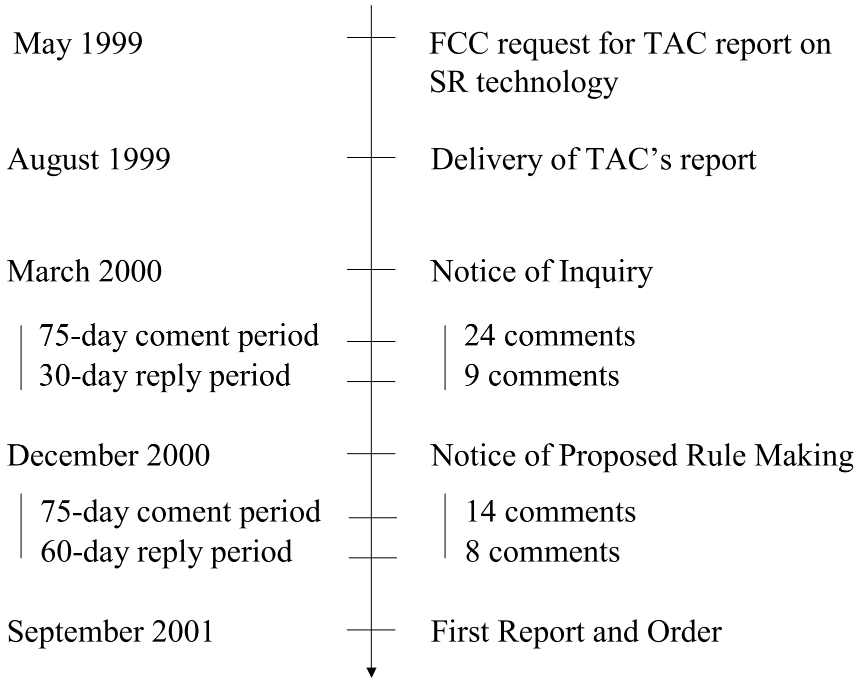



**Figure 58. Timeline of the FCC ET-Docket 00-47 on SR technology.**

## II. FCC assessment on SR and proposed rules

The "Notice of Proposed Rule Making" has two main purposes. First, the document reviews the answers to the "Notice of Inquiry" and summarizes FCC conclusions about the four requested points. Second, the text proposes a set of rules based on these conclusions. The notice also calls for comments on the suggested regulations. This section describes both conclusions and proposed rules.

As explained in the previous paragraph, the discussion section of the "Notice of Proposed Rule Making" reviews the four points for comment in the "Notice of Inquiry" and provides FCC conclusions about each point:

- State of the technology: SR technology allows controlling most radio parameters by software. The most significant are modulation, frequency and output power. However, the technology faces important limitations:
    - Size, weight and power consumption for a single function are higher in software radios that in hardware radios.

- More linear amplifiers are required. Analog-to-digital (A/D) and digital-to-analog (D/A) converters need higher bandwidth and dynamic range.
- Faster and low power processors will improve SR performances.

In consequence, software radio technology is currently limited to base station products. Nevertheless, the technology is improving fast. These limitations will be soon surmounted and software radio technology will reach the handset market.

- Improving interoperability between radio services: The FCC and most actors believe that SR technology will improve the interoperability between radio systems. However, the Commission thinks that the technology is not mature enough and no change in the rules is required yet.
- Improving spectrum efficiency and spectrum sharing: Most actors agree in the important role of SR in spectrum management. Some of them propose SR as a practical solution for the implementation of secondary markets. The Commission is more conservative on this point and considers that the technology is not mature enough and no change in the rules is required yet.
- Equipment approval process: The Commission recognizes that the current approval process is burdensome for software radio equipment and agrees in providing new rules for SR certification.

As result of the previous discussion, the FCC proposed the following set of rules regarding software radios:

- Definition of Software Defined Radios: Before defining any rule, it is necessary to specify which equipment will be under the new regulation. The FCC defines a software defined radio as

  "*a radio that includes a transmitter in which the operating parameters of the transmitter, including the frequency range, modulation type or maximum radiated or conducted output power can be altered by making a change in software without making any hardware changes*" [12].

The SDR Forum contested this definition because it thinks that the FCC characterization is so broad to include software installed in radio devices that is not SR technology. Even more, the Forum considers that this definition could exclude software that reconfigures existing hardware. In the Forum opinion, the text does not contain one of the main properties of software radios, to be reconfigured once installed. For these reasons, the Forum proposed the following changes:

"*a radio that includes a transmitter in which the operating parameters of the transmitter, including the frequency range, modulation type or maximum radiated or conducted output power can be altered in the* ***field*** *by making a change in software* ***without replacing hardware***" [76].

- <u>Class III permissive changes:</u> Nowadays, radio transmitters must be approved by the FCC or a Telecommunication Certification Body (TCB) before being marketed. If any change is made on the equipment, it is considered a new product and has to be approved again before entering the market. The FCC proposed a new Class III certification process. Changes in frequency, power and modulation will require a streamlined filing process including test data showing that the equipment comply with the rule parts for the new service and RF exposure requirements.

- <u>Unauthorized Software Modifications:</u> The FCC announced its intention to obligate manufacturers to ensure that only software that has been approved can be used.

- <u>Labels:</u> The Commission suggested the use of electronic labels to display SR certification information as a faster and more efficient way to deal with Class III permissive changes.

- <u>Required measurements:</u> Some comments supported the addition of new measurements to make sure that software modifications do not degrade emission performances. The FCC considers that there is no need for these measures. The Commission retains the radio transmitters measurements requirements of Part 2 for software radios.

- Telecommunication Certification Body (TCB): The Commission allows TCBs to validate radio equipment. The Commission expects many questions and eventually, some changes in the rules to better meet SDRs needs. In consequence, the TCBs could not approve software radio changes before six months after the adoption of the software radio rules.

### III. Current SR regulation

Once the SR players had the opportunity to discuss the proposed rules, the FCC made public its "First Report and Order" on September 2001. This report modified Part 1 and Part 2 rules to add specific regulation on SR technology. The new regulation mostly focuses on SR definition, certification and security/authentication. The rules can be summarized as follows:[44]

- Identification as a software defined radio (*47 C.F.R. §2.1 (c)*): A software radio is:

  *"a radio that includes a transmitter in which the operating parameters of frequency range, modulation or maximum power (either radiated or conducted) can be altered by making a change in software without making any changes to hardware components that affect the radio frequency emissions."*

  Existing devices can file a new request for an authorization as a software radio.

  Important points of this definition are:

  - The FCC does not impose any requirement over architectures, use of signal processing techniques or general-purpose hardware platforms. This definition focuses only on external effects of the subjacent radio: control through software changes of frequency, modulation and power.

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[44] In *Italics*, the Parts 1 and 2 of the Title 47 of the Code of Federal Regulations including the new rules. The references included in the subtitles have been modified. The references included in the explanations already existed and now apply to SR devices.

- Changes such as the installation of memory modules and the reconfiguration of existing hardware or firmware logic, i.e. hardware that does not affect RF emissions, would be permitted under this definition.
- This definition may exclude software reconfiguration of existing hardware that affects RF emissions such as Figure 13.
- The FCC disagrees that the definition needs to take into account different levels of software but gives no explanation on this issue.
- The FCC declines to require a radio to be programmable in the field for it to be classified as a software radio.
- The FCC declines to include receivers in the definition for software radios because the Commission considers that they have a relatively low potential for interference to radio services. Receivers are subject to manufacturer's self-approval.

- Bundle of hardware and software (*47 C.F.R. §2.932 (e)*): Each combination of hardware and software must be approved together.
- Class III permissive changes (*47 C.F.R. §2.1043 (a), 47 C.F.R. §2.1043 (b)(1), 47 C.F.R. §2.1043 (b)(2), 47 C.F.R. §2.1043 (b)(3)*): Class III permissive changes include **modifications to the software** of a software radio transmitter that **change frequency, power and modulation.** These changes require a **streamlined filing process including test data** showing that the equipment comply with the rule parts for the new service and the RF exposure requirements. Once the change has been approved, the equipment could be **upgraded in the field**. The label will not change and the Commission will keep record of all authorized changes to one licensing number. A piece of equipment with this label could operate in any of those modes. For being eligible for Class III changes, a device must previously be classified as a software radio.
- Third party permissive changes: **Only the party holding the grant of equipment authorization for a software defined radio can file a Class III permissive change**.

- <u>Means to allow third parties to develop new and innovative software for software defined radios:</u>
    - The original grantee may authorize a third party to file an application on its behalf as permitted now for other devices (*47 C.F.R. §2.911 (c)*). **The original grantee would continue to be responsible for the continued compliance of the device.**
    - **A third party can obtain a new identification number for a device and become the party responsible for its compliance.**
- <u>Labeling (*47 C.F.R. §2.925 (e)*):</u> An electronic label will be used to display FCC identification numbers. **A number indicates the party responsible for the compliance of the device such that only this party will be allowed to make modifications on the device under that number.** Electronic label will provide a method to re-label equipment in the field if a new approval were obtained. Electronic label is only available for software radios.
    - <u>Type of display:</u> Electronic labels can use LEDs and LCDs readily accessible. The user manual must include information on how to access the electronic label. It is not required that the electronic label be visible when the power is removed from the device.
    - <u>Information to be displayed:</u> Only the FCC identification numbers associated to the software running in the radio are required to be displayed. The rest of information is available on the FCC database, accessible through the its web site, under the FCC number. Manufacturers can display other information if they want.
- <u>Software modifications/security (*47 C.F.R. §2.932 (e)*):</u> The Commission considers necessary to ensure that software changes cannot be made to a radio that will cause it to operate with parameters outside of these that were approved in order to prevent interference to authorized radio services. The FCC does not impose a specific method to assure security or authentication but **requires manufacturers to take adequate steps to prevent unauthorized changes to the software that drives their equipment**. The SDR Forum and the European

Telecommunications Standard Institute (ETSI) are developing a standard for software protection and authentication. The FCC prefers do not impose any method before these works are finished.

- Combined hardware and software changes (*47 C.F.R. §2.1043 (b)(3)*): The FCC allows combinations of Class I[45] permissive changes to hardware and Class III permissive changes in a single device. However, the Commission forbids combinations of Class II permissive changes to hardware and Class III permissive changes on a single device. Classes II and III affect radio frequency emissions and compliance may be ambiguous. Moreover, it is not clear that a device that needs to make hardware changes to allow software modification may be considered a software radio (see SR definition).

- Limits on the number of hardware and software combinations per authorization request: No limit is placed on the number of hardware and software combinations permitted under a single authorization request.

- Filing of copies of radio software for certification purposes (*47 C.F.R. §2.944*): The applicants will not be required to supply a copy of the radio software on regular bases. However, cases may arise wherein the staff may need to examine the software code used in a device as part of determining its compliance. In these cases, the Commission may require the submission of the software code.

- Filing fees (*47 C.F.R. §1.1103*): The FCC adopts a fee for Class III permissive changes that reflects the expected review time for Class III changes and is the same as the FCC required for approval of transmitters used in licensed services. Where a radio will operate under multiple rule parts, requiring increased review time, the Commission will charge multiple fees as currently set out in the rules.

45 There are two kinds of permissive changes other than Class III changes that do not require a new certification process. Class I includes modifications that do not affect the RF emissions. No filing is required. Class II refers to modifications other than frequency, modulation and power that affect the RF emissions. For these cases, there is a streamlined filing procedure. The applicant just files a description of the changes and measures that show that the new equipment complies with the rules.

- Testing: Software radios should be tested for compliance with each software application under which the radio will operate. It is not required that the device be tested with combinations of software when the software radio can support multiple software applications, only if it can operate in different modes simultaneously.
- Certification by Telecommunication Certification Bodies (CTBs): TCBs will not be permitted to certify software radios until at least six months after the effective date of the rules adopted in this proceeding. The Chief of the Office of Engineering and Technology will determine when TCBs may certify software radios and will announce the decision by public notice.
- Enforcement: No special measures for software radios.

# Glossary

**ACM (*Adaptable Computing Machine*):** QuickSilver's product name, an ACM is an evolved ASIC with reconfigurable capacities.

**A/D converter (*Analog to Digital converter*):** A/D devices sample analog signals to convert them into bits sequences (digital signals).

**ASIC (*Application Specific Integrated Circuit*):** Chip designed for a particular application. ASICs can achieve high efficiencies because their hardware is optimized to perform a particular task. However, they have long times of design and cannot be reprogrammed. New applications require the design and manufacture of new chips.

**D/A converter (*Digital to Analog converter*):** D/A devices convert digital samples into analog signals.

**DSP (*Digital Signal Processor*):** Programmable special-purpose microprocessors that perform a small number of repetitive tasks commonly used in digital communications, such as compressing voice signals or converting them into digital form.

**FCC (*Federal Communications Commission*):** Governmental agency in charge of Telecommunications regulation.

**FPGA *(Field-Programmable Gate Array)*:** Logic chip that can be programmed. An FPGA is similar to a PLD but while PLDs are generally limited to hundreds of gates, FPGAs support thousands of gates. They are especially popular for prototyping integrated circuit designs. Once the design is set, hardwired ASICs are produced for faster performance.

**GSM *(Global System for Mobile Communications Service)*:** European digital cellular standard. GMA uses TDMA to provide 8 channels of 13kb/s voice on a 200kHz carrier channel.

**GSM-R *(Railway GSM)*:** Adaptation of GSM standard to provide wireless communications to railways.

**IC** ***(Integrated Circuit)*****:** Another name for a chip, an integrated circuit (IC) is a small electronic device made out of a semiconductor material. Integrated circuits are used for a variety of devices, including microprocessors, audio and video equipment, and automobiles. The number of transistors and other electronic components they contain often classifies integrated circuits.

**IS-95** ***(cdmaOne)*****:** CDMA second-generation cellular standard, mostly used in North America.

**ITU (*****Independent Transmitter Unit*****):** The ITU layer controls the RF physical parts of the radio. This layer is in charge of generating and amplifying the RF signal from the SPU data stream.

**OEM (*****Original Equipment Manufacturer*****):** Company that buys computers in bulk and customize them for a particular application. They then sell the customized computer under their own name. The term is really a misnomer because OEMs are not the original manufacturers – they are the customizers.

**PLD (*****Programmable Logic Device*****):** Integrated Circuit that can be programmed in a laboratory to perform complex functions. A PLD consists of arrays of AND and OR gates.

**RCP (*****Reconfigurable Communications Processor*****):** Chameleon's product name, an RCP is an evolved ASIC that includes low-level software tools to reconfigure the chip. Instructions are very close to assembly language making difficult and long to reconfigure the chip.

**RF (*****Radio Frequency*****):** Any frequency within the electromagnetic spectrum associated with radio wave propagation. When an RF current is supplied to an antenna, an electromagnetic field is created that then is able to propagate through space.

**SPU (*****Signal Processing Unit*****):** The SPU layer takes the user information (voice and data) and transforms it through signal processing to provide the ITU (Independent Transmitter Unit) with a base band or low IF (Intermediate Frequency) version of the RF (Radio Frequency) signal. The SPU software deals with modulation, states machines, transmission timing, power control algorithms and other feature that characterized the communication standard.

**TAC (*Technological Advisory Council*):** FCC committee that provides technical advice to the FCC and makes recommendations on the issues and questions presented to it by the FCC. The TAC will address questions referred to it by the FCC Chairman, or by the FCC Chief Technologist or Chief Engineer. The questions referred to the TAC will be directed to technological and technical issues in the field of communications.

**TCB (*Telecommunication Certification Body*):** FCC accredited organisms to certify different kinds of equipment.

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