University of Trento

Master Degree Thesis

A NEW VISION OF SOFTWARE DEFINED RADIO: FROM ACADEMIC EXPERIMENTATION TO INDUSTRIAL EXPLOITATION

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CONTENTS

1. SUMMARY

The broad objective of this study is to examine the role of Software Defined Radio in an industrial field. Basically examines the changes that have to be done to achieve moving this technology in a commercial domain. It is important to predict the impacts of the introduction of Software Defined Radio in the telecommunications industry because it is a real future that is coming.

The project starts with the evolution of mobile telecommunications systems through the history. Following this, Software Defined Radio is defined and its main features are commented such as its architecture. Moreover, it wants to predict the changes that the telecommunications industry will might suffer with the introduction of SDR and some future structural and organizational variations are suggested. Additionally, it is discussed the positive and negative aspects of the introduction of SDR in the commercial domain from different points of view and finally, the future SDR mobile phone is described with its possible hardware and software.

2. EVOLUTION OF MOBILE COMMUNICATIONS SYSTEMS

Communications is a vital factor which allows people to connect with each other around the world. From the very early ages, people thought of having communication methods to connect with the rest of the world. Early people used symbolic formations, sounds to express their feelings to others and eventually they started to speak. Then with the advancement of communications, the languages were formed as formal communicating methods and people understood the importance of communication with the rest of the world [1]. So they started to move forward in communications and thus various techniques were found. From paper based media to electronic media like telephones, television, radio, the communications was developed rapidly during the last century. As they are wired media, the use is limited to certain perimeter and soon people found that it is a great limitation in communication. So people did so many experiments to have wireless communication, to overcome the limitations of the wired communications media. As a result of that, the mobile communication was found to make communication more efficient and effective.

2.1. First Generation of mobile communications systems (1G)

First Generation (1G) cellular mobile telephones were based on the analogue system. The introduction of cellular systems in the late 1970s was a quantum leap in mobile communication, especially in terms of capacity and mobility. Semiconductor technology and microprocessors made smaller, lighter, and more sophisticated mobile systems a reality. However, these 1G cellular systems still transmitted only analogue voice information. The prominent ones among 1G systems were Advanced Mobile Phone System (AMPS), Nordic Mobile Telephone (NMT), and Total Access Communication System (TACS) [2]. All of these systems offered handover and roaming capabilities but the cellular networks were unable to interoperate between countries. This was one of the inevitable disadvantages of first generation mobile networks.

2.1.1. Advanced Mobile Phone System (AMPS)

The AMPS cellular standard used analog FM and full duplex radio channels. The Frequency Division Multiple Access (FDMA) technique enabled multiple users to share the same region of spectrum [3]. This standard supported clear communication and inexpensive mobile telephones, but the transmissions were easy to intercept on a standard radio receiver and therefore were susceptible to eavesdropping.

2.1.2. Nordic Mobile Telephone (NMT)

NMT was developed specially by Ericsson and Nokia to service the rugged terrain that characterizes the Nordic countries. There are to variants of NMT, NMT - 450 and NMT - 900. The number indicates the frequency band uses. The NMT specifications were free and open, allowing many companies to produce NMT hardware and pushing the prices down.

2.1.3. Total Access Communication System (TACS)

Total Access Communication System (TACS) and ETACS are mostly obsolete variants of AMPS which were used in some European countries. TACS was also used in Japan under the name Japanese Total Access Communication (JTAC). ETACS was an extended version of TACS with more channels.

2.2. Second Generation of mobile communications systems (2G)

Second Generation (2G) mobile systems were introduced in the end of 1980s. Second Generation mobile telephones used digital technology. Low bit rate data services were supported as well as the traditional speech service. Compared to first generation systems, second generation systems use digital multiple access technology, such as Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). Consequently, compared with first generation systems, higher spectrum efficiency, better data services, and more advanced roaming were offered by 2G systems [2]. In Europe, the Global System for Mobile Communications (GSM) was deployed to provide a single unified standard. GSM provides voice and limited data services, and uses digital modulation for improved audio quality.

Today, multiple IG and 2G standards are used in worldwide mobile communications.

2.2.1. Time Division Multiple Access (TDMA)

TDMA is a multiplexing method that divides network connections into time slices, where each device on the TDMA network connection gets one or more time slices during which it can transmit or receive data. TDMA is often used to refer to early digital mobile phone networks that made use of TDMA multiplexing, such as the original network implemented by AT&T/Cingular before it moved to GSM, which is it based on TDMA technology [4].

2.2.2. Code Division Multiple Access (CDMA)

CDMA is a form of multiplexing which allows numerous signals to occupy a single transmission channel, optimizing the use of available bandwidth. The technology is used in Ultra High Frequency (UHF) cellular telephone systems in the 800 MHz and 1.9 GHz bands.

CDMA employs Analog to Digital Conversion (ADC) in combination with spread spectrum technology. Audio input is first digitized into binary elements. The frequency of the transmitted signal is then made to vary according to a defined pattern (code), so it can be intercepted only by a receiver whose frequency response is programmed with the same code, so it follows exactly along with the transmitter frequency [5]. There are trillions of possible frequencies sequencing codes, which enhances privacy and makes cloning difficult.

2.2.3. Global System for Mobile Communications (GSM)

GSM is a digital mobile telephony system that is widely used in Europe and other parts of the world. GSM uses a variation of Time Division Multiple Access (TDMA) and is the most widely used of the three digital wireless telephony technologies (TDMA, GSM, and CDMA). GSM digitizes and compresses data, then sends it down a channel with two other streams of user data, each in its own time slot. It operates at either the 900 MHz or 1800 MHz frequency band.

Mobile services based on GSM technology were first launched in Finland in 1991. Today, more than 690 mobile networks provide GSM services across 213 countries and GSM represents 82.4% of all global mobile connections.

GSM, together with other technologies, is part of the evolution of wireless mobile telecommunications that includes High Speed Circuit Switched Data (HSCSD), General Packet Radio System (GPRS), Enhanced Data GSM Environment (EDGE), and Universal Mobile Telecommunications Service (UMTS) [6].

2.3. 2.5 Generation of mobile communications systems

2.5 Generation is the 2nd Generation enhanced version of 2G technology. The enhancement achieved through implementing a packed switched domain in addition to circuit switched domain. This is to give user better services and access to the internet. 2.5G gives higher data rates and additional capabilities.

2.4. 2.75 Generation of mobile communications systems

Another enhancement in 2G technology is the 2.75G and it is the head to the 3G technology. GPRS networks evolved in Enhanced Data Rates for GSM Evolution (EDGE). EDGE, Enhanced GPRS (EGPRS), or IMT Single Carrier (IMT-SC) is a backward compatible digital mobile technology and it allows improved data transfer rates. Higher data rates are achieved by switching to more sophisticated methods of coding with existing GSM timeslots.

2.5. Third Generation of mobile communications systems (3G)

Third generation (3G) wireless offers the promise of greater bandwidth, basically bigger data pipes to users, which allow them to send and receive more information. To become more pervasive there is need to have efficient available bandwidth, long rage connection, seamless roaming, real time data flow and high speed data rate [7].

The 3G technology adds multimedia facilities to 2G phones by allowing video, audio, and graphics applications. Over 3G phones, you can watch streaming video or have video telephony.

Other than mobile telephony other wireless communication system becomes major part of 3G communication systems such as WLAN. Some of the known WLAN protocols are Bluetooth, HiperLan, home RF and 802.11 protocol suits. All these systems were designed independently, targeting different service types, data rates, and users. As these systems all have their own merits and shortcomings, there is no single system that is good enough to replace all the other technologies. The idea behind 3G is to have a single network standard instead of the different types adopted in the US, Europe, and Asia [2].

3G cellular services, known as Universal Mobile Telecommunications System (UMTS) or IMT-2000, will sustain higher data rates and open the door to many Internet style applications. The main characteristics of IMT-2000 3G systems are; a single family of compatible standards that can be used worldwide for all mobile applications, support for both packet switched and circuit switched data transmission, data rates up to 2 Mbps (depending on mobility), and high spectrum efficiency.

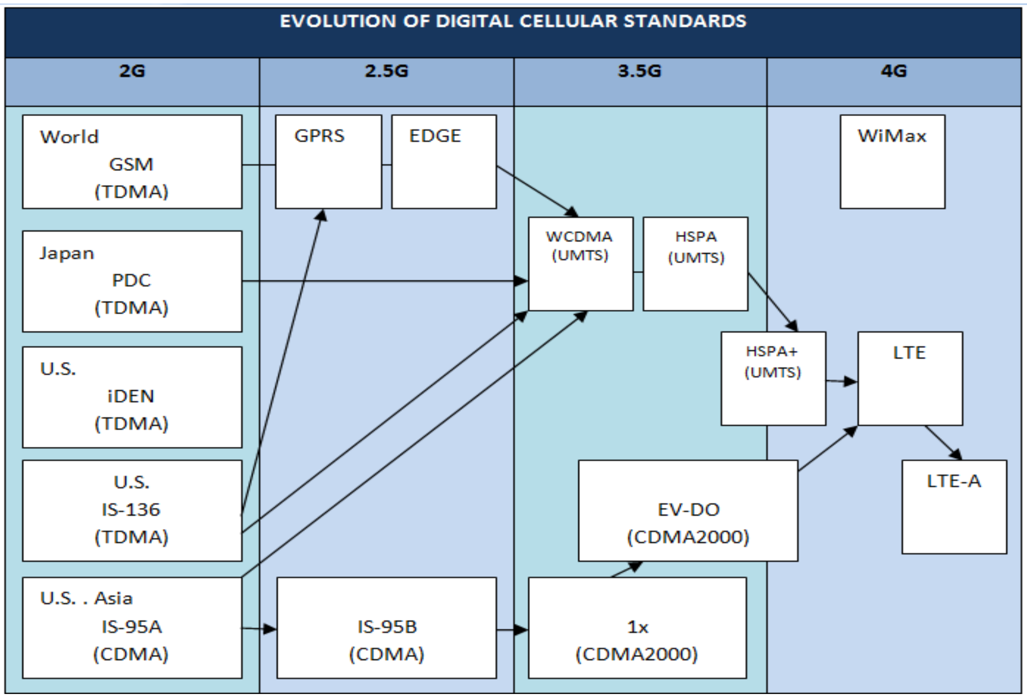


Figure 1.Evolution of digital cellular standard
Source: From Computer Desktop Encyclopedia [8].

2.5.1. CDMA2000

Code Division Multiple Access 2000 (CDMA-2000) is a third generation (3G) standard developed by the International Telecommunication Union (ITU). This protocol uses CDMA access to send voice and data and signals between mobile phone and cell sites.

Enhanced services can be provided to CDMAOne subscribers through CDMA-2000. Data communications speeds ranging from 114 Kbps to 2 Mbps can be supported by this standard. This term is also known as IMT-Multi-Carrier or IS-2000.

The main capacity of CDMA-2000 is to deliver a radio interface system that is better than the second generation systems. SK Telecom (Korea) launched the first commercial system that used this platform (based on the CDMA 2000 1x technology) in October 2000 [9]. From then, several other versions have been developed. Other technologies include CDMA2000 1xEV-DO (Evolution Data Optimized) Technologies which further is comprised of several revisions.

2.5.2. Universal Mobile Telecommunications System (UMTS)

UMTS is a Third Generation (3G) broadband, packet based transmission of text, digitized voice, video, and multimedia at data rates up to 2 Mbps. UMTS offers a consistent set of services to mobile computer and phone users, no matter where they are located in the world. UMTS is based on the Global System for Mobile (GSM) communication standard. It is also endorsed by major standards bodies and manufacturers as the planned standard for mobile users around the world. Computer and phone users can be constantly attached to the Internet wherever they travel. Users have access through a combination of terrestrial wireless and satellite transmissions.

Previous cellular telephone systems were mainly circuit switched; meaning connections were always dependent on circuit availability. A packet switched connection uses the Internet Protocol (IP), meaning that a virtual connection is always available to any other end point in the network. UMTS also makes it possible to provide new services like alternative billing methods or calling plans. For instance, users can choose to pay per bit, pay per session, flat rate, or asymmetric bandwidth options. The higher bandwidth of UMTS also enables other new services like video conferencing or IPTV [10]. UMTS may allow the Virtual Home Environment (VHE) to fully develop, where a roaming user can have the same services to either at home, in the office or in the field through a combination of transparent terrestrial and satellite connections.

2.6. 3.5 GENERATION OF MOBILE TELECOMMUNICATIONS SYSTEMS

3.5G is the next generation in mobile technology which is also called High Speed Downlink Packet Access (HSDPA). It is a mobile telephony protocol and is a packed based data service in W-CDMA, downlink with a data transmission up to 8 - 10 Mbit/s over a 5 MHz bandwidth. HSDPA is enabled with a new transport layer channel which is called High Speed Downlink Shared Channel (HS-DSCH) to send packets on the downlink. In HSDPA or 3.5G technology, the data is transmitted together with error correction bits, thus can be corrected without retransmission. The HS-DSCH channel is shared between users using channel dependant scheduling to make the best use of available radio conditions. So the packed scheduling in 3.5G phones is very faster than other technologies. Adaptive modulation and coding is another significant improvement in 3.5G technology. As well as improving data rates, it also decreases latency and so the round trip tie for applications also reduced.

2.7. FOUR GENERATION OF MOBILE TELECOMMUNICATIONS SYSTEMS (4G)

Researchers are currently developing frameworks for future 4G networks. Different research programs, such as Mobile VCE, MIRAI, and DoCoMo, have their own visions on 4G features and implementations. Some key features (mainly from the users' point of view) of 4G networks are stated as follows:

- High usability; anytime, anywhere, and with any technology;
- Support for multimedia services at low transmission cost;
- Personalization;
- Integrated services;

First, 4G networks are all IP based heterogeneous networks that allow users to use any system at anytime and anywhere. Users carrying an integrated terminal can use a wide range of applications provided by multiple wireless networks.

Second, 4G systems provide not only telecommunications services, but also data and multimedia services. To support multimedia services, high data rate services with good system reliability will be provided. At the same time, a low per bit transmission cost will be maintained.

Third, personalized service will be provided by this new generation network. It is expected that when 4G services are launched, users in widely different locations, occupations, and economic classes will use the services. In order to meet the demands of these diverse users, service providers should design personal and customized services for them.

Finally, 4G systems also provide facilities for integrated services. Users can use multiple services from any service provider at the same time [11].

This motivates Software Defined Radio (SDR). SDR are used to implement radio function such as transmission and reception of signal. The spectrum management for transmission and reception of signal should be handled effectively. Spectrum is scarce resource and recent study observes that the static spectrum allocation scheme used in communication system is not as efficient as it should be. The dynamic allocation scheme becomes solution for efficient spectrum allocation.

Cognitive radio is one of the approaches to manage spectrum dynamically. Cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The cognitive radio network is one of the promising technologies for future wireless communication. A cognitive radio is an unlicensed communication system that is aware of its environment, learns from its environment, adapts to the statistical variations of its environment and use this to achieve reliable communication [7].

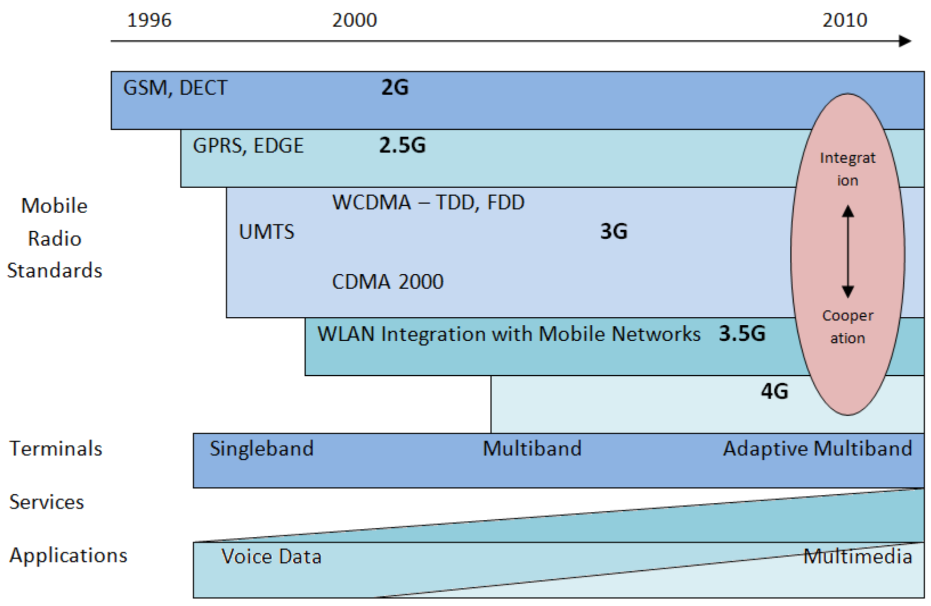


Figure 2.Evolution of communication system

Source: "Cognitive Radio: Emerging Trend of Next Generation Communication System" [7].

2.7.1. Wi-Fi

Wi-Fi is the industry name for Wireless Local Area Network (WLAN) communication technology related to the IEEE 802.11 family of wireless networking standards [12]. It primarily provides short range wireless high speed data connections between mobile data devices (such as laptops, PDAs or phones) and nearby Wi-Fi access points (special hardware connected to a wired network).

There are several variants of 802.11. The most common is 802.11b, which provides speeds up to 11 Mbps. 802.11g and 802.a are faster versions. Many 802.11g and 802.11a products are backward compatible with the original 802.11b.

Wi-Fi is generally much faster than data technologies operating over the cellular network like GPRS, EDGE, 1xRTT, HSDPA, and EV-DO. It is much shorter range, however. Wi-Fi coverage is only provided in small, specific areas called "hot spots". Other than some corporate or educational campuses, Wi-Fi coverage is not widespread. Range for a typical Wi-Fi base station (access point) is typically around 100 to 300 feet indoors and up to 2000 feet outdoors.

Most Wi-Fi operates in the 2.4 GHz unlicensed frequency band. This is the same band as Bluetooth and some cordless phones, although the technologies are designed to coexist and not interfere. 802.11a operates in the 5 GHz unlicensed frequency band [13].

Wi-Fi networks can be set up and operated by anyone, with different networks allowing different kinds of access. A public "hot spot" at an airport or coffee shop might charge an hourly rate for access. A hotel might offer free Wi-Fi to guests. A company or university might offer on premises free access for verified employees/students. Or a home user could set up their own network to which only they had access.

While most Wi-Fi connections are between a mobile device and an access point, it is also possible to create an "ad-hoc" network directly among two or more devices, without an access point.

2.7.2. WiMAX

The name "WiMAX" was created by the WiMAX Forum, which was formed in June 2001 to promote conformity and interoperability of the standard. The forum describes WiMAX as "a standard based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL". WiMAX offers data transfer rates that can be superior to conventional cable modem and DSL connections, however, the bandwidth must be split among multiple users and thus yields lower speeds in practice.

WiMAX refers to interoperable implementations of the IEEE 802.16 family of wireless networks standards ratified by the WiMAX Forum. Similarly, Wi-Fi refers to interoperable implementations of the IEEE 802.11 Wireless LAN standards certified by the Wi-Fi Alliance. On the other side, Wi-Fi, the most common wireless technology, has very limited coverage and it is not always easy to find a Wi-Fi hotspot. WiMAX comes as a solution: it provides high quality broadband access and has a very high penetrability, in that the microwaves it emits can be accessed at every nook and corner of its large coverage area. WiMAX is a type of wireless technology that provides wireless internet service over longer distances than standard Wi-Fi [14]. IEEE 802.16 is the standard to state the radio frequency of fixed Broadband Wireless Access. WiMAX is the trade name of “IEEE 802.16 Standard”.

WiMAX uses fixed and mobile stations to provide users with access to high speed voice, data, and Internet connectivity. WiMAX technology has not been widely accepted by the technology community, but its popularity continues to grow as businesses and consumers seek out better ways to constantly stay connected.

WiMAX can give you connectivity in your desktop computer, laptop and even mobile device. For a simple scenario, you can connect to the Internet through your WiMAX connection at home, at work, in the park and even at the seaside, given that your WiMAX service provider's networks covers all these places. This said, you can even make cheap and free VoIP phone calls using a WiMAX enabled mobile phone, or simply your laptop computer [14].

2.7.3. LONG TERM EVOLUTION (LTE)

Long Term Evolution (LTE) is a 4G wireless broadband technology developed by the Third Generation Partnership Project (3GPP), an industry trade group. 3GPP engineers named the technology "Long Term Evolution" because it represents the next step (4G) in a progression from GSM, a 2G standard, to UMTS, the 3G technologies based upon GSM.

LTE provides significantly increased peak data rates, with the potential for 100 Mbps downstream and 30 Mbps upstream, reduced latency, scalable bandwidth capacity, and backwards compatibility with existing GSM and UMTS technology. Future developments could yield peak throughput on the order of 300 Mbps.

The upper layers of LTE are based upon TCP/IP, which will likely result in an all IP network similar to the current state of wired communications. LTE will support mixed data, voice, video and messaging traffic. LTE uses OFDM (Orthogonal Frequency Division Multiplexing) and, in later releases, MIMO (Multiple Input Multiple Output) antenna technology similar to that used in the IEEE 802.11n Wireless Local Area Network (WLAN) standard [15]. The higher Signal to Noise Ratio (SNR) at the receiver enabled by MIMO, along with OFDM, provides improved coverage and throughput, especially in dense urban areas.

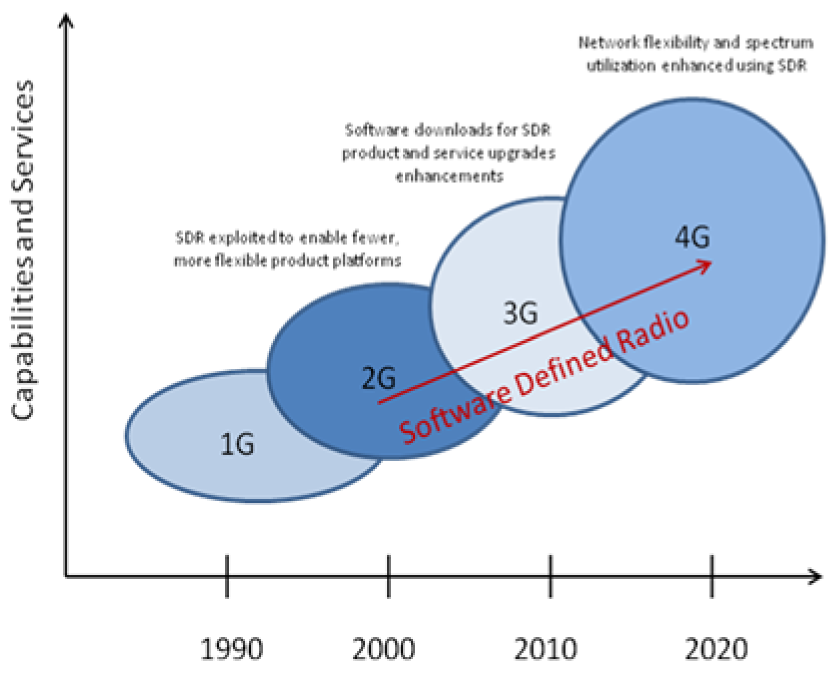

Capabilities and Services
Network flexibility and spectrum utilization enhanced using SDR
Software downloads for SDR product and service upgrades enhancements
SDR exploited to enable fewer, more flexible product platforms
1G
2G
3G
4G
Software Defined Radio
1990
2000
2010
2020

Figure 3.SDR Capabilities and Services timeline
Source: SDR Forum [16].

Specification	**Wi-Fi Ultra-wideband**	**802.11a/b/g**	**802.11n**	**Wireless Broadband (WiBro)**	**Mobile WiMax (802.16 – 2005)**	**3G LTE (cellular WAN)**	**Digital Video Broadcasting - Handheld**	**Digital Video Broadcasting - Terrestrial**
Applications	High-speed local interconnect, wireless USB	Medium-speed LAN	High-speed LAN	Mobile wireless access	Mobile wireless access	Mobile data/voice	Mobile TV	Mobile TV
Range	10 m	80 m	50 – 150 m	1 – 5 km	1 – 5 km	1 + km	Broadcast	Broadcast
Rate	480 Mbps	11 Mbps (b), 54 Mbps (a/g)	100 – 600 Mbps	3 – 50 Mbps (downlink)	63 Mbps (downlink)	100 Mbps (downlink)	384 Kbps	7 Mbps
Frequency	3.1 – 10.6 GHz	2.45/5.8 GHz	2.45/5.8 GHz	2 – 6/2, 3 GHz	2 – 6/2, 3 GHz	1.25/2.2/5/10/20 GHz	0.8 MHz, 1.6GHz	0.8 MHz, 1.6 GHz
Modulation	Orthogonal frequency division multiplexing	Direct-sequence spread spectrum/ complementary code keying, carrier sense multiple access, orthogonal frequency division multiplexing	Carrier sense multiple access, orthogonal frequency division multiplexing	Orthogonal frequency division multiple access	Orthogonal frequency division multiple access	Orthogonal frequency division multiple access/single carrier frequency division multiple access	Orthogonal frequency division multiple multiplexing	Orthogonal frequency division multiple multiplexing

Table 1.Mobile phone standards
Source: NXP semiconductors [17].

3. SOFTWARE DEFINED RADIO

The idea of implementing radio functions in software rather than hardware had already been established when, in 1991, Josep Mitola coined the term “Software Radio”. SDR Technology was originally conceived as a means to facilitate better communications between the different forces of the US military. SDR was seen as a technology that could facilitate the interworking of all different radios and radio systems used within the forces. The aim was to eventually reduce the number of different radio systems used in the different military services.

3.1. SOFTWARE DEFINED RADIO DEFINITION

Software Defined Radio (SDR) is a radio communication technology that is based on software communication protocols instead of hardwired implementations [18]. Frequency band, air interface protocol and functionality can be upgraded with software download and update instead of a complete hardware replacement.

The main idea is how flexibility the radio waveform can be changed through changing software and without modifying the SDR platform. A SDR is capable of being reprogrammed or reconfigured to operate with different waveforms and protocols. These waveforms and protocols can contain a number of different parts, including modulation techniques, security and performance characteristics defined in software as part of the waveform itself.

A Software Defined Radio (SDR) is a communications system that performs many of its required signal processing tasks in a dedicated Digital Signal Processor (DSP) engine [19]. The SDR’s software reprograms the DSP segment of the radio’s physical layer to reconfigure the radio system parameters and can thus synthesize multiple radios.

It is important not to confuse SDR with application software and other software not associated with the radio. SDR describes the software emulating part, or all, of the signal path. Thus, considering the Open System Interconnection (OSI) reference model, shown in *Figure4*, SDR refers in general to functionality within the physical and data link layers and perhaps parts of the network layer [20]. Functionality in the higher layers is not specific to SDR and should not therefore be classed as such.

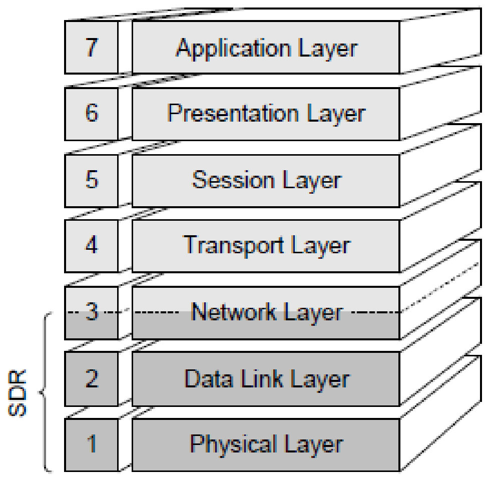


Figure 4.The seven layer OSI reference model
Source: "An Evaluation of Software Defined Radio" [20].

The SDR Forum, a non-profit corporation set up to support the development, deployment and use of open architectures for advanced wireless systems, have developed a multi-tiered definition of SDR. The five tier concept is summarised in *Table2*.

Tier	Name	Description
0	Hardware Radio	Baseline radio with fixed functionality.
1	Software Controlled Radio	Radio in which some or all of the physical layer functions are controlled by software. The radio's sgnal path is implemented using application specific hardware.
2	Software Defined Radio	Radio in which some or all of the physical layer functions are Software Defined.
3	Ideal Software Radio	Radio that implements much more of the signal path in the digital domain.
4	Ultimate Software Radio	Represents the "blu-sky" vision of the SDR. It accepts fully programmable traffic and control information, supports operation over a broad ranfe of frequencies and can switch from one air-interface/application to another in milliseconds.

Table 2.SDR Forum's tier definitions
Source: "An Evaluation of Software Defined Radio" [20].

The following figure illustrates an abstraction of the five tier definition, where the length of the arrow indicates the proportion of the software content within the radio.

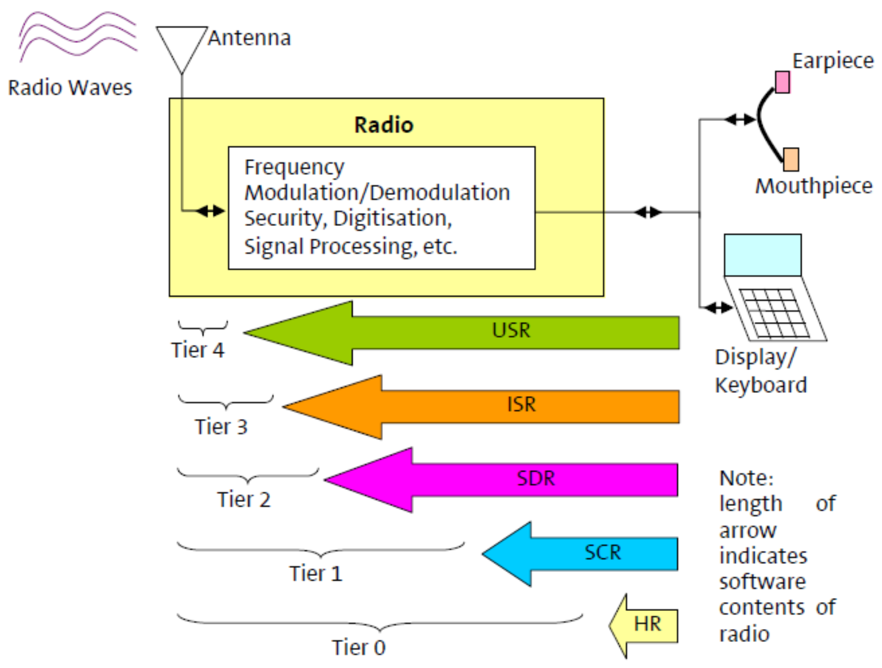


Figure 5.High level abstraction of the SDR forum tier definition
Source: "An Evaluation of Software Defined Radio" [20].

3.2. GENERAL ASPECTS OF SOFTWARE DEFINED RADIO

There are some characteristics that a SDR has to possess. There are mentioned some of them in the following list.

Multiband: Most traditional radio architectures operate on a single band or range of frequencies but there are many applications where multiple frequencies of operations are desired. Thus multiple radios are used; each designed to operate in one specified band. A multiband radio has the ability to operate on two or more bands either sequentially or simultaneously, as in the case of a base station that may be linking handsets from different bands.

Multicarrier: A multicarrier or multichannel radio has the ability to simultaneously operate on more than one frequency at a time. This may be within the same band or, in the case of a multiband radio, in two different bands at the same time. Quite often, multicarrier applies to a base station that may be servicing many users at once, but it can also apply to a user terminal that may be processing both voice and data on different Radio Frequency carriers.

Multimode: Multimode implies the ability to process several different kinds of standards (AM, FM, GMSK, and CDMA). These modes or standards may be sequential or simultaneous, in the case of a multicarrier radio.

Multirate: Multirate is closely related to multimode. A multirate radio is one that either processes different parts of the signal chain at different samples rates, as in a multirate filter, or one where the radio has the ability to process different modes that require different data rates.

Variable Bandwidth: A traditional radio determines the channel bandwidth with a fixed analog filter such as an SAW (Surface Acoustic Wave) or ceramic filter. An SDR, however, determines the channel bandwidth using digital filters that can be altered. While a series of switched analog filters could be used to change the channel bandwidth in a traditional receiver, only a small number would be practical. Additionally, digital filters have the potential to implement filters not possible in the analog domain. Lastly, digital filters can be tailored to both adapt around interferers and compensate for transmission path distortion, both features that analog filters are hard pressed to accomplish.

3.3. Related Technologies

3.3.1. Adaptive Radio

Adaptive radio is a radio in which communications systems have a means of monitoring their own performance and modifying their operating parameters to improve this performance. The use of SDR technologies in an adaptive radio system enables greater degrees of freedom in adaption, and thus higher levels of performance and better quality of service in a communications link.

3.3.2. Cognitive Radio

Cognitive radio is a paradigm for wireless communication in which either network or wireless node itself changes particular transmission or reception parameters to execute its tasks efficiently. This parameter alteration is based on observations of several factors from external and internal cognitive radio environment, such as radio frequency spectrum, user behaviour, and network state.

Cognitive radio will lead to a revolution in wireless communication with significant impacts on technology as well as regulation of spectrum usage to overcome existing barriers. Cognitive radio, including SDR as enabling technology, is suggested to realize a flexible and efficient usage of spectrum. Cognitive radio is an enhancement of SR which again emerged from SDR. Thus, cognitive radio is the consequent step from a flexible physical layer to a flexible system as a whole similar to reconfigurable radio.

The term cognitive radio is derived from “cognition”. According to [21] cognition is referred to as:

- Mental processes of an individual, with particular relation;
- Mental states such as beliefs, desires and intentions;
- Information processing involving learning and knowledge;
- Description of the emergent development of knowledge and concepts within a group;

Resulting from this definition, the cognitive radio is a self-aware communication system that efficiently uses spectrum in an intelligent way. It autonomously coordinates the usage of spectrum in identifying unused radio spectrum on the basis of observing spectrum usage. The classification of spectrum as being unused and the way it is used involves regulation, as this spectrum might be originally assigned to a licensed communication system. This secondary usage of spectrum is referred to as vertical spectrum sharing. To enable transparency to the consumer, cognitive radios provide besides cognition in radio resource management also cognition in services and applications.

In observing the environment, the cognitive radio decides about its action. An initial switching on may lead to an immediate action, while usual operation implies a decision making based on learning from observation history and the consideration of the actual state of the environment [22].

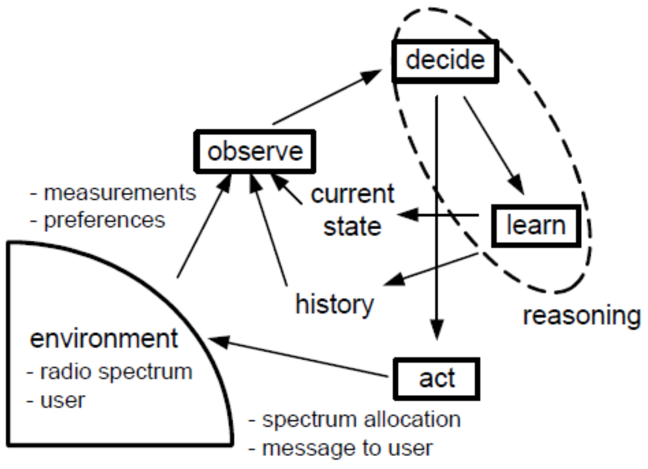


Figure 6.Mental processes of a Cognitive Radio based on the cognition.
Source: Wireless World Research Forum, "Cognitive Radio and Management of Spectrum and Radio Resource" [22].

The Federal Communications Commission (FCC) has identified the following features that cognitive radios can incorporate to enable a more efficient and flexible usage of spectrum:

- Frequency Agility – The radio is able to change its operating frequency to optimize its use in adapting to the environment.
- Dynamic Frequency Selection (DFS) – The radio senses signals from nearby transmitters to choose an optimal operation environment.
- Adaptive Modulation – The transmission characteristics and waveforms can be reconfigured to exploit all opportunities for the usage of spectrum.
- Transmit Power Control (TPC) – The transmission power is adapted to full power limits when necessary on the one hand and to lower levels on the other hand to allow greater sharing of spectrum.
- Location Awareness – The radio is able to determine its location and the location of other devices operating in the same spectrum to optimize transmission parameters for increasing spectrum reuse.
- Negotiated Use – The cognitive radio may have algorithms enabling the sharing of spectrum in terms of prearranged agreements between a licensee and a third party or on an ad-hoc/real-time basis.

This understanding of cognitive radios is summarized in the following definition of cognitive radio from *Haykin [23]*:

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g., transmit power; carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i.) highly reliable communication whenever and wherever needed and (ii.) efficient utilization of the radio spectrum.

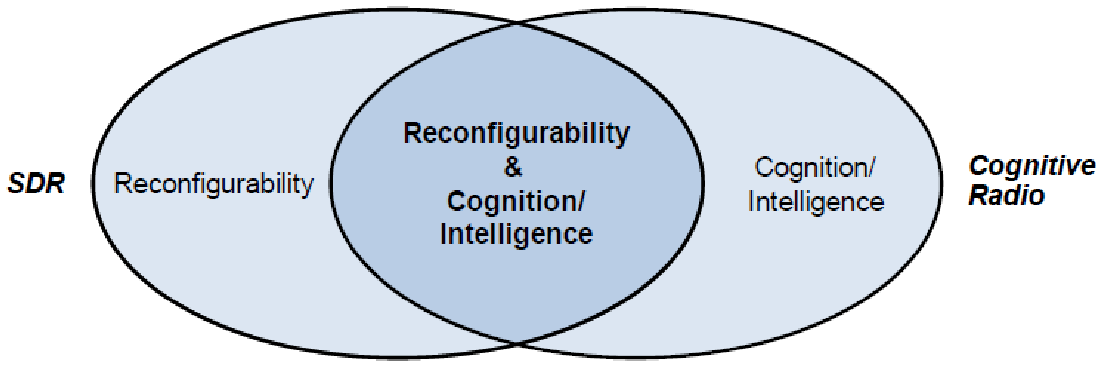


Figure 7.SDR and Cognitive Radio
Source: "Computing Resource in Software Defined and Cognitive Radio" [24].

3.3.3. Intelligent Radio

Intelligent radio is cognitive radio that is capable of machine learning. This allows the cognitive radio to improve the ways in which it adapts to changes in performance and environments to better serve the needs of the end user.

The following diagram illustrates the relationship between associated advanced wireless technologies.

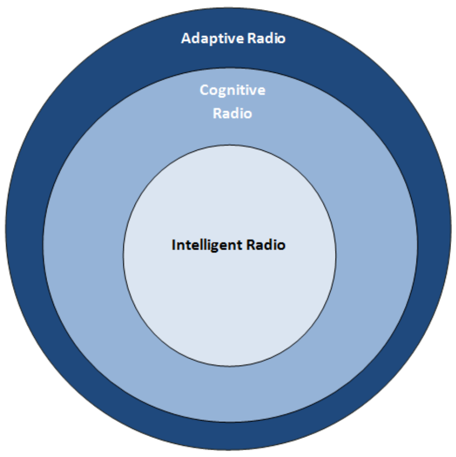


Figure 8.Relationship between Advanced Technologies
Source: SDR Forum [16].

3.4. Benefits of Software Defined Radio

The benefits of Software Defined Radio can be classified according the following criteria:

Benefits for radio equipment manufacturers and system integrators

- A family of radio products can be implemented using common platform architecture. The radio waveform can be changed flexible though changing software and without modifying the SDR platform;
- Now features and capabilities can be added to existing infrastructure;
- Software reuse;
- Reduction of obsolescence;
- Reduction of development and manufacturing cost;
- SDR allows the implementation of fully reprogrammable and reconfigurable terminals with reduce size and power consumption;
- High performance;
- SDR opens up a range of possibilities by making existing types of radio applications easier to implement, and by allowing new types of applications;
- Steady but slower paced progress in the performance and cost of high speed, high dynamic range ADCs and DACs;
- Over the air or other remote reprogramming it allows big fixes to occur while a radio is in service, thus reducing the time and costs associated with operation and maintenance;

Benefits for radio service providers

- The use of a common radio platform to multiple markets can significantly reduce logistical support and operating expenditures;
- Its radio parameters are reconfigurable under program control. One of the advantages of a reconfiguration radio is that its supports communications between a wide range of (currently incompatible) communications systems;
- The rapid evolvement of communications standards makes software upgrades of base stations a more attractive solution than the costly replacement of base stations;

Benefits for end users

- Reduce costs in providing end users with access to ubiquitous wireless communications, enabling them to communicate with whomever they need, whenever they need to and in whatever manner is appropriated;
- SDR gives the availability of two way communication systems that can interface with any other two way system;
- Remote software downloads, through which capacity can be increased, capability upgrades can be activated and new revenue generating features can be inserted;
- For the military sector SDR helps to protect investments by prolonging the useful service life of communication systems. This is facilitated through SDR allowing the possibility to change the waveforms and/or load new waveforms on already acquired SDR equipment;
- SDR is also beneficial for space applications as it provides the flexibility that will allow deployed satellite communications equipment to be Software Upgraded according to advances in algorithms and communications standards.

3.5. DESIGN OF SOFTWARE DEFINED RADIO ARCHITECTURE

The first step in system architecture design is identifying reconfigurable and fixed system functions. Fixed components include specific interconnect and backplane technology, power supplies and various physical interface support. All other electronics require reconfigurability. All digital logic components other than standalone memory and storage devices can be effectively implemented in either processors or Field Programmable Gate Arrays (FPGAs).

Next, there is the identification of the different types of operations required and the optimal processing approach for each. These divide logically into system control and configuration and signal processing and data path control. System control and configuration maintain and control the system's state. These control flow intensive tasks require complex software implementations with little computational load and generally are performed by control processors. In contrast, signal processing data path and control operations typically make up the bulk of the processing load. Systems with light processing demands can be implemented in software, while those with heavier loads are best implemented in software plus hardware system combining Digital Signal Processor (DSP) and FPGA based architectures.

Typical SDR architectures will implement the system control, configuration and the signal processing data path using a combination of microcontrollers, FPGAs and programmable DSPs. The microcontroller controls the system; the FPGA and DSP handle the high rate data flow processing.

The partitioning between the FPGA and the DSP depends on system bandwidth. For example, a DSP can handle all the processing for low bandwidth systems, such as FM and voice TDMA, while an FPGA will handle the majority of processing in wideband systems.

A typical programmable narrowband system uses an FPGA to perform the high computational load filtering and digital download conversions that cannot be handled by a DSP. In most narrowband systems, the majority of the processing capability is consumed by filtering operations. These operations can be computed much more efficiently on dedicated hardware coprocessors, while the light load baseband processing is generally handled by the DSP.

In the typical wideband system, on the other hand, the FPGA performs the majority of the physical layer processing, leaving only the symbol processing to the DSP. The signal processing requirements of such systems can be delivered at least 10 times more efficiently with an FPGA as opposed to a DSP.

Although many commercial radio applications implement these same wideband systems in ASICs, the trend has been to move back to FPGAs as the wideband standards continue to evolve and the costs of designing and maintaining ASIC-based systems continue to rise exponentially [25].

3.6. Software Communications Architecture (SCA)

The most widely used software architecture for SDR is the Software Communications Architecture (SCA) [26]. The SCA is an open architecture that wants to standardize the development of software defined radio, improve communications systems interoperability, and reduce development and deployment cost [27].

The SCA is a distributed system architecture, allowing the various parts of applications to run on different processing elements [26]. The communication between the components, and between components and devices, is based on using the Common Object Request Broker Architecture (CORBA) middleware.

The Common Object Request Broker Architecture (CORBA) is the backbone of the software architecture. The SCA dictates the use of minimum CORBA to provide transparent exchange of information across components. It was chosen due to its simplicity, openness, and platform independence. CORBA provides the SCA with the ability to distribute applications seamlessly. It creates a flexible software bus to support modular, reconfigurable platforms. For a given application, different components can be deployed on different processors, boards, computers, or networks and yet appear as if they were collocated.

The main SCA goals are:

- Cost effective utilization of Commercial off-the-shelf (COTS) technology: the SCA relies on COTS components, standard interfaces, and well known design patterns to provide an operational environment to manage and operate SDR applications, deliver platform independence, and improve intellectual property;
- Waveform portability: to facilitate waveform portability, the SCA was developed as a scalable architecture supporting platforms with widely different capacities, from fixed communications hubs to handheld devices;

- Software reuse;
- Interoperability;
- Technology insertion;
- Hardware abstraction;

SCA only describes the behaviour expected from components, waveforms, and operational environments; it does not provide implementation details.

One common misconception is that the SCA is SDR. While the SCA is the most complete and robust open SDR architecture developed so far, following it is not a requirement to implement SDR technology [27]. SDR can be developed without following the SCA, and the SCA can be used to implement applications other than SDR.

There are many components involved in the development and deployment of Software Communication Architecture (SCA) based Software Defined Radio (SDR) systems; from the multiple target software components that make up the SCA Operating Environment (OE) to the tools that enable design, deployment, debug and optimization of individual waveforms and the complete system.

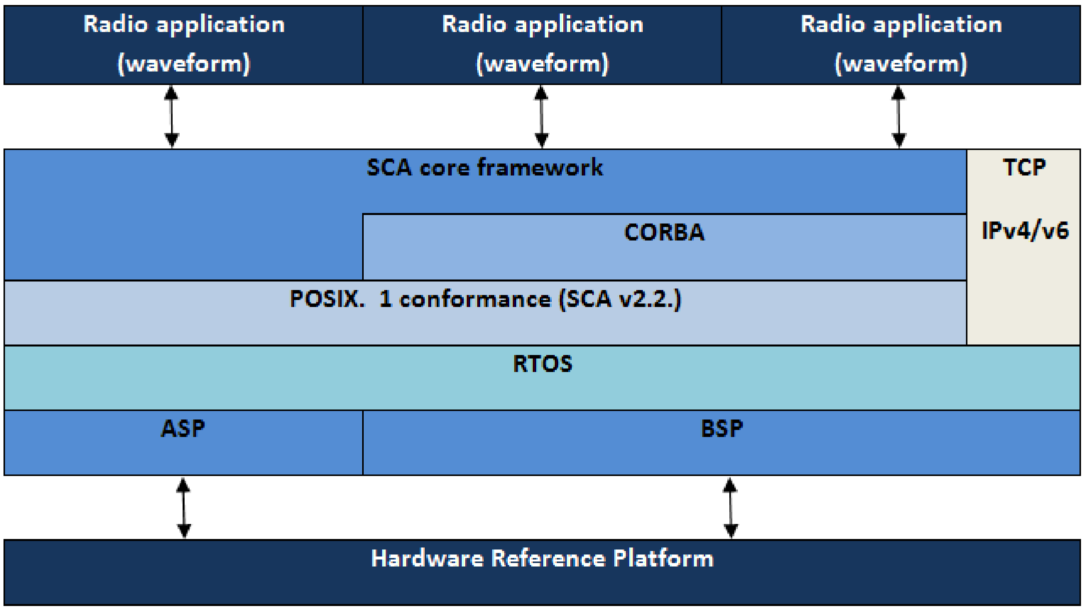

Radio application (waveform)
Radio application (waveform)
Radio application (waveform)
SCA core framework
CORBA
TCP
IPv4/v6
POSIX. 1 conformance (SCA v2.2.)
RTOS
ASP
BSP
Hardware Reference Platform

Figure 9.Operating environment for and SCA enabled radio.
Source: "The Green Hills Platform for SDR provides a complete operating environment compliant with the latest POSIX and SCA standards [28]"

The limitations with the SCA are linked to the fact that it was developed for the military sector and the dynamics of a military market are different from the commercial market. Some of the differences are showed in the following table.

Defense	Commercial
Architecture must ensure long life for the system without too many revisions	Architecture not geared towards ensuring long life
Low maintenance costs	Low development costs
Architecture must ensure error free operation	Errors should be minimized
Modular/Distributed Processor architecture	Centralized Processor Architecture
Architecture supports rigid interfaces without concern for development time or costs.	Architecture needs to support flexible interfaces to minimize development time and costs

Table 3.Defense vs. Commercial implementation architecture
Source: "Software Defined Radio: The transition from defense to commercial markets" [29].

To solve this differences the Object Management Group (OMG) standards body has developed a commercial version of the SCA called the OMG SWRADIO specification. This is now complete and mature for commercial use, it is much more flexible than SCA and it provides the platform independence required for third party software providers.

3.7. ARCHITECTURAL CHALLENGES

3.7.1. RECONFIGURABILITY

A Software Defined Radio (SDR) design must meet today's reconfigurability requirements and adapt to emerging standards, as well as accommodate cost, power and performance demands.

Reconfigurability challenges a number of areas ranging from user, business and regulatory aspects to radio resource/spectrum and system level interactions.

The technological challenges for the reconfiguration are not only on enabling technologies necessary for the development of reconfigurable terminals and base stations but also on network and equipment architectures (HW/SW) supporting reconfiguration, on interactions between terminals and networks, on mode switching negotiation and vertical handovers, on reconfiguration management, etc.

While open programmable and configurable hardware platforms are the basis for reconfigurable communications equipment, suitable software architectures and mechanisms to facilitate reliable, secure and trustworthy reconfiguration on the equipment are essential [30]. Thereby, suitable system and software architectures capable to implement any possible radio configuration on an open programmable platform have to be specified.

Few years ago there were some reasons to consider the SDR like "partial software upgradeability". These reasons were:

- Reconfigurability was limited to a particular family of standards and didn't allow "cross-standards" upgrades.
- The cost of enabling "partial software upgradeability" was especially at the RF front end due to the need for separate "RF chains" to support different protocols and frequency bands.
- The time to develop software upgradeable base station was high due to lengthy hardware design cycles. This has a direct impact on the time to market, a critical factor in the commercial world.
- The economies of scale that the SDR market needs can only come from handsets. SDR had unable to make inroads into the wireless handset market. Until now, multimode handsets have been using "hard-coded" ASICs with partitions and separate RF chains, which lead to lengthy and complicated design cycles and high developments costs. The absence of soft transceivers and reconfigurable baseband modems for multimode handsets has been due to particular technological bottlenecks in SDR.

The limitations and bottlenecks of "partial software upgradeability" are now being overcome with the provision of MPMB reconfigurability.

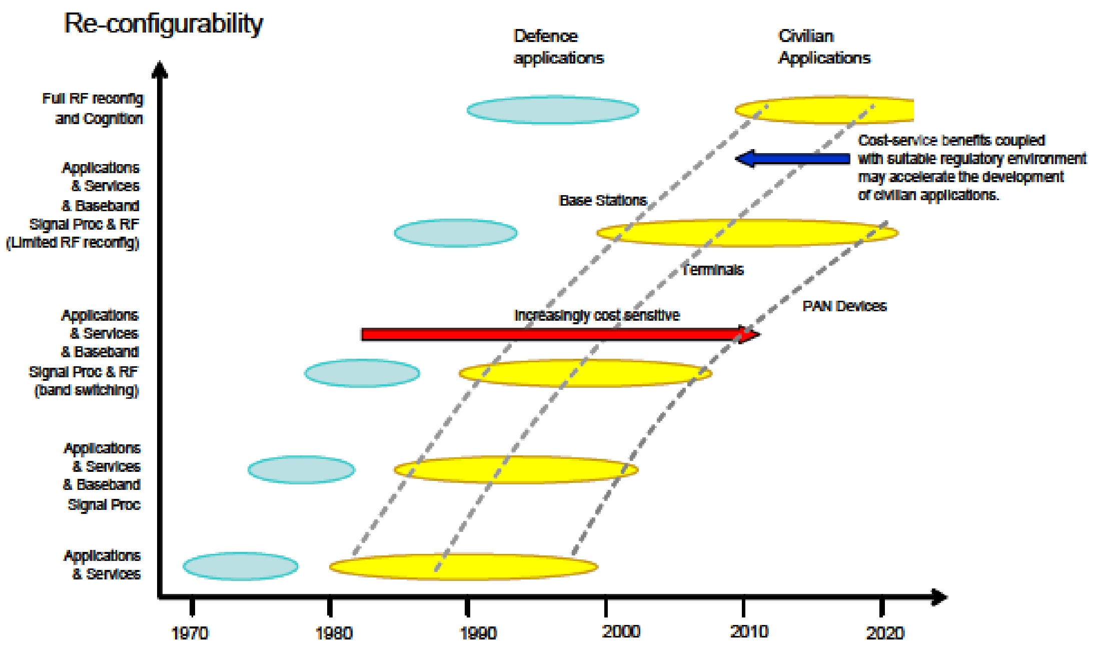

Re-configurability
Defence applications
Civilian Applications
Full RF reconfig and Cognition
Applications & Services & Baseband Signal Proc & RF (Limited RF reconfig)
Applications & Services & Baseband Signal Proc & RF (band switching)
Applications & Services & Baseband Signal Proc
Applications & Services
Cost-service benefits coupled with suitable regulatory environment may accelerate the development of civilian applications.
Base Stations
Terminals
PAN Devices
Increasingly cost sensitive
1970
1980
1990
2000
2010
2020

Figure 10.Regulatory influence on SDR deployment roadmap
Source: "Evaluation of Software Defined Radio Technology" [36].

3.7.2. Portability

The idea of portability is rather simple. The developer takes a waveform implementation from one SDR platform and ports it to another platform. Absolute portability implicates that no effort is necessary for this porting step. However, such absolute portability typically does *not* exist. Thus portability cannot be defined as a binary property with the values portable or not portable. The porting effort depends on different factors such as the differences of the hardware platform, the selected implementation level, the waveform development tools, etc. Since these factors are highly multidimensional, the definition of portability cannot be given by a single equation.

SCA contributes portability by providing a standard for deployment and management of SCA based applications. It also standardizes the interconnection and intercommunication both between the components of the application, and between components and system devices. SCA also standardizes the minimum subset of operating system capabilities that must be available for the applications, and hence the limited subset that applications may use.

The SCA compliance of an application is not sufficient to cover all aspects of portability. Significant pieces that are not standardized by the SCA itself are the APIs to the services and devices of the system platform. Since these are linked to the actual implementation of the system platform, they are supposed to be standardized per system or domain. Another related portability issue is the various alternatives for transport mechanisms for the communication with components deployed on DSPs and FPGAs.

Lastly, portability obviously requires that the component code is interpreted correctly on the platform. This again has two aspects, language compatibility issues and target processor functionality compatibility. Since SCA is based on CORBA which has support for several programming languages, using different code languages will be possible as long as the appropriate compilers and libraries are available. However, different processing elements, in particular different types of DSPs and FPGAs, support different functionalities and features. This either requires several component implementations, one for each family of processing elements, resulting in an overhead of work-hours used. The other approach is to have the component functionality defined in a high-level language, which is compiled to create a correct code image for the actual processing element to be used. Obviously such a compiler may become very complicated. The resulting target code or image may also become less optimal than a target code written specifically for the target processor [26].

Portability Aspects	Standardized through SCA?
Environment and protocol for the installation, instantiation, control, connection and intercommunication of application components...	Yes. (But SCA Security requirements not public)
Defined allowed Operating System Access	Yes, through AEP
APIs to system units (devices) and system services	No. (SCA states is to be handled per domain)
Communications (message transport) with specializes processors (DSPs, FPGAs)	No. Multiple solutions available
ORB	SCA specifies CORBA. There are however some minor differences between ORB implementations
Programming Language	No, but this merely presumes availability of compilers, libraries, …
Target processor compatibility of the code	No. Different DSPs and FPGAs may support different features

Table 4.A summary of Portability issues for SCA based applications
Source:" Software Defined Radio: Challenges and Opportunities" [26].

3.7.3. Common Object Request Broker Architecture (CORBA)

Common Object Request Broker Architecture (CORBA) is an architecture and specification for creating, distributing, and managing distributed program objects in a network. It allows programs at different locations and developed by different vendors to communicate in a network through an "interface broker."

CORBA enables separate pieces of software written in different languages and running on different computers to work with each other like a single application or set of services. More specifically, CORBA is a mechanism in software for normalizing the method-call semantics between application objects residing either in the same address space (application) or remote address space (same host, or remote host on a network).

The essential concept in CORBA is the Object Request Broker (ORB). ORB support in a network of clients and servers on different computers means that a client program (which may itself be an object) can request services from a server program or object without having to understand where the server is in a distributed network or what the interface to the server program looks like [31]. To make requests or return replies between the ORBs, programs use the General Inter-ORB Protocol (GIOP) and, for the Internet, it is Internet Inter-ORB Protocol (IIOP). IIOP maps GIOP requests and replies to the Internet's Transmission Control Protocol (TCP) layer in each computer.

The CORBA is the backbone of the software architecture. The SCA dictates the use of CORBA to provide transparent exchange of information across components. It was chosen due to its simplicity, openness, and platform independence.

CORBA provides the SCA with the ability to distribute applications seamlessly. It creates a flexible software bus to support modular, reconfigurable platforms. For a given application, different components can be deployed on different processors, boards, computers, or networks and year appear as if they were collocated.

There have been concerns about latency overhead introduced by CORBA. While CORBA adds a layer of complexity, and when not used efficiently it can become a burden for SDR, the benefits in terms of consistent and interoperable distributed application development outweigh the added overhead in many situations. It is important to mention that CORBA delays are mostly due to transport mechanisms. This is because the standard transport protocol distributed with CORBA implementations is the Internet Inter-ORB Protocol (IIOP), which relies in TCP/IP, thereby causing long and non-deterministic delays. In order to avoid this dependency on IIOP, ORB developers provide the ability to plug in custom optimized transport mechanisms. When used adequately, CORBA delays represent only a small fraction of the total processing delays and can be tolerated, allowing its inclusion in several SDR implementations.

3.8. Multi-Standards User Terminals

One of the main challenges posed by 4G wireless communication systems is achieving flexible, programmable multi-standard radio transceivers with maximum hardware share amongst different standards at minimum power consumption.

SDR provides an efficient and relatively inexpensive solution to the design of multi-mode, multi-band, multi-functional wireless devices that can be enhanced using software upgrades only. Another advantage of the SDR template is the possibility to implement real adaptive systems.

The optimal way of realizing a multi-standards terminal is to identify the common functions and operators between standards. This yields generic architectures depending on a set of parameters, characterizing the function or operator associated with a specific standard [32].

Multimode user terminals are essential as they can adapt to different wireless networks by reconfiguring themselves. This eliminates the need to use multiple terminals (or multiple hardware components in a terminal).

3.9. MIMO Technology

Multiple Input Multiple Output (MIMO) techniques for wireless channels, involving the use of multi-element antenna arrays at both the transmitter and receiver, have been identified in the past few years as a means of dramatically increasing the capacity of wireless communication systems and networks.

The fundamental basis of MIMO techniques is to exploit multi path propagation in the radio channel. Multi-path is an effect (that has traditionally been regarded as deleterious rather than advantageous), which arises when the radio signal travels from transmitter to receiver via multiple paths rather than a single, dominant line of sight path. The multiple paths (or simply multi-paths) occur due to reflection and scattering from objects such as buildings, trees and the general geographic features (or indoors from wall, furniture, etc.), as shown in *Figure11*. The paths interfere at the receiver to cause Rayleigh fading; if the multiple antenna elements are sufficiently separated, the fading at different elements may be largely uncorrelated, allowing diversity reception.

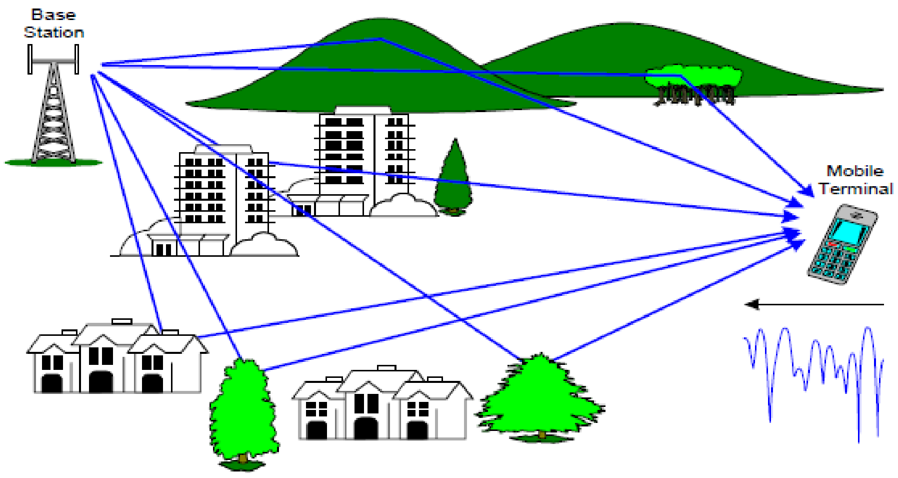


Figure 11.Illustration of multi-path propagation
Source: "An Evaluation of Software Defined Radio" [20].

The MIMO channel is generally modelled as a matrix. Apart from the capacity enhancement, the MIMO channel, in principle, also provides a diversity advantage. The elements of the channel matrix each can potentially provide a signal, and hence, provided they each fade independently; the available diversity order is related to the size of the matrix.

Clearly the performance of MIMO systems, both in terms of capacity and diversity, depends strongly on the propagation environment. In some cases, where there is a strong line of sight and very little multi-path, MIMO gives no advantage because there is no spatial diversity available. It has been traditional to evaluate the performance of MIMO systems assuming uncorrelated Rayleigh fading between each pair of transmit/receive antennas, but this, in effect, assumes an infinitely rich multipath environment.

MIMO has the ability to significantly increase raw data throughput in spectrally limited environments, while at the same time providing immunity to the multipath effects common in urban settings. Therefore MIMO architecture is proposed for SDR [33].

The methods available to increase the capacity of a wireless link in a traditional Single Input, Single Output (SISO) wireless system are fairly limited. The problem of these techniques is that any increase in power or bandwidth can negatively impact other communications systems operating in adjacent spectral channels or within a given geographic area. As such, bandwidth and power for a given communications system are generally well regulated, limiting the ability of the system to support any increase in capacity or performance.

MIMO technologies overcome the deficiencies of these traditional methods through the use of spatial diversity. Data in a MIMO system is transmitted over T transmit antennas through what is referred to as a "MIMO channel" to R receive antennas supported by the receiver terminal.

- Space-Time diversity coding

In space-time diversity coding, each modulated symbol is encoded and transmitted from each of the transmit antennas. This maximizes the total available spatial diversity from the MIMO channel, on a per symbol basis, offering a significant increase in bit error rate performance over an equivalent SISO channel operating at the same transmit power.

This scheme is a simple example of a space-time trellis code (STTC), and is typically decoded through the use of a fairly complex maximum likelihood sequence estimator in the front-end of the receiver. One of the more popular schemes for space-time diversity coding is the Alamouti scheme. This scheme utilizes a simple space-time block code (STBC) that encodes two modulated symbols into a matrix that is two rows by two columns in size.

- Spatial Multiplexing

Spatial multiplexing maximizes the link capacity that is sent over a given bandwidth by transmitting a different symbol on each antenna during each symbol period. Thus the number of symbols transmitted per symbol period is equal to the number of transmit antennas.

For spatial multiplexing to work, the number of receive antennas must be greater than or equal to the number of transmit antennas. The space-time code in a spatial multiplexing scheme is inherent in the multiplexing function.

The predominant encoding schemes associated with spatial multiplexing break into two types: horizontal encoding and vertical encoding. In horizontal encoding, the bit stream to be transmitted is demultiplexed into T separate data streams. Each of these data streams is then temporally encoded, interleaved and converted to transmission symbols, with different modulation schemes allowed on each transmit channel. In contrast, in vertical encoding, the bit stream to be transmitted is encoded using a space-time block code and then converted into transmission symbols. The transmission symbols are then demultiplexed into T bit streams and transmitted.

Vertical encoding offers improved diversity gain over horizontal encoding because each data bit can be spread across all of the transmit antennas. However horizontal encoding accrues an advantage in receiver complexity in that the individual data streams are decoded separately, typically using a relatively simple linear receiver.

3.9.1. SDR Technology and MIMO systems

With careful design, support for MIMO technology can be inherent in the SDR architecture with little or no impact on per unit cost. Thus through the use of SDR technology, MIMO can be supported in an economical manner, allowing a system to be fielded today with MIMO capabilities added as a future software upgrade [33].

A number of architectural elements are required in realizing a conceptual model for SDR architecture system that can support a future MIMO upgrade.

First, a processing engine must be established to act as a minimum unit of scalability within the overall modem architecture. This "modem-processing engine" would generically incorporate the number and types of processing devices required in supporting a single modem channel following the traditional radio model.

These processing devices would be selected to provide additional capacity over what is necessary to meet contemporary waveform requirements, effectively future proofing the system by allow the addition of new features and capabilities over time, including the addition of MIMO technology.

Once the modem-processing engine is defined, a communications infrastructure must be created to support the required connectivity within the overall processing architecture. This infrastructure must provide "any-to-any" connectivity between the processing devices of the modem processing engines to facilitate distribution of data on a per channel basis to and from common space-time processing elements.

This requirement is best addressed through the creation of a data plane based on a high speed switched fabric interconnect such as RapidIO. In this type of architecture, data is routed between processing devices based on a destination address embedded in each transmitted packet, with the switched fabric providing a transport layer capable of end-to-end routing and multiple links.

As such, switched fabric technologies provide efficient support of the logical channels necessary to interconnect the waveform components associated with each instantiated waveform application across multiple disparate processing elements throughout the overall radio architecture.

Support for the deterministic latency through the switched fabric interconnect required for data plane communications implies a need to allocate fabric capacity on a per channel basis as a part of the overall setup of each waveform. Properties that must be allocated include both sustained bandwidth and end-to-end transmission latency.

A number of switched fabric architectures provide support for these features. For example, RapidIO offers extensions to its base protocol stack to include flow control and data streaming to provide for traffic management and predictable latency.

The use of a switched fabric to support data plane communications, however, requires additional consideration is given to the issues associated with multi-channel synchronization necessary in MIMO processing. Switched fabric interconnects generally operate asynchronous to the sample clock, and as such have no inherent mechanism for temporally aligning samples received from multiple channels at the space-time processor.

This issue can be addressed by tagging the transported samples with a "sample count" that is maintained on both sides of the asynchronous fabric and can be used by the waveform processing components to associate samples from multiple channels coherently in time.

It should be noted that the proposed use of a switched fabric between the RF and modem-processing function has the added benefit of allowing these two subsystems to be hosted in geographically disparate locations. If necessary, for example, the RF subsystem could be placed on a communications tower with the modem processing for multiple towers, interconnected via the switched fabric, centrally located in a common "base station hotel", reducing the overall operating expense on a per channel basis.

4. THE CHANGING INDUSTRY STRUCTURE

During the last decade the structure of the consumer electronics industry has been changing profoundly passing through a number of structural types. This part of the project wants to analyse the transition in the consumer electronics industry using the case of mobile phones because it is thought that the industry transition follows a similar evolution.

The main reasons to choose the development of mobile phones are the significant amount of software that they contain, the mobile phones are considered "young" and have gone through a rapid evolution in a short time, they have different features set and business model, and a lot of information is available.

In the beginning, the industry for consumer electronics was dominated by a small group of consumer electronics companies that were responsible for the complete design of its products and developed many of the product components. In that moment the cost of designing a product was negligible compared with the material and manufacturing costs. However, as the functionality increased the relative design cost became a significant factor.

4.1. Previous Definitions and Knowledge

Here there are list some key definitions useful in the following parts of the project [34]:

- Value chain: describes the activities needed to make a product and the value that each of activities created for the end product.

- Value system: analyses value chains in an inter-organizational context, including the activities of upstream and downstream participants in a supply chain.

- Supply chain: "A network that starts with raw material, transforms them into intermediate goods, and then into final product delivered to customers. Each participant consumes logical and/or physical products from one or more upstream suppliers, adds value, usually by incorporating them into more complex products, and suppliers the results downstream consumers." (Lee and Billington, 1994) [35]. In a supply chain, each of the participants uses components containing variability, combines them in-house developed components, and delivers specialized components containing variability to its customers.

- Software Supply Networks: software architecture created based on products and services from others parties in the network.

4.2. Classification of Industry Structures

To start with the analysis first it is proposed a classification of different kinds of industry structures. These structures are presented from the perspectives of software architecture and industry structure.

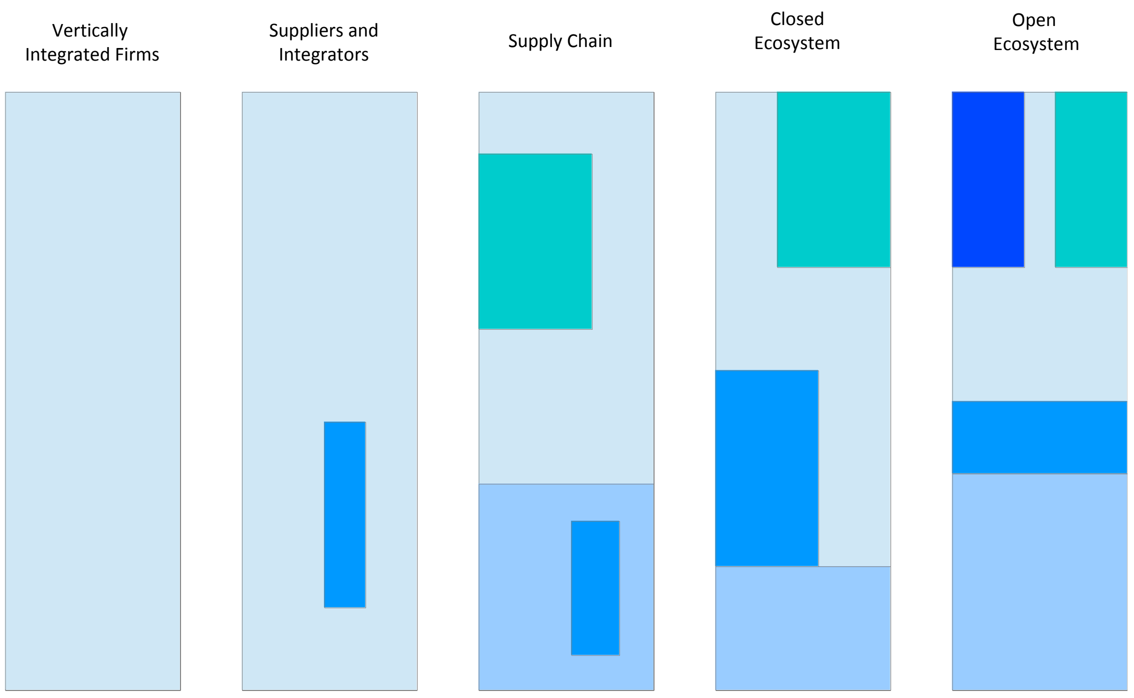


Figure 12.Model of industry structure types, visualized
Source: "The changing industry structure of software development for consumer electronics and its consequences for oftware architectures" [34].

Vertically integrated firms	This kind of industry develops their entire product and delivers it to the market. It has the complete control over the specifications, architecture, and develops the software based on its customers' needs. All functionality has to be developed by one company.
System integrators and specialized suppliers	The system integrators are responsible for the end solution. The system integrator has complete control over the overall architecture and has close contact with the final customer. They are responsible for the requirements of the product and the high level software architecture. They use components from specialized suppliers to reduce their own development effort or when the knowledge is not available to develop that part of the product.
Supply chains	The product is developed by a group of companies, each with their own specialty. In this type the system integrator does not own the product architecture. Instead, the product architecture is shared by the players and might not be defined through rigorous industry wide standards. The software is developed using supply chains, where the supplied software has to be tailored for each customer and integration maybe done in stages. The software integration accounts for a substantial proportion of the development effort. The participants share control over the architecture and the functionality is developed by several parties where each party delivers specialized variants of products to the next party in the chain.
Closed ecosystem	In an ecosystem, the product is developed by a group of companies and the product architecture is defined through standards. In a closed ecosystem the ecosystem is formed around one specific vendor. This vendor opens up their platform so that other parties can add functionality for their own use. Other parties could be the customers, the end-users or third party software vendors. The advantage for the vendor is that it can offer a wider product line with less development effort and the customers or third parties can add functionality more easily. Control over the architecture is owned by the party that develops the platform. Third parties and customers can add functionality, based on close contact with the final customer.

Open ecosystem	In an open ecosystem the architecture is rigorously defined through industry standards and the several components are interchangeable. The standards are open, meaning that they are available for anybody to implement. Open standards allow competition at the subsystem level, since suppliers can create competitive components. Hence the likelihood of one firm becoming dominant is reduced. The "openness" of an ecosystem is not an absolute because some of these properties can be relaxed making the standard less open but still not closed or proprietary. The architecture is defined through open industry standards. The integrator has close contact with the final customer and can create a product by combining interchangeable components. All parts of the system can developed by alternative parties and are interchangeable. Tailor-made solutions can be made by several parties for specific customer needs.

Table 5.Classification of industries structure

4.3. TRANSITION IN THE DEVELOPMENT OF MOBILE PHONES

Initially mobile phones were developed by a small group of vertically integrated companies that developed the entire product and sold these to their customers, usually through the mobile network operators. The functionality was limited to that of voice calls and SMS.

The move from analog to digital technology drove the need for a Digital Signal Processor (DSP) core to be added to the architecture. The first manufacturers of mobile phones, e.g. Nokia, Ericsson, Motorola and Siemens, were large, vertically integrated companies that owned the entire development, manufacturing and sales process. During the 1990s end users and mobile network operators were willing to pay for enhanced functionality and usability. To meet these demands, products were made with customized components since standardized components could not meet the high performance requirements. Hence a vertically integrated firm was the most suited industry structure because only large companies could make these investments. These companies also developed their own software. Different products were made to serve different standards and market segments. When the amount software grew, product line engineering was applied to reduce development effort for creating variants of the products.

Around 1996 new functionality was introduced to mobile phones, such as cameras, downloadable ringtones and MP3 playback. The vertically integrated companies used specialized suppliers for these components, mostly originating from consumer electronics firms, and integrated these components into their products.

In 2002 functionality that was originally used in Personal Digital Assistants (PDAs) was incorporated into mobile phones. This introduced the need for dedicated application processors and operating systems. Separate hardware and software platform suppliers were created, often through spin-offs of the vertically integrated companies. The overall software architecture was now controlled by a combination of the mobile phone manufacturers, the operating system vendors and the platform suppliers.

With the introduction of data and multimedia services, a mobile phone must interface with E-mail systems, the Internet and be able to handle a wide range of non-voice content, such as music, videos and games. As a result, several new technologies must be incorporated, such as GPS, e-mail clients, web browsers, etc. This development was encouraged by the mobile network operators, who offered phones at low price with a subscription, because the new functionality required large amounts of data transfer which was a major source of revenue.

The development investments became significantly higher, both for hardware and software, and the vertically integrated companies needed to decide where they could excel and choose their own focus in this value chain. Separate platform suppliers were created through spin-offs of the vertically integrated companies and specialized IC vendors. For instance, Qualcomm focused on being hardware and software platform supplier, Motorola spun off Freescale that focuses on delivering a hardware platform with software drivers, leaving integration to third parties. Ericcson Mobile Platform focuses on using hardware and software components from other suppliers and so does MediaTek. As a result, the industry transitioned and the suppliers, who defined part of the product architecture, determined a significant part of the functionality.

It is necessary to pay more attention to companies like Qualcomm. Qualcomm Incorporated is a wireless communications company dedicated to the creation of innovative mobile phone systems. Qualcomm started out providing contract research and development services, with limited product manufacturing for the wireless telecommunications market. Then, it patented Code Division Multiple Access (CDMA) technology that is used by telecommunications companies across the globe and has played an integral role in the development of a single international standard for wireless communications. This company was born of an idea and the owners of the idea achieved to develop it thank a more horizontal structure. Another company to be mentioned is The MITRE Corporation. MITRE is a not-for-profit company that provides systems engineering, research and development, and information technology support to the government. It operates federally funded research and development centers for the Department of Defense, the Federal Aviation Administration, and the Internal Revenue Service, with principal locations in Bedford, Mass., and McLean, Va. When Joe Mitola created some of the first SDRs for the military in the early 1990s, he was a consulting scientist of MITRE and the corporation was very supportive of his efforts to consolidate his research in software designed radio. It is the same concept as before, he had the idea and with the help of MITRE he could developed it.

The industry structure that was established around 2005 made it possible for new handset manufacturers to enter the market since components for mobile devices became commodities and hardware platforms became available.

The availability of third generation (3G) technology made it possible for faster connection to the Internet. An API was created that enabled third parties to develop applications that the end user could download and purchase through the Internet, thus forming an ecosystem. This situation emerged around 2008 and still exists today. In this way, the handset makers can offer more functionality to their end users without making the development effort themselves.

Handset manufactures such as RIM and Apple use this business model with their proprietary platforms, as did the open source platforms, such as Android and Symbian. The rapid commercial success of the Apple iPhone can be explained because it made use of two existing supply chains, namely that of the handset and the supply chain through their existing iTunes store. The industry structure for the majority of mobile phone industry is now a combination of two different structures: the structure for third party applications and the industry structure for the mobile devices.

Several attempts for industry standardization have been made since the year 2000 in order to create a modular architecture, allowing for easier product integration and multiple parties to contribute more easily.

For wireless telecommunication standards, there is a broad adoption since that enables a mobile device to function in a network, but does not dictate software architectures. For the standardization of the hardware and software there are a number of different strategies of the different players but several reasons exist for the lack of standardization:

- The fear that a dominant firm takes most of the revenue;
- The convergence of additional functionality from other consumer products can be expected and therefore the speed of innovation will hinder the definition of stable interfaces;
- A high degree of modularity cannot be achieved because this would cause inefficiency and optimal use of resources remains an important design objective;

All this transition took place in several small steps. The initial phase of de-verticalization started when functionality outside the traditional domain was introduced for which specialized suppliers where used. Furthermore, the fast growth of the amount of software started when functionality was shifted from being implemented in hardware towards software. Product manufacturers had to focus their investments and spun out their IC business. Also, software integrators, middleware suppliers and operating systems vendors emerged. The overall software architecture was now controlled by several parties. Consequently products are created through a supply chain where each customer receives specialized components from its suppliers. Standardization attempts for creating a modular architecture across the industry have failed due to different viewpoints of the involved parties and rapid changes of the technology. For the development of downloadable applications, ecosystems have been created, currently mainly for mobile phones.

4.4. Forces of Moving from one Industry Type to Another

Figure13 shows the forces that help or restrain the evolution from the vertically integrated structure to the more ecosystem-centric structure.

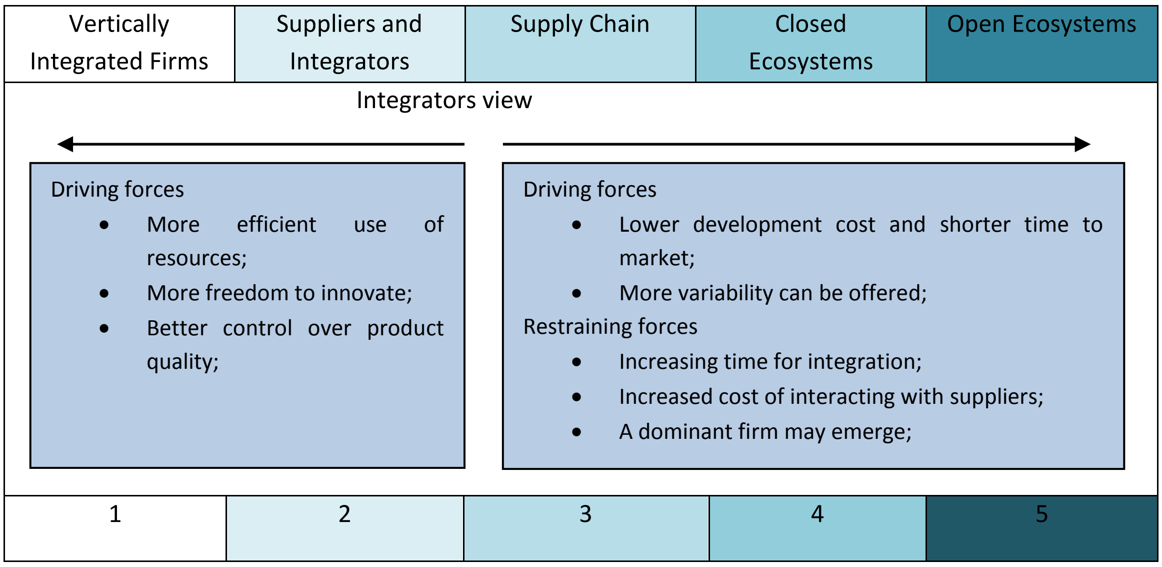

Vertically Integrated Firms
Suppliers and Integrators
Supply Chain
Closed Ecosystems
Open Ecosystems
Integrators view
Driving forces
More efficient use of resources;
More freedom to innovate;
Better control over product quality;
Driving forces
Lower development cost and shorter time to market;
More variability can be offered;
Restraining forces
Increasing time for integration;
Increased cost of interacting with suppliers;
A dominant firm may emerge;
1
2
3
4
5

Figure 13.Forces of moving from one industry type to another
Source: "The changing industry structure of Software development for consumer electronics and its consequences for software architectures" [34].

<u>Advantages of staying or moving to a more vertically integrated approach</u>

- Modular and layering introduces inefficiency in the implementation. In a vertically integrated approach, direct control of the hardware is possible, thus allowing for better resource utilization;
- In a supply chain or ecosystem centric approach there are few possibilities to change the system architecture and APIs since the industry structure depends on its stability. This may constrain innovation and impose the requirements for backwards compatibility;
- The overall product quality depends on the combination of software from different vendors and failures often occur because of component interaction, unclearly documented APIs or unknown use of the system. A more vertically integrated company has control over the architecture and its constituent components and can therefore guarantee the product quality more easily;

Advantages of moving to a more ecosystem-centric approach

- Specialized firms are used to develop part of the system. In this way the total development cost are reduced because an individual firm does not have to invest in developing the entire software stack;
- Variability can be offered more easily to the customers by using components from different suppliers or by enabling third parties and customers to develop the functionality they need;

Disadvantages, or consequences, of moving to a more ecosystem-centric approach

- Increased uncertainty and time needed for system integration. This is especially the case in the Supply Chain, in which heterogeneous architectures have to be combined;
- Co-operating with suppliers leads to additional interaction costs;
- When the industry adopts an ecosystem centric approach, some firm may be able to take a dominant position and create a monopoly. This is often possible for a firm that develops the middleware or the spanning layer.

4.5. Optimal Industry Structure for different Market Segments

Some authors have discussed whether a more vertically integrated or a more horizontal structure would be most suitable for the mobile phone industry. Using this model of industry structures and the forces, these strategic choices can easily be verified.

Anderson identified that for the entry-levels devices, which contain little variability, vertically integrate firms offers better possibilities to obtain the lowest costs because increased resource efficiency [37].

Andserson and Constrantinou argued that a more integrated approach might be more suited for high-end and new-to-market products [34]. For this product range, bringing novel functionality to the market is more important than the higher development costs since the sales price is much higher than the manufacturing costs. As a small case of study, considers Apple’s mobile products. Initially, Apple and Motorola co-developed the ROKR, a mobile phone with MP3 playback and iTunes connectivity. The resulting device lacked sufficient innovative features to attract many customers. The Apple developed the iPhone, now keeping control of the hardware architecture, although based on a combination of existing hardware components from various suppliers. Moreover, Apple providing the software, derived from the Macintosh OS X. This degree of control enabled Apple to create very innovative product and immediately attracted many customers. The development cost could be amortized because of the large market share that Apple has obtained and a huge margin on the manufacturing costs. Furthermore additional revenues are generated by selling additional applications developed by third parties. Note that for the handset, Apple's range contains very little variability, with the amount of internal memory being the principal variation point. Although Apple has become an Integrator that uses specialized suppliers, they continue to rely heavily on the close ecosystem approach for downloads applications.

4.6. Future prevision

With software becoming the key component of MPMB products and with hardware equipment being treated as a naked platform upon which various waveforms can be ported, a new business model and disruptive value chain is likely to emerge. There is the possibility of a new entrant in the value chain, known as the third party software provider, who will provide the functional software, which is the key to any SDR radio.

With the introduction of SDR in the market there are bounds to be changed in the business model that operate in the wireless space. This includes the possibility of a handset service upgrade model which is capable of replacing the current handset replacement model. This essentially means that the end user can benefit by purchasing a naked handset and upload the necessary protocols that would suit his particular needs. In this case, the wireless operator would also need to adapt the current subsidized handset model and suit it to providing protocols and services rather than locking the end user to a particular phone or wireless protocol.

However, as expected, there is a large amount of opposition from OEMs and wireless operators in adopting handset service upgrade model, which directly affects handset volumes, which in turn drives the current replacement hardware model. However it is quite likely that wireless operators will play a prominent role in provisioning of the software due to the security and piracy concerns associated with software. Therefore, in the long run it is more likely that the third party software providers will get consolidated in the value chain rather than remain as independent identities.

The benefits and anticipated opportunities for SDR technology are having a significant impact on the wireless industry's value chain. This chain consists of product based and service based providers, with value added at each stage, ultimately resulting in SDR end products and services that meet the needs of the end users and subscribers.

The first impacts or changes that industry suffer are that new features and capabilities are to be added to existing infrastructure, the use of a common radio platform to multiple markets significantly reduce the logistical support and the operational expenditures and the remote software downloads, through which capacity can be increased, capability upgrades can be activated and new revenue generating features can be inserted.

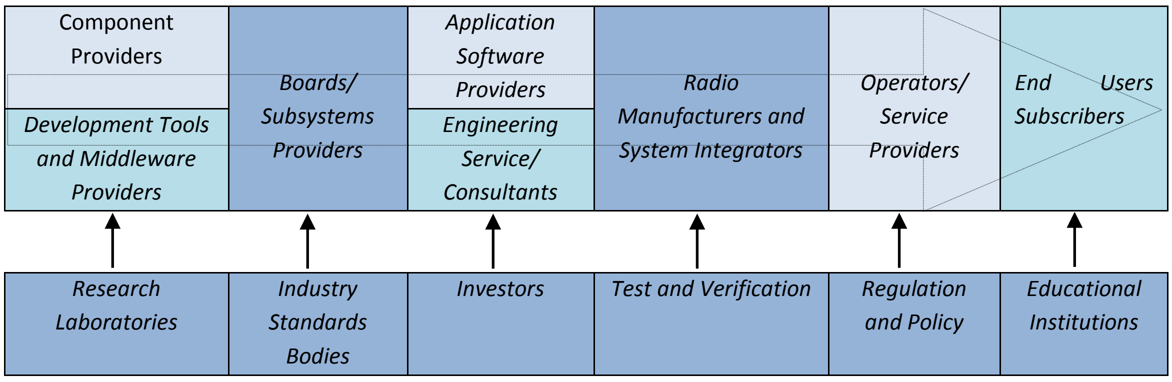

Component Providers
Development Tools and Middleware Providers
Boards/ Subsystems Providers
Application Software Providers
Engineering Service/ Consultants
Radio Manufacturers and System Integrators
Operators/ Service Providers
End Users Subscribers
Research Laboratories
Industry Standards Bodies
Investors
Test and Verification
Regulation and Policy
Educational Institutions

Figure 14.SDR Value Chain: product and service based providers and supporting organizations Source: SDR Forum [16].

Companies may represent more than one category in the value chain. Equally most component providers also provide development tools.

Hence, an ecosystem-centric approach can offer variability more easily to the customers by using components from different suppliers or by enabling third parties and customers to develop the functionality they need.

Standardization is needed to make possible for a system integrator to integrate software and hardware from different suppliers easily but as it is said before, there are several reasons for the lack of standardization.

On the other hand, modular and layering introduces inefficiency in the implementation. In a supply chain or ecosystem centric approach there are few possibilities to change the system architecture and APIs since the industry structure depends on its stability. This may constrain innovation and impose the requirements for backwards compatibility.

Furthermore, in case of different evolving hardware configurations, compatibility of applications may easily be broken and could easily become a major source of inefficiency, which is a major concern for embedded devices. Thus, a company that uses a more vertically integrated approach has control over the architecture and its constituent components and can therefore guarantee the product quality more easily; it has the freedom to innovate more freely.

5. Introduction of SDR in the Commercial Market

Until now Software Defined Radio has been seen as a military technology with a limited market in the commercial application, but with the recent innovations in technology SDR can move to a commercial market success.

One of the main markets for commercial SDR is the wireless infrastructure and devices market [29]. The inability to provide software reconfigurability and wideband capacity at the RF front end has been a major reason for the lack of interest from commercial wireless vendors. Due to the technological bottlenecks, SDR has been viewed as a technology that simply enables “partial software upgradeability”.

However, the technological innovations are now beginning to bring out a change in the perception of SDR. SDR is now being viewed as an enabler for Multiprotocol Multiband (MPMB) support. MPMB SDR is being seen as the solution an ever increasing complex world of rival standards like GSM, CDMA and OFDMA, which are being promoted by competing vendor factions.

5.1. Commercial drivers

In this part it is examined the key factors that can drive the introduction of SDR in the commercial area. It is analysed the commercial drivers that are likely to define the progress that will be made in this area in the years to come. There are considered the commercial drivers from a range of different perspectives.

5.1.1. Manufacturer’s perspective

A range of different manufacturers are involved in the design, development and production of radio equipment. The reasons for adopting SDR are:

Infrastructure Vendors

Cost is one of the main aspects in the development and production of telecommunications infrastructure equipment, but in recent years its importance has increased significantly such that it is perhaps the single, dominant factor on which infrastructure vendors compete for business.

With the introduction of SDR the cost can be impacted with the following ways:

- Decreased equipment development cost;
- Decreased hardware platform cost;
- Faster time to market;
- Ability to track changing wireless standards;
- Post manufacturer bug fixes;

Terminal Manufacturers

In large scale mobile radio networks, the business of designing, manufacturing and selling terminal is quite different to the business of designing, manufacturing and selling infrastructure equipment. The end customers are quite different; hence, they have different requirements and priorities. These two key aspects of the terminal business may affect the uptake of SDR techniques within these devices:

- End user requirements;
- Volume sales;

Semiconductor Houses

Digital semiconductor devices used within radio equipment appear to fall into three main categories, namely general programmable devices, wireless specific programmable devices and technology specific devices.

Test Equipment Manufacturers

It is also important to consider the test equipment manufacturer. The SDR approach has a number of benefits from the perspective of a test equipment manufacturer, including the following:

- Lower development cost;
- Increased customer loyalty;

Software Houses

SDR presents an opportunity for companies to develop and sell software to run on SDR platforms. It seems that there are two main types of software product opportunities within the SDR market. Firstly we have IP blocks, which are software modules or device configuration files that can be used to implement parts of a radio system on a programmable device, and the second type of software providers are those organisations who develop complete software applications to run on an SDR platform.

5.1.2. A Network Operator's Perspective

Consider the commercial drivers for the use of SDR within network operators, i.e. organisations which deploy and operate large scale public access or private radio systems (e.g., cellular network operators, public safety network operators, fixed wireless access network operators). These drivers can be divided into two broad categories. The one category of drivers relies on the use of programmable devices in the equipment and these do not require the equipment to be reconfigurable after manufacture. The other category relies on the use of programmable devices in the equipment and the ability to reconfigure the equipment once it has entered operation, i.e. post manufacture.

5.1.3. A Consumer's Perspective

It appears that the key factors in the consumer's purchasing decisions are the cosmetic appearance of the product, the size, weight and battery life and the number of features supported.

Clearly the cosmetic appearance has little to do with whether or not the product makes use of SDR techniques. As far as the size, weight and battery life of the product are concerned, they will tend to drive users away from devices based on SDR hardware, since these will tend to lead to bulkier, more power hungry devices. Therefore, it seems that the key driver towards the adoption of SDR from the perspective of the consumer is the ability of the product to support more and more features. If devices based on an SDR platform can support more features than non SDR devices, then this may encourage their uptake within the cellular subscriber base. However, given the price sensitive nature of the consumer market, the cost associated with adding this SDR flexibility to the product must be kept to a minimum and this may prove to be a barrier to its adoption.

SDR Technology	
Advantages	**Disadvantages**
User	
Portability	Complexity increase
Flexibility	Restriction to basic control
Compatibility	Security vulnerability
"AAA" (anything, anyplace, anytime) service	Complex billing
Interoperability	Problems in provision of services
Openness to configure as wanted	
Increased service availability	
Operators (Network and Service Provider)	
Better control of systems	Additional provision of services
Easy problem fixes	Possible diversification of client roles
Mass upgrade	
Utilisation of the network efficiently	
Manufacturer (Network and Terminal Equipment Provider	
Easy to maintain the equipment	More competition from 3rd party software providers when using open architectures
Easy to develop and support systems	
Concentration on the software side	
Single platform	

Table 6.SDR Technology: deployment advantages-disadvantages
Source: "Evaluation of Software Defined Radio Technology" [36].

5.2. Opportunities in the commercial domain

5.2.1. Multiprotocol Multiband Base Stations

SDR provides an opportunity to switch from conventionally designed cellular base stations to Software Defined Multiprotocol Multiband (MPMB) base stations.

SDR MPMBs allow standardization of hardware platforms, which reduces the amount of capital tied up in hardware inventory. Since the total lifetime cost of the system is more important than the initial cost, the SDR solution may be preferred even if the initial cost of the SDR platform is higher [26].

The reasons why MPMB is expected to drive commercial SDR are the following:

- A single Common RF Head/RF Chain reduces hardware components and lowers costs of equipment for supporting MPMB.
- A Common reconfigurable platform for multiband along with multiprotocol reduces the development time, and shortens time to market. This advantage holds true in both infrastructures products like base stations as well as devices like handsets and handhelds.
- Supporting multiple protocols in different bands is the major advantage for the end user, whether it is a cellular operator or a handset user. Cellular operators can use a single platform and upgrade across different protocols, eliminating the need to choose a specific wireless standard. It also allows a handset manufacturer and the end user to use a dingle handset and enable operability in different regions with disparate protocols and frequencies.
- Simultaneous protocol supports is only possible with MPMB. This allows for rural operators to take advantage of roaming revenues using MPMB base station and also allows a handset to simultaneously provide support for cellular protocols like GSM, CDMA and wireless broadband protocols like Wi-Fi and WiMAX. This functionality can be provided using a single modem chip and a common RF frond end. This drastically reduces de BOM (Bill of Material) cost and development cost for multimode handsets when compared to current hardware approaches.

5.2.2. Mobile Multi-standard Terminals

Mobile Multi-standard Terminals (MMTs) represent another large market opportunity for SDR [26]. As the number of standards needing to be served by the MMT grows, SDR will at some point provide a cost advantage relative to a conventionally designed MMT. Further it provides opportunities for future mobile wireless users to change and personalize their units by installing additional pieces of waveform software, and upgrade their units as new standards emerge or as standards are updated. More importantly, with the future reconfigurable and cognitive radio networks it will be a necessity for the units to be able to add waveform applications or components dynamically.

MMTs presently are also characterized by a relatively small amount of dominant manufacturers having a high degree of vertical integration and proprietary solutions. There are, however, some signs of interfaces being opened up and value chain restructuring. An obvious observation is the trend of employing third party operating systems allowing third party user applications to be loaded. This has an effect in making end users accustomed to adding SW applications to their units.

5.2.3. Cognitive Radio

The projected evolution into CR capable MPMBs and MMTs represents a large future market opportunity and driver for SDR technology. CRs may both provide context aware services for the user and improve spectrum utilization through dynamic spectrum access [26]. In order to continuously take advantage of spectrum opportunities and adapt to the specific context, CR requires platforms that have fast dynamic reconfiguration abilities.

The following table shows some services and applications that SDR can offer.

Military	Commercial	Public Safety
• Secure, encrypted communications • Mission flexibility • Options to select communications channel by availability • Real-time flexibility • Portable command post • Integrated radio, router, and computer • International connectivity to prevailing networks	• International connectivity • Location awareness • Multimedia applications • Virtual private networks – Closed user groups • Media distribution • Combined delivery of e-mail, voice mail, messages and faxes • Browser capability	• Nationwide portable station for response crisis management • Improved emergency communications by the use of one device that can operate on multiple systems • Closed user groups • Database access • International connectivity (especially for Federal use and search and rescue operations)

Table 7.Potential services and applications

5.3. Introduction of SDR in a ICT Industry

Nowadays the telecommunication companies that dedicate its efforts in software technology are specialized in applications aspects or in mathematic tools. There are not so much known companies that apply the software technology in the commercial market.

5.3.1. Implementation of Software technology

When a telecommunications company wants to implement the SDR its organization structure undergoes many changes. First of all it needs a big number of people working on the software design and time to create all the aspects that involve the software. This means an increment of wages and a large expenditure of money.

Following it is analysed the tree main aspects that includes a design project; the cost, time and scope.

5.3.1.1. Cost

It is not easy to estimate the cost of the software design because it involves a lot of aspects. There are different methods of estimating software development costs, also known as software metrics. The vast majority of these methods are based on measuring the number of Source Lines of Code (SLOC) which contains the development (excluding comments and blank lines from the sources).

One of the methods is the COCOMO (Constructive Cost Model). A method for estimating development cost is only a mathematical relationship between the effort and time required to develop a product or a project. The model uses a basic regression formula with parameters that are derived from historical project data and current project characteristics.

First of all it is need a classification about the kind of project:

- Organic: relatively simple projects. A small group of experienced programmers develop software in a familiar environment. The software size varies from a few thousand lines (small) to tens of thousands of lines (middle).
- Semidetached: Projects intermediate in complexity and size. In this type, the project has strong restrictions, which may be related to the processor and interface hardware. The problem to solve is unique and is difficult to rely on experience, since it cannot any.
- Embedded: quite complex projects without experience. They fall into a place of great technical innovation. Moreover, they work with very stringent requirements and high volatility.

Now, on the other hand, there are defined the different COCOMO models: Basic Model, Intermediate Model and Advanced Model.

<ins>Basic Model</ins>

Basic COCOMO computes software development effort (and cost) as a function of program size. Program size is expressed in estimated thousands of Source Lines of Code (SLOC). The basic COCOMO equations take the form:

$$Effort\ Applied\ (E) = a_b\ (KLOC)^{b_b} \qquad [person - months] \qquad [1]$$

$$Development\ Time\ (D) = c_b (Effort\ Applied)^{d_b} \qquad [months] \qquad [2]$$

$$People\ Required\ (P) = \frac{Effort\ Applied}{Development\ Time} \qquad [count] \qquad [3]$$

Where, KLOC is the estimated number of delivered lines (expressed in thousands) of code for project. The coefficients a_b, b_b, c_b and d_b are given in the following table:

Software project	a_b	b_b	c_b	d_b
Organic	2.4	1.05	2.5	0.38
Semi-detached	3.0	1.12	2.5	0.35
Embedded	3.6	1.20	2.5	0.32

Table 8.Coefficients

Source: Wikipedia [38].

The effort estimation is expressed in units of person-months (PM). It is the area under the person-month plot as shown in figure below. It should be carefully noted that an effort of 100 PM does not imply that 100 persons should work for 1 month nor does it imply that 1 person should be employed for 100 months, but it denotes the area under the person-month curve.

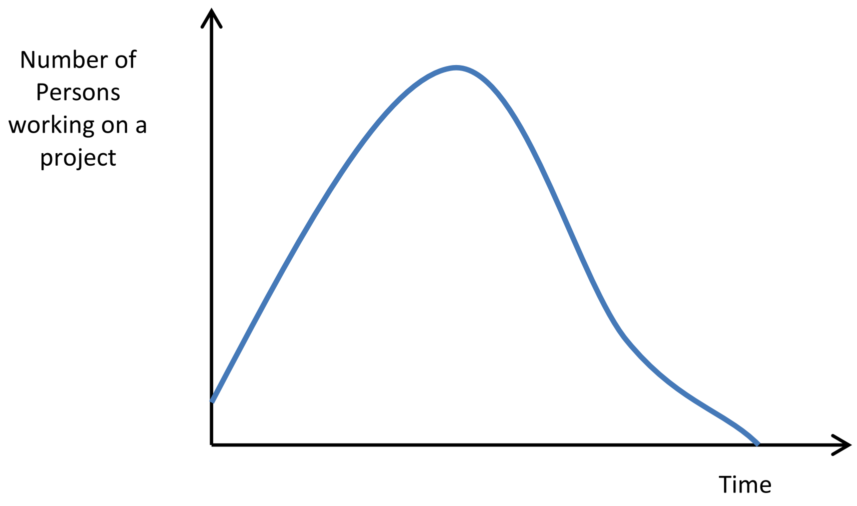


Figure 15.Person-month curve

Source: [39].

From the following figure which shows a plot of estimated effort versus product size it is observed that the effort is somewhat superlinear in the size of the software product. Thus, the effort required to develop a product increases very rapidly with project size.

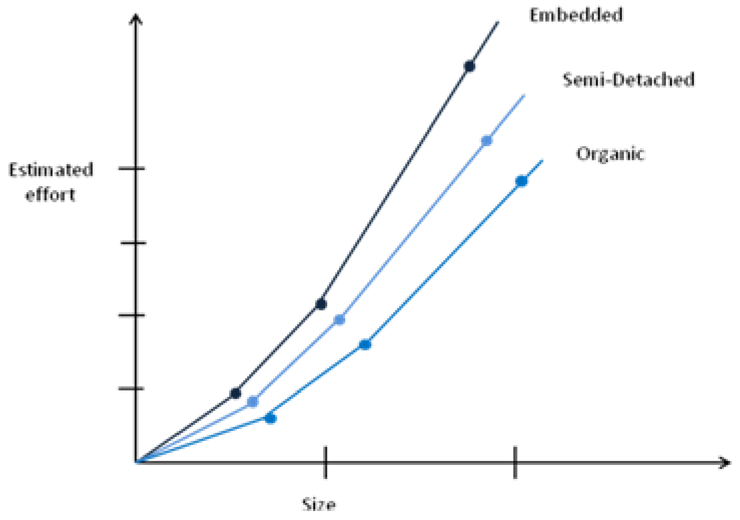


Figure 16.Effort versus Product size
Source: [39].

Now the following figure plots the development time versus the product size in KLOC. Can be observed that the development time is a sublinear function of the size of the product, i.e. when the size of the product increases by two times, the time to develop the product does not double but rises moderately.

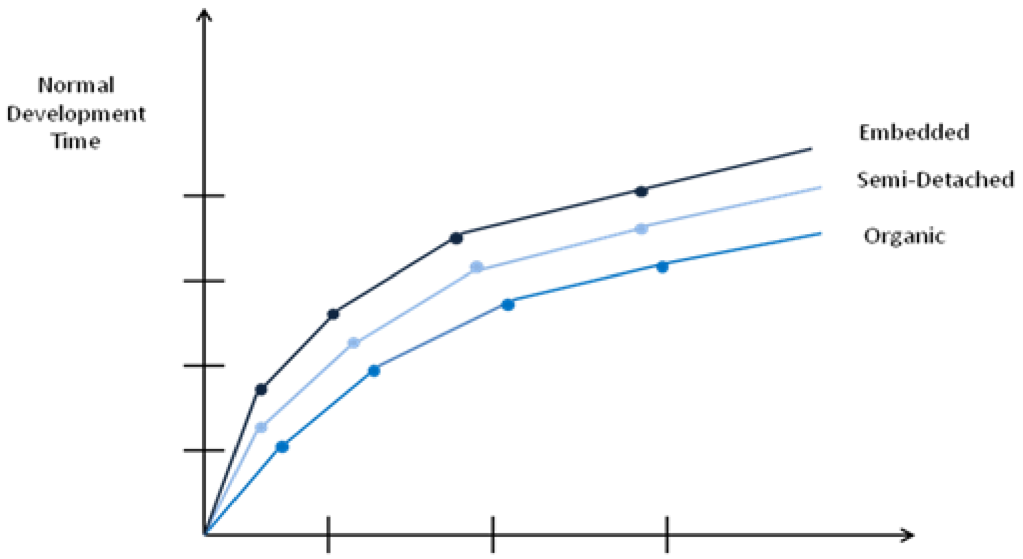


Figure 17.Development time versus Size
Source: [39].

It is to be noted that the effort and the duration estimations obtained using the COCOMO model are called as nominal effort estimate and nominal duration estimate. Basic COCOMO is good for quick estimate of software costs. However it does not account for differences in hardware constraints, personnel quality and experience, use of modern tools and techniques, and so on.

Intermediate Model

Intermediate COCOMO computes software development effort as function of program size and a set of "cost drivers" that include subjective assessment of product, hardware, personnel and project attributes. This extension considers a set of four "cost drivers", each with a number of subsidiary attributes:

Cost Drivers	**Ratings**					
	Very Low	**Low**	**Nominal**	**High**	**Very High**	**Extra High**
Product attributes						
Required software reliability	0.75	0.88	1.00	1.15	1.40	
Size of application database		0.94	1.00	1.08	1.16	
Complexity of the product	0.70	0.85	1.00	1.15	1.30	1.65
Hardware attributes						
Run-time performance constraints			1.00	1.11	1.30	1.66
Memory constraints			1.00	1.06	1.21	1.56
Volatility of the virtual machine environment		0.87	1.00	1.15	1.30	
Required turnabout time		0.87	1.00	1.07	1.15	
Personnel attributes						
Analyst capability	1.46	1.19	1.00	0.86	0.71	
Applications experience	1.29	1.13	1.00	0.91	0.82	
Software engineer capability	1.42	1.17	1.00	0.86	0.70	
Virtual machine experience	1.21	1.10	1.00	0.90		
Programming language experience	1.14	1.07	1.00	0.95		
Project attributes						
Application of software engineering methods	1.24	1.10	1.00	0.91	0.82	
Use of software tools	1.24	1.10	1.00	0.91	0.83	
Required development schedule	1.23	1.08	1.00	1.04	1.10	

Table 9.Attributes and ratings
Source: Wikipedia [38].

Each of the 15 attributes receives a rating on a six point scale that ranges from "very low" to "extra high" (in importance or value). An effort multiplier from the table below applies to the rating. The product of all effort multipliers results in an Effort Adjustment Factor (EAF). Typical values for EAF range from 0.9 to 1.4.

The Intermediate COCOMO formula now takes the form:

$$E = a_i\,(KLOC)^{b_i} \cdot EAF \qquad [4]$$

Where E is the effort applied in person-months, KLoC is the estimated number of thousands of delivered lines of code for the project, and EAF is the factor calculated above. The coefficient a_i and the exponent b_i are given in the next table.

Software Project	a_i	b_i
Organic	3.2	1.05
Semi-detached	3.0	1.12
Embedded	2.8	1.20

Table 10.Coefficients
Source: Wikipedia [38].

The Development time D calculation uses E in the same way as in the Basic COCOMO.

Advanced Model

Detailed COCOMO incorporates all characteristics of the intermediate version with an assessment of the cost driver's impact on each step (analysis, design, etc.) of the software engineering process.

The detailed model uses different effort multipliers for each cost driver attribute. These Phase Sensitive effort multipliers are each to determine the amount of effort required to complete each phase.

In detailed COCOMO, the effort is calculated as function of program size and a set of cost drivers given according to each phase of software life cycle. A Detailed project schedule is never static.

The five phases of detailed COCOMO are:

1. Plan and requirement;
2. System design;
3. Detailed design;
4. Module code and test;
5. Integration and test;

At this point it is good to remember that these models are oriented to the magnitude of the final product, measuring the size of the project in lines of code. By the fact that is based on the number of lines of code, it is measured the product and its size but not is measured the productivity.

Category	Programmers	Duration	Lines of Code	Example
Trivial	1	0 – 4 weeks	< 1k	Utility Management
Small	1	1 – 6 weeks	1k – 3k	Function Library
Medium	2 - 5	0.5 – 2 years	3k – 50k	C Compiler
Big	5 – 20	2 – 3 years	50k – 100k	Small SO
Very big	100 – 1000	4 – 5 years	100k – 1M	Big SO
Giant	1000 – 5000	5 – 10 years	> 1M	Distribution System

Table 11.Project difficulty according to their lines of code
Source: "Costes del Desarrollo de software" [40].

Estimation Cost of our Software Development Project

To make a first estimation about the software development cost it is utilized the Basic Model.

The software development project can be considered as an "embedded project" because it is a complex project without previous experience. Hence, the coefficients are:

$$a_b = 3.6\,, b_b = 1.20\,, c_b = 2.5\ and\ d_b = 0.32\,;$$

If it is considered the GNU Radio project the Lines of Code are 268310. This value is obtained from the addition of Header, Phynton and FPGA; *.h, *.cc, *.py and *.v. Hence:

$$Effort\ Applied\ (E) = 3.6\ (268)^{1.2} = \ 2951.65 \quad [\text{person} - \text{months}] \qquad [5]$$

$$Development\ Time\ (D) = 2.5\ (2951.65)^{0.32} \ = 32.23 \quad [months] \qquad [6]$$

$$People\ required\ (P \uparrow) = \frac{E}{D} \ = 92 \quad [person] \qquad [7]$$

If it is considered a Basic Model that follows the curve of the *Figure15,* it is possible to make an estimation comparing both areas under the curve. It is a qualitative evaluation.

It can be believed that the Lines of Code increases in a software project like this, so:

$$Effort\ Applied\ (E \uparrow\uparrow) = 3.6\ (KLOC \uparrow\uparrow)^{1.2} \quad [\text{person} - \text{months}] \qquad [8]$$

$$Development\ Time\ (D \uparrow) = 2.5\ (E \uparrow)^{0.32} \quad [months] \qquad [9]$$

$$People\ required\ (P \uparrow) = \frac{E}{D} \quad [person] \qquad [10]$$

Hence, the area under the curve increases. A possible plot of the effort can be:

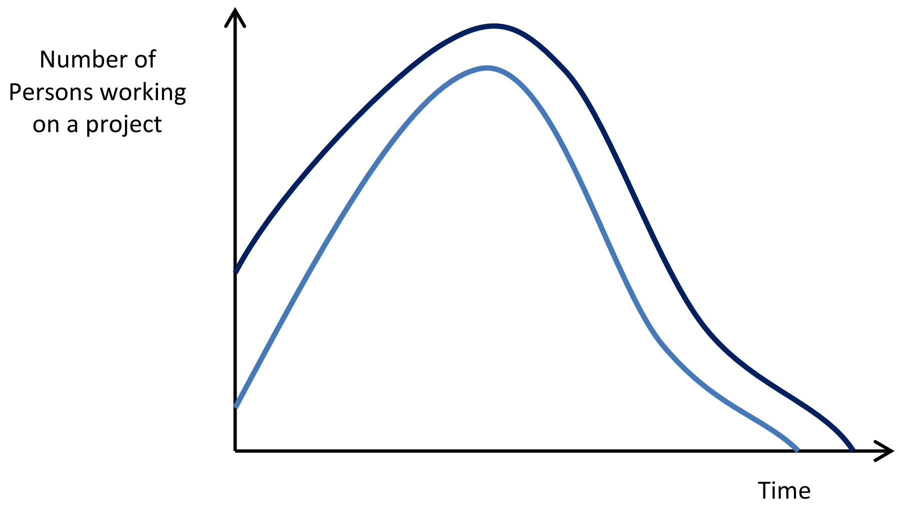


Figure 18.Person-Months curve comparison

If the estimation is done with the Intermediate Model the values of the attributes in this can of project can be:

Cost Drivers	**Ratings**					
	Very Low	**Low**	**Nominal**	**High**	**Very High**	**Extra High**
Product attributes						
Required software reliability	0.75	0.88	1.00	1.15	[✓ 1.40]	
Size of application database		0.94	[✓ 1.00]	1.08	1.16	
Complexity of the product	0.70	0.85	1.00	[✓ 1.15]	1.30	1.65
Hardware attributes						
Run-time performance constraints			1.00	1.11	1.30	[✓ 1. 66]
Memory constraints			1.00	[✓ 1.06]	1.21	1.56
Volatility of the virtual machine environment		0.87	[✓ 1.00]	1.15	1.30	
Required turnabout time		0.87	1.00	[✓ 1.07]	1.15	
Personnel attributes						
Analyst capability	1.46	1.19	[✓ 1.00]	0.86	0.71	
Applications experience	1.29	1.13	[✓ 1.00]	0.91	0.82	
Software engineer capability	1.42	1.17	[✓ 1.00]	0.86	0.70	
Virtual machine experience	1.21	1.10	[✓ 1.00]	0.90		
Programming language experience	1.14	1.07	[✓ 1.00]	0.95		
Project attributes						
Application of software engineering methods	1.24	1.10	1.00	0.91	[✓ 0.82]	
Use of software tools	1.24	1.10	1.00	0.91	[✓ 0.83]	
Required development schedule	1.23	1.08	[✓ 1.00]	1.04	1.10	

Table 12.Project difficulty according to their lines of code
Source: "Costes del Desarrollo de software" [40].

The product of all effort multipliers is:

$$\text{Effort Adjustment Factor (EAF)} \; = 2.06$$

And the coefficients are:

$$a_i = 2.8\,, \qquad b_i = 1.20$$

Hence,

$$Effort\ Applied\ (E) = 2.8\ \ (268)^{1.2} \cdot 2.06 \quad = 4736.26 \quad [person - months]\ \ [11]$$

$$Development\ Time\ (D) = 2.5\ (4736.26)^{0.32}\ = 37.5 \quad [months] \qquad [12]$$

$$People\ required\ (P\uparrow) = \frac{E}{D}\ = 127 \quad [person] \qquad [13]$$

Using this model of estimation it can be said that a project with this kind of dimensions can take more than three years with more than a centenary of workers.

5.3.2. Duration

One the other hand it is basic to estimate correctly the duration of the project. To make a good estimation is necessary to have the programming of the tasks well defined and specified. To successfully complete a project, the time constraint should be comprised of a schedule. If the duration of the project is lengthened without conscience the costs of the project can increase substantially.

5.3.3. Scope

The third constraint of project management is scope. Scope can be defined as the tools and resources that are needed to achieve the end objective of the team. Perhaps one of the most important aspects of the scope is the quality of the end product or service that is produced. How much time the team puts into the project is directly connected to its quality. Some projects will require a longer period of time in order to be completed properly.

5.4. The main idea

As it is said before there are no so many companies that dedicate its efforts in software radio and less in software radio for the commercial domain. If a telecommunication company wants to work with software radio first need to develop the software and it means a big inversion of money and time in the beginning of the project. Once the company has the software designed and implemented the positive think is that the software does not need a huge effort in maintenance or management costs. Hence, in the beginning the company needs to involve a lot of money and time designing the software but it is realistic to think that in the future it will back the inversion and the company will have benefits.

It is necessary to talk about the hardware too. It is known that the software design is always ahead of hardware. Because of this, a lot of money is invested to adapt the software to the hardware existent. As a result of this it can be said that one company that wants to implement SDR cannot use the actual hardware and needs to design new one to assemble with the new software.

The telecommunications companies that would be able to implement the software technology would be the “small ones”. In a “big company” the software is designed by specialized third parties but in a small company is this one that produces all the steps to develop the product or system.

Hence, it is supposed that the companies that would be able to introduce the software technology would be the small ones or the specialized in software development.

6. EVOLUTION FROM TODAY'S MOBILE PHONE TO SDR MOBILE PHONE

With all the sophistication that characterizes mobile phones today, it is easy to forget that the handset, at heart, is a radio. Put simply, the mobile phone's basic function is to send and receive radio signals carrying voice or data information. These signals travel on different frequencies, utilizing various waveforms. However, the growing base of mobile subscribers worldwide, along with the increasing sophistication of devices and the uptake of richer mobile applications, is leading to an increasing demand for additional waveforms and new frequency bands.

Traditionally, radios have been implemented entirely in hardware, with new waveforms added by integrating new hardware. However, jump forward three years and it is foreseeable that handsets sold into developed markets will need to support the following wireless standards: GSM, GPRS, EDGE, WCDMA, HSDPA, Long Term Evolution (LTE), GPS, mobile TV, Wi-Fi, Bluetooth and UWB. Add WiMAX to the mix, as well as multimode handsets able to work across GSM and CDMA networks, and the number of waveforms to be supported is considerable.

Integrating additional radio hardware into a device is impractical beyond a point because it increases handset size, complexity and cost. The attraction of Software Defined Radio (SDR) is its ability to support multiple waveforms by re-using the same hardware while changing its parameters in software. This has enormous benefits for handset size, cost, development cycle, upgrade and interoperability.

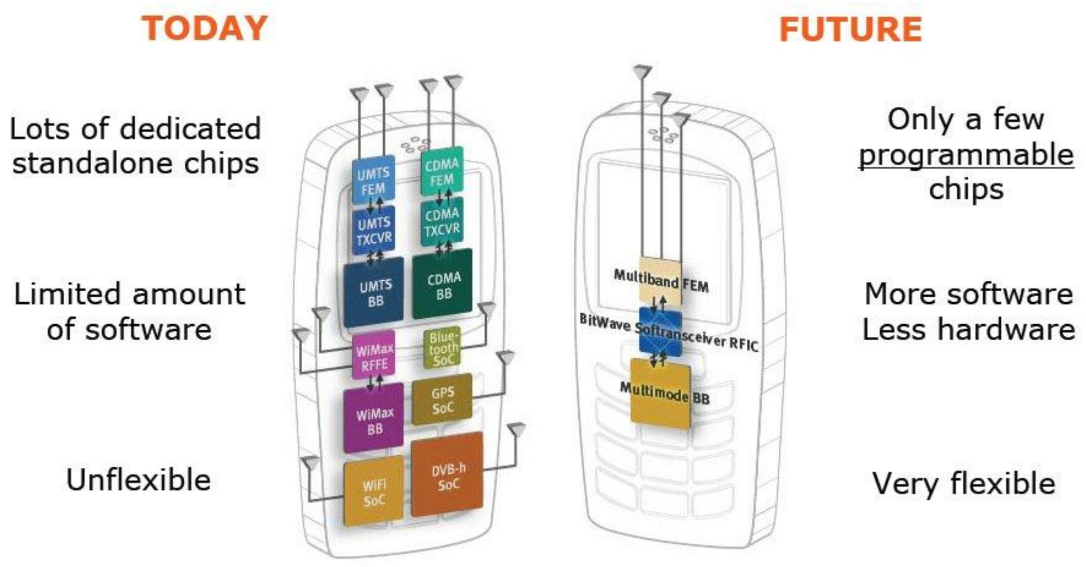


Figure 19.Future SDR mobile phone
Source: Bitware Semiconductor [41].

6.1. Open Source SDR

6.1.1. GNU Radio

GNU Radio is a free and open source software development toolkit that provides signal processing blocks to implement software defined radio systems. It can be used with readily available low cost external RF hardware to create software defined radios, or without hardware in a simulation like environment. It is widely used in hobbyist, academic and commercial environments to support both wireless communications research and real world radio systems.

GNU Radio applications are primarily written using the Python programming language, while the supplied performance critical signal processing path is implemented in C++ using processor floating point extensions, where available. Thus, the developer is able to implement real time, high throughput radio systems in a simple to use, rapid application development environment. While not primarily a simulation tool, GNU Radio does support development of signal processing algorithms using pre-recorded or generated data, avoiding the need for actual RF hardware.

GNU Radio is a signal processing package, which is distributed under the terms of the GNU General Public License. All of the code is copyright of the Free Software Foundation. The goal is to give ordinary software people the ability to 'hack' the electromagnetic spectrum, that is, to understand the radio spectrum and think of clever ways to use it.

As with all software defined radio systems, reconfigurability is the key feature. Instead of purchasing multiple expensive radios, a single more generic radio is purchased, which feeds into powerful signal processing software. Currently only a few forms of radio are duplicated in GNU Radio, but if one understands the math of a radio transmission system, one can reconfigure GNU Radio to receive it.

The GNU Radio project utilizes the Universal Software Radio Peripheral (USRP) which is a computer-based transceiver containing four 64 mega sample per second (MS/s) 12 bit analog to digital (A to D) converters, four 128 MS/s 14 bit digital to analog (D to A) converters, and support circuitry for the interface to the host computer. Depending on the model, the host to USRP interface is either USB 2.0 or Gigabit Ethernet. The USRP can process signals up to 25 MHz wide, depending on the model. Several transmitter and receiver plug in daughter boards are available covering various bands between 0 and 5.9 GHz. The USRP was developed by Matt Ettus.

6.1.1.1. USRP – Hardware platform

The USRP product family is intended to be a comparatively inexpensive hardware platform for software radio. USRPs connect to a host computer through a high speed USB or Gigabit Ethernet link, which the host based software uses to control the USRP hardware and transmit/receive data. Some USRP models also integrate the general functionality of a host computer with an embedded processor that allows the USRP Embedded Series to operate in a standalone fashion.

The USRP family was designed for accessibility, and many of the products are open source. The board schematics for select USRP models are freely available for download; all USRP products are controlled with the open source UHD driver. USRPs are commonly used with the GNU Radio software suite to create complex software defined radio systems.

The USRP product family includes a variety of models that use a similar architecture. A motherboard provides the following subsystems: clock generation and synchronization, FPGA, ADCs, DACs, host processor interface, and power regulation. A modular front end, called a daughterboard, is used for analog operations such as up/down conversion, filtering, and other signal conditioning. This modularity permits the USRP to serve applications that operate between DC and 6 GHz.

In stock configuration the FPGA performs several DSP operations, which ultimately provide translation from real signals in the analog domain to lower rate, complex, baseband signals in the digital domain. In most use cases, these complex samples are transferred to/from applications running on a host processor, which perform DSP operations. The code for the FPGA is open source and can be modified to allow high speed, low latency operations to occur in the FPGA.

Basically, the USRP is an integrated board which incorporates Analog to Digital Converters (ADC) and Digital to Analog Converters (DAC), some forms of RF front end, and an FPGA which does some important but computationally expensive pre-processing of the input signal. The USRP is low cost and high speed, which is the best choice for a GNU Radio user to implement some real time applications. You can purchase the USRP boards from Ettus Research. A USRP board consists of one mother board and up to four daughter boards. The price for the mother board is $700 and daughter boards cost anyware between $75 and $275 each. *Figure20* shows the picture of a USRP board equipped with four daughter boards (2 for RX and 2 for TX).

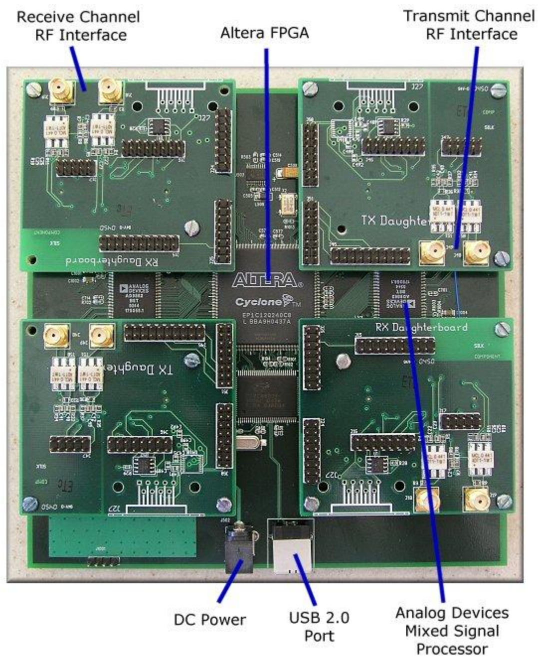

Receive Channel RF Interface
Altera FPGA
Transmit Channel RF Interface
DC Power
USB 2.0 Port
Analog Devices Mixed Signal Processor

Figure 20.USRP board
Source: [42].

6.1.1.2. HARDWARE COMPONENTS

This section introduces the hardware components on the USRP board. A typical setup of the USRP board consists of one mother board and up to four daughter boards, as shown in *Figure21.*

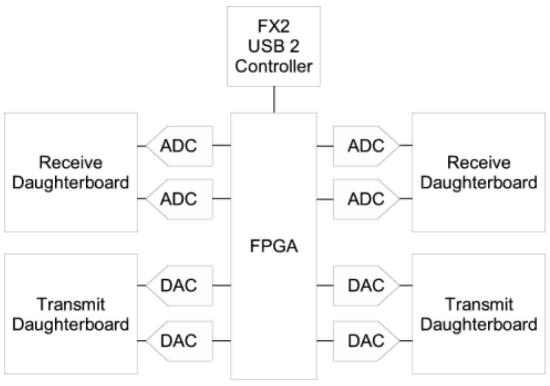


Figure 21.Typical setup of USRP board
Source: [42].

On the mother board, there is the DC power input and the USB 2.0 interface. At this stage, USB 1.x is not supported at all.

- ADCs / DACs

There are 4 high speed 12 bit ADCs. The sampling rate is 64 M samples per second. In principle, it could digitize a band as wide as 32MHz. The ADCs can band pass sample signals of up to about 150 MHz, though. If it is sampled a signal with the IF larger than 32 MHz, it is introduced aliasing and actually the band of the signal of interest is mapped to some places between - 32 MHz and 32 MHz. Sometimes this can be useful, for example, someone can listen to the FM stations without any RF front end. The higher the frequency of the sampled signal, the more the SNR will be degraded by jitter. 100 MHz is the recommended upper limit.

The full range on the ADCs is 2V peak to peak, and the input is 50 ohms differential. This is 40 mW, or 16 dBm. There is a Programmable Gain Amplifier (PGA) before the ADCs to amplify the input signal to utilize the entire input range of the ADCs, in case the signal is weak. The PGA can be set from 0 dB up to 20 dB. Note that it can be used

other sampling rates if desired. The available rates are all submultiples of 128 MHz, such as 64 MS/s, 42.66 MS/s, 32 MS/s, 25.6 MS/s and 21.33 MS/s.
At the transmitting path, there are also 4 high speed 14 bit DACs. The DAC clock frequency is 128 MS/s, so the Nyquist frequency is 64 MHz. However, someone will probably want to stay below about 50MHz or so to make filtering easier. So a useful output frequency range is DC to about 50 MHz. The DACs can supply 1V peak to a 50 ohm differential load, or 10 mW (10dBm). There is also a PGA used after the DAC, again providing up to 20 dB of gain. Note that the PGAs on both RX and TX paths are programmable.

So in principle, it has 4 input and 4 output channels if it is used real samplings. However, it has more flexibility (and bandwidth) if it use complex (IQ) sampling.

- The Daughter Boards

On the mother board there are four slots, where can be plugged in up to 2 RX daughter boards and 2 TX daughter boards. The daughter boards are used to hold the RF receiver interface or tuner and the RF transmitter.

There are slots for 2 TX daughter boards, labeled TXA and TXB, and 2 corresponding RX daughter boards, RXA and RXB. Each daughter board slot has access to 2 of the 4 high speed ADCs / DACs (DAC outputs for TX, ADC inputs for RX). This allows each daughter board which uses real (not IQ) sampling to have 2 independent RF sections and 2 antennas (4 total for the system). If complex IQ sampling is used, each board can support a single RF section, for a total of 2 for the whole system. There numerous daughter boards available are:

BasicTX/ BasicRX $75	Nothing fancy on it. Two SMA connectors are used to connect external tuners or signal generators. It can be treated as an entrance to the ADC or an exit from the DAC for the signal without affecting it. Some form of external RF front end is required.
LXTX/ LFRX $75	Very similar to the BasicTX / BasicRX but they use differential amplifiers, allowing signals to be received at DC.
TVRX $100	Equipped with the Microtune 4937 Cable Modem tuner. This is a receive only daughter board that converts the VHF and UHF TV bands. The RF frequency ranges from 50 MHz to 800 MHz, with an IF bandwidth of 6 MHz. Useful for the reception of TV and FM signals, but it can also fulfill any receive only function in this frequency band.

DBSRX $150	Similar to the TVRX boards, this board receive only. The RF frequency ranges from 800 MHz to 2.4 GHz and has a channel filter tunable between 1 MHz and 60 MHz.
RFX Transceiver Series $275	Transceiver boards that are the choice for doing most two-way communication, whether analog or digital. There are a number of versions for operating in different frequency bands from 400 MHz up to 2.9 GHz.

Table 13.Daughter boards available
Source: [42].

- The FPGA

Probably the most important aspect for the GNU Radio user to understand about the USRP is what transpires in the FPGA. As shown in *Figure21*, all the ADCs and DACs are connected to the FPGA. It plays a key role in the GNU Radio system. Basically, it performs high bandwidth math to reduce the data rates to something you can manageably transfer over the USB2.0 link. The FPGA connects to the Cypress FX2, which implements the USB interface. Everything (FPGA circuitry and USB Microcontroller) is programmable over the USB2 bus.

Our standard FPGA configuration includes Digital down Converters (DDC) implemented with Cascaded Integrator-Comb (CIC) filters. CIC filters are very high performance filters that use only adds and delays. The FPGA implements 4 digital down converters (DDC), allowing 1, 2 or 4 separate RX channels. On the RX path, we have 4 ADCs and 4 DDCs, each of which has two inputs, I and Q. Each of the 4 ADCs can be routed to either the I or Q input of any of the 4 DDCs. This allows for selection of multiple channels out of the same ADC sample stream.

The Digital up Converters (DUCs) on the transmit side are actually contained in the AD9862 CODEC chips, not in the FPGA. The only transmit signal processing blocks in the FPGA are the interpolators. The interpolator outputs can be routed to any of the 4 CODEC inputs.

The multiple RX channels (1, 2, or 4) must all be the same data rate (i.e. same decimation ratio). The same applies to the 1, 2, or 4 TX channels, which each must be at the same data rate (which may differ from the RX rate). *Figure22* shows the block diagram of the USRP's receive path and the diagram of the digital down converter.

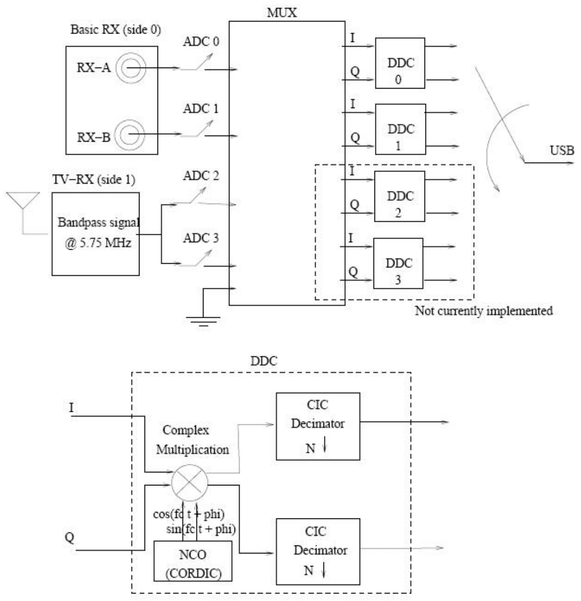


Figure 22.The block diagram of the USRP receive path
Source: [42].

6.1.1.3. UHD

UHD is the "Universal Software Radio Peripheral" (USRP) Hardware Driver. It works on all major platforms (Linux, Windows, and Mac); and can be built with GCC, Clang, and MSVC compilers. Several frameworks including GNU Radio, LabVIEW, MATLAB and Simulink use UHD. The functionality provided by UHD can also be accessed directly with the UHD API, which provides native support for C++. Any other language that can import C++ functions can also use UHD.

The goal of UHD is to provide a host driver and API for current and future Ettus Research products. Users will be able to use the UHD driver standalone or with third-party applications. UHD provides portability across the USRP product family. Applications developed for a specific USRP model will support other USRP models if proper consideration is given to sample rates and other parameters.

6.1.2. HSPDR

The HPSDR is an open source (GNU type) hardware and software project intended as a "next generation" Software Defined Radio (SDR) for use by Radio Amateurs ("hams") and Short Wave Listeners (SWLs). It is being designed and developed by a group of SDR enthusiasts with representation from interested experimenters worldwide.

The rationale behind the project is to break the overall design up into a number of modules. Each module is designed by an individual or group and connects to other modules using a pre-defined and common bus. This modular approach enables prospective users to incorporate just the modules that interest them as well as designing their own variants if desired. The approach also enables new ideas and circuits to be tested by replacing an existing module. Since the majority of modules will be retained, such experimentation can be done with minimum disruption to an existing working system.

6.1.2.1. HARDWARE BLOCK DIAGRAM

The following block diagram is a listing of the main parts of a HPSDR system. Note that there is a bold black line coming in which is the common +13.8v DC power and the blue line indicates the connection to the computer.

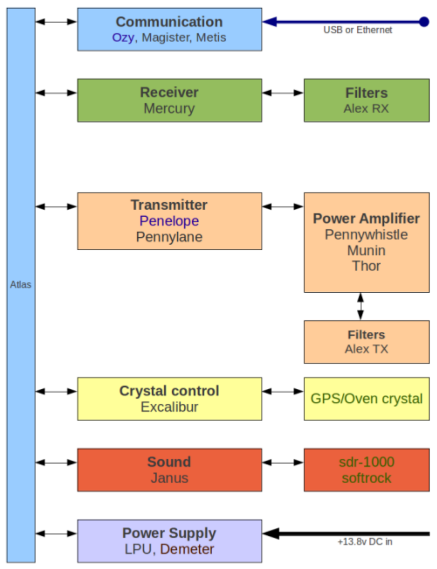


Figure 23.Hardware block diagram
Source: [43].

In the *Appendix I* there are the basic features of the main parts of the HPSDR system.

6.1.2.2. SOFTWARE BLOCK DIAGRAM

The following block diagram list the software currently available as open source to operate the HPSDR hardware. The blue line indicates the connection to the hardware.

There are other programs that can work with HPSDR hardware. Some these include WinRad, WinRadHD, CWSkimmer to name a few.

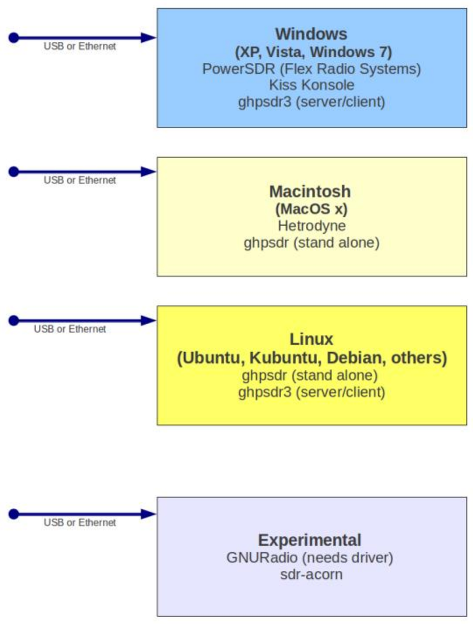


Figure 24.Software block diagram
Source: [43].

For more information about the software see *Appendix II*.

6.1.2.3. HERMES BLOCK DIAGRAM I

The following is a block diagram for the Hermes project. The Hermes project uses technology developed in the HPSDR boards but combines them in to two boards that fit in a Euro style box. This radio might be for those that wish to go mobile with their SDR or do not wish to use the modular approach used in the development of the other boards.

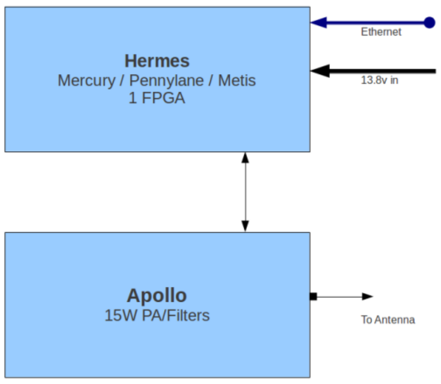


Figure 25.Hermes block diagram
Source: [43].

Hermes is a single board Digital Up and Down Conversion (DUC/DDC) full duplex HF + 6m multi-mode transceiver. It is basically the Mercury, Penelope, Metis and Excalibur boards rolled into one PCB. The board communicates to an associated PC via 100T/1000T Ethernet. *Appendix III* shows the Hermes hardware block diagram.

Apollo is to be a companion 15W PA and Low Pass Filter for Hermes. The idea is to build a self-contained HPSDR Transceiver into a box similar to the one used for the two Alex boards.

6.1.3. OSSIE

OSSIE is an open source Software Defined Radio (SDR) development effort based at Wireless@Virginia Tech. The project's primary goals are to enable research and education in SDR and wireless communications. The software package includes: an SDR core framework based on the JTRS Software Communications Architecture (SCA); the Waveform Workshop, a set of tools for rapid development of SDR components and waveforms applications; and an evolving library of pre-built components and waveform applications. In addition, free laboratory exercises for SDR education and training are being developed in cooperation with the Naval Postgraduate School. OSSIE is distributed under the GNU General Public License 2.0 or later (signal processing components and tools) and GNU Lesser General Public License 2.1 (core framework) [44].

6.1.3.1. CORE FRAMEWORK

The OSSIE project is written in C++ using the omniORB CORBA ORB, which is openly available. Current development is primarily focused on the Linux operating system, however they welcome reports from people trying to build on other operating systems, such as BSD, OSX, Windows, QNX and Integrity.

OSSIE implements key elements of the SCA specification. Backward compatibility will remain a priority as changes are made that enhance SCA compatibility. The 0.7.4 release runs on Intel and AMD based PCs. A release that includes enhanced support for embedded as well as PC-based applications is planned for fall 2009. Instructions will be provided detailing any changes needed for porting components to the new release.

6.1.3.2. PROCESSING HARDWARE/OPERATING SYSTEMS SUPPORTED

OSSIE 0.7.4 runs on the general purpose processor of most PCs using a recent version of Linux such as Fedora Core 10 or Ubuntu 9.04. A release that includes enhanced support for embedded processors is planned for fall 2009.

Experimental embedded versions have been ported to the following platforms:

- TI 320C6416 DSP (Lyrtech SignalMaster Quad);
- ARM 9 (OMAP Starter Kit and Lyrtech small form factor SDR board);
- Marvell PXA270 (Gumstix Verdex XL6P);
- PowerPC (Efika board);
- PowerPC 405 (Xilinx ML403 board);

6.1.3.3. RF/DATA ACQUISITION HARDWARE SUPPORTED

- Universal Software Radio Peripheral (USRP) and current daughter boards (Basic RX, Basic TX, DBSRX, RFX 400, RFX 900, RFX 2400, RFX 1200 and RFX 1800);
- Tektronix Test Equipment (loadable device wrappers for some equipment exist for OSSIE version C);

6.1.3.4. WAVEFORM WORKSHOP

This set of rapid prototyping tools allows users to create, run, observe, and control OSSIE signal processing components and waveform applications. The tools in the Waveform Workshop include:

- The OSSIE Eclipse Feature (OEF): This tool leverages the Eclipse open-source integrated development environment to provide a simple drag-and-drop interface for creating new waveform applications. It also provides GUI-based creation of signal processing components and autogeneration of skeletal code for interfacing with OSSIE and CORBA. In addition, OEF allows launching most OSSIE tools and applications from a GUI environment;
- The OSSIE Waveform Developer (OWD): This legacy tool provided much of the current functionality of OEF with a menu-based interface. OWD allows users to specify available devices on a given platform and to create the appropriate Device Manager profiles, and will be phased out once this capability is integrated into OEF;
- ALF, visualization and debugging environment for OSSIE waveform applications. ALF allows users to launch waveform applications, display them in block diagram form, and inject and/or monitor signals at various points in the application. ALF can be used for remote execution and monitoring of applications. Multiple instances of applications or multiple applications can run simultaneously, resources permitting. ALF also provides the capability to package and launch OSSIE signal processing components as self-contained applications, and to interconnect components that are running as part of the same application or in separate applications;
- The Waveform Dashboard (WaveDash) uses the SCA query and configures methods to allow users to interactively configure waveform applications at run time, from an easily customized GUI. This combined with the monitoring capabilities of ALF provides real-time feedback to students and researchers. WaveDash also eliminates the need to invest time in GUI development for prototype applications. Users can interactively specify which components and properties are visible, and select the appropriate type of control (text box, slider, etc.) for each property.

6.1.3.5. Application Software

Components currently distributed with OSSIE include those necessary to build narrowband AM and narrowband or wideband FM receivers. The USRP is assumed as the RF front end, but the applications can be adapted to other hardware. In addition, a demonstration transmitter that generates a predefined QPSK signal, a component that simulates an AWGN channel with phase offset and a QPSK receiver that counts bit errors are packaged with OSSIE. Additional digital components are included beginning with version 0.7.3.

6.1.3.6. Waveform Applications Demonstrated

- AM Receiver;
- Narrowband FM transmitter and receiver;
- Wideband FM receiver;
- BPSK/CVSD Voice transmitter and receiver;
- CIREN cognitive radio with BPSK/QPSK/16-QAM modulated packetized data transmitter and receiver;

6.1.4. ALOE

The Abstraction Layer and Operating Environment (ALOE) is an open source execution environment for software defined radios [45]. It is essentially based on a hardware abstraction layer, lightweight and time driven software architecture, and a simple interface format. ALOE accounts for heterogeneous multiprocessor platforms. Its cognitive computing source management capabilities enable flexible and dynamic management of SDR platforms and applications for distributed real time execution of applications and dynamic reconfiguration of platforms.

6.1.5. Concepts and functionalities

ALOE supports heterogeneous multiprocessor platforms, where a single silicon device may encapsulate several Processing Elements (PEs). A PE here abstracts any bounded silicon area-static logic (GPP, DSP, ASIC) or a Dynamically Reconfigurable Area (DRA). PEs with multitasking operating systems access the ALOE services through an Application Programming Interface (API). PEs without operating system (e.g., DRAs or ASICs) access the middleware services through a static logic interface.

ALOE abstracts the platform's physical network interfaces. The PE network (mesh, star, shared bus, or any other) has implications on the processing throughput and latency. The task of ALOE is to deal with these network characteristics while providing inter-PE communication capabilities as a service.

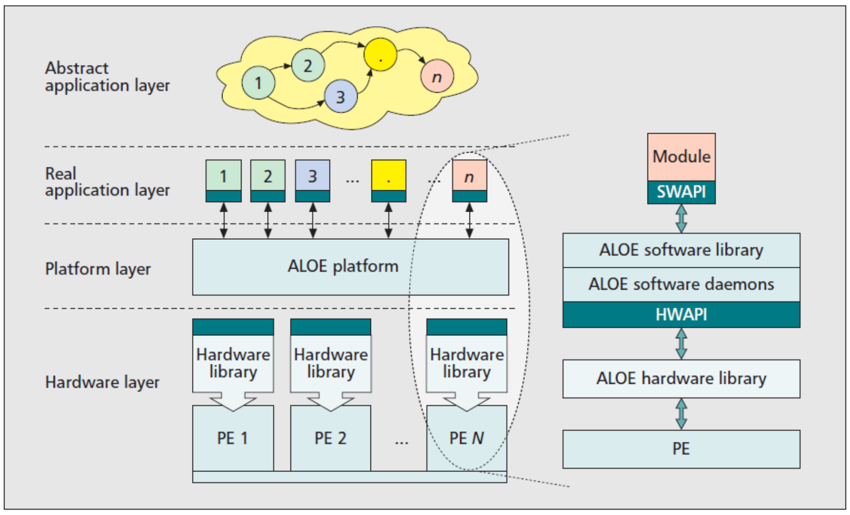


Figure 26.The ALOE layers
Source: "ALOE: An Open Source SDR execution environment with cognitive computing resource management capabilities" [45].

Figure26 illustrates the ALOE layers. The *hardware layer* at the bottom shows a cluster of PEs and their physical interconnection. The *abstract application layer* at the top consists of graphs that model the application tasks and their data flow dependencies. At the *real application layer* these tasks are treated as individual modules, which use the ALOE services for assembling the waveform. The *platform layer* provides a pseudo-homogeneous and virtual execution environment, where all tasks see the same abstract platform, the *ALOE platform*. It enables:

- Real time execution;
- Waveform execution control;
- Synchronized distributed computing;

- Packet-oriented data flows;
- Cognitive computing resource management;
- External configuration and management;

6.1.6. Architecture and services

The ALOE architecture encompasses several components that enable hardware independent access to ALOE services. The ALOE services are implemented as isolated modules (*software daemons*), which run as background processes on the PEs. An application *module* interacts with the system through the software API (SW API).

The SW API enables a seamless access to the *ALOE software library*, which interacts with the software daemons via the hardware API (HW API). This ensures the portability of all layers above the HW API. Hence, only the *ALOE hardware library* is platform specific.

The ALOE hardware library abstracts the hardware specific management functions, including task or process creation and management, variable management, and interfacing and timing issues. Each PE implements these functions in a different manner. The HW API provides a standard interface for accessing the PE-specific hardware library. The ALOE software library, on the other hand, implements the services that are required by the application modules. It can be considered a link between the application and the ALOE software daemons, providing functions for the creation of data flows, statistics, and log files, among others. The application programmer uses the SW API for accessing these functions.

	ALOE	SCA	GNU Radio
Program model	Multiprocessor One process per module Time-driven	Multiprocessor One process per module Event-driven	Single processor One process per core Event driven
Application range	Digital signal processing (DAGs)	Any	Any
Hardware support	GPPs, TI DSPs, FPGAs	GPPs, TI DSPs, FPGAs	GPPs
Software requirements	RT POSIX or DSP BIOS	RT POSIX or DSP BIOS + ORB middleware	Linux + Python
Data interfaces	FIFO-like, message-based	Remote/local procedure calls. CORBA-IDL	Local procedure calls
Interface latency	Fixed, packet size and location independent Internal: 1 time slot External: 1 time slot	Medium-high Internal: 9.1 µs/kbyte External (over RapidIO): 45 µs/kbyte	Low Internal: 0.41 µs/kbyte External not allowed
Processing overhead	2.1 %	N/A	6 %
Test waveform throughput	1.28 Mb/s	0.72 Mb/s	0.59 Mb/s
Size overhead	GPP: 16 MB + 260 KB/module DSP: 208 kB + 21 kB/module FPGA: 4%	GPP: 32 – 64 MB DSP: < 1MB FPGA: 11%	GPP: 32 – 64 MB DSP: N/A FPGA: N/A
Computing resource	Computing resource awareness (plug-and-play), resource monitoring	None	None
Task mapping and scheduling	Automatic mapping at runtime, pipelined scheduling	Manual mapping at design time, operating system scheduling	Single processor, best effort scheduling
Dynamic reconfiguration	Supported: well defined execution status enables a pipelined loading, initialization and replacement of components	Partially supported: application definition must be reparsed and interfaces recompiled	Supported, but must be implemented in Python

Table 14.Comparision between ALOE, SCA and GNU Radio
Source: "ALOE: An Open Source SDR execution environment with cognitive computing resource management capabilities" [45].

Table13 compares ALOE with the SCA and GNU Radio. The simplicity of the ALOE implementation, providing specific services for digital signal processing applications, explains the low memory and area overheads. ALOE guarantees deterministic interface delays, which are data and location independent.

Although the SCA and GNU Radio have both been designed for SDRs, they can be applied to other computing contexts as well. This increases their scope but decreases the performance of digital signal processing applications and resource-constrained platforms. The abstraction layer and operating environment (ALOE) is an alternative SDR framework. It targets multiprocessor platforms and embedded systems with tight resource constraints. ALOE is a lightweight, open source SDR framework with cognitive computing resource management capabilities. It is not SCA-compliant and uses a specific message passing scheme instead of CORBA.

6.2. WAVEFORM DEVELOPMENT

The waveform in software defined radio (SDR) is the important application software which fulfills the function of communication [46]. The waveform development is one of the most important aspects in the industry of SDR. In order to improve its portability and reusability, the waveform software should be developed according to a special flow. In some sense the design and development of communication systems based on SDR is turning to the development of waveform software.

6.2.1. PRELIMINARY KNOWLEDGE NEEDED IN SDR WAVEFORM DEVELOPMENT

The Software Communication Architecture (SCA) specification specifies the hardware architecture, software architecture, security architecture and application program interface (API). The SCA specification is built on the existing commercial infrastructures and is independent from bottom hardware. The goals of SCA specification includes reducing the development expense through adopting existing commercial standards and reducing the development time through reusing existing components. The final idea is to guarantee the portability of software and the reconfigurability of hardware platform.

The essential of the SCA specification is an open and universal architecture which provides a standard, open and interoperational communication software platform for radio. Through this software platform, the bottom hardware is isolated from the software which implements the waveform function. Accordingly those characteristics such as portability, reconfigurability, scalability and reusability can be realized.

The software infrastructure in SCA specification is shown in *Figure27*. Apparently it is a layered architecture and those layers are respectively device driver, operating system, CORBA middleware, application environment profile, framework control service interface and waveform application from the top down. The layer of waveform application component shown in *Figure27* is called application layer. It mainly finishes the user’s communication function such as digital signal processing in MODEM level, protocol processing in data link and network level, routing in internet, security processing and embedded application, etc.

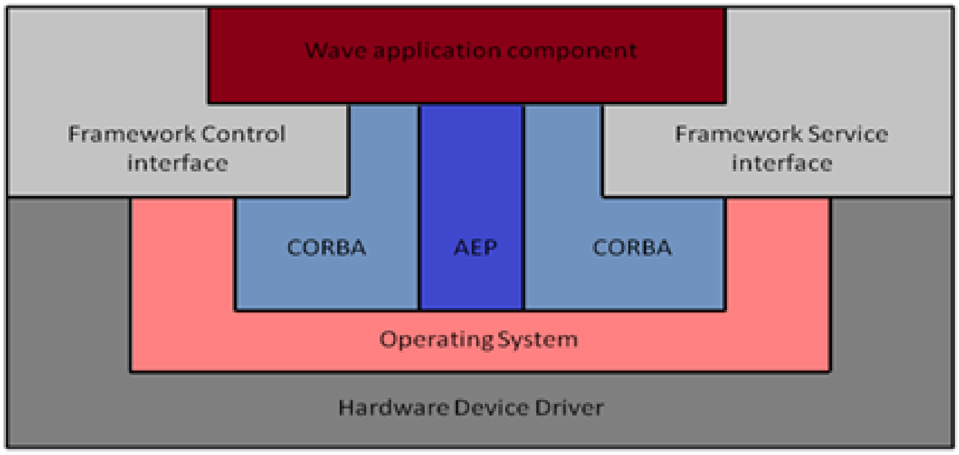

Wave application component
Framework Control interface
Framework Service interface
CORBA
AEP
CORBA
Operating System
Hardware Device Driver

Figure 27.Layered software architecture in SCA specification
Source: “The general waveform development flow of Software Defined Radio” [46].

By all appearances the waveform of SDR is a kind of application. The SCA specification doesn’t specify particular means and process about the detailed realization, but this doesn’t mean that there is no any requirement about waveform development. In fact the SCA specification clearly specifies how the waveform application interacts and interfaces with operating environment. And it also specifies that the waveform application should use the interface and service provided by the Core Framework (CF). The direct access to operating system is limited within the services defined by the SCA POSIX, too.

6.2.2. The composition of SDR waveform

Following it is identified the features required to support a component based on software radio application that can run on a modular, reconfigurable platform. This helps in understanding some of the design decisions in the SCA.

In the SCA context any radio application is known as a waveform. Let us start the requirements identification by considering the two general waveforms, W_1 and W_2, shown in *Figure28*.

$C_{i,j}$: is a standalone entity that performs some sort of signal processing or control functionality required by the waveform.

Components can have multiple implementations, each one targeted to a specific processing device D, while preserving their functionality and interfaces. In *Figure28,* $C_{2,1}$ is depicted as having three different implementations.

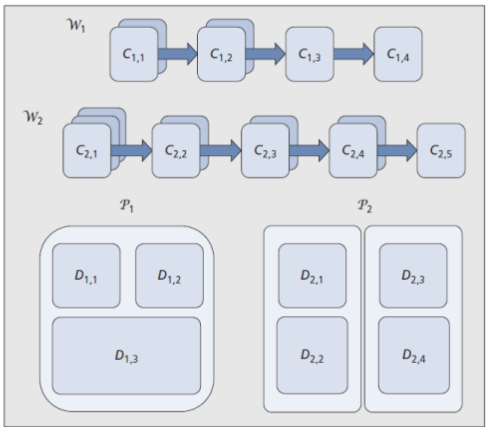


Figure 28.Block diagrams of sample SDR waveforms and platforms.
Source: “Understanding the Software Communications Architecture” [27].

Both waveforms are supposed to run on the two platforms, P_1 and P_2. These platforms have different reprogrammable processing devices, $D_{m,n}$, and while the nature of them is inconsequential, let assume that at least one of them is a digital processor. Consider P_1 a single board platform, where no new elements can be added. P_2, on the other hand, is modular, and extra processing elements can be added.

Component Model	Defines the semantics of components, the interfaces that are expected from them, and the protocols to manage and exchange information with other components.
Operational Environment	The decision of which waveform is to be deployed on which platform is made at runtime. Therefore, it is need to develop waveforms independent of their final deployment configuration. It guarantees the independence of the waveform.
Applications Factory	Launch waveforms. This artefact must find the waveforms in memory and perform all the required tasks to deploy them on the selected platform.
Assembly Instructions	Launching a waveform requires, at minimum, finding, loading, and instantiating each individual component on the appropriate device in the platform, connecting the components, and performing any initialization tasks necessary to have the waveform running properly. It is needed to pass in the Application factory all these A*ssembly Instructions* for our waveforms.
File System	Memory. It is a way store, organize, and access memory.
Middleware	Guarantees the communication mechanism between components. Each waveform should be able to be deployed on both platforms without changing its logic and granularity. Given the modular nature of P_2, we need a communication mechanism to exchange information and data across different nodes on the platform.
Manager	Mechanism that control and keep track of all the available hardware and software resources, and to interface with the user.
Proxies for Physical Devices	It is a way to interact with different hardware components. This will give the ability to configure them, and to Exchange data and control information with them.
Capacity model	Describe the available resources and requirements. Different platforms will have different physical capacities which may be reconfigurable and unknown at development time. Similarly, different waveforms will have different resource requirements. It is necessary to validate that the hosting platform has enough capacity for the waveform at hand.

Table 15.SCA CF Interfaces.

Source: "Understanding the Software Communications Architecture" [24].

6.2.3. SCA SPECIFICATIONS

The SCA defines in the CF a core set of interfaces that rule the deployment and management of waveforms and their components. These interfaces define the architecture and other tedious low level details of the system, allowing developers to focus only on applications. The SCA CF includes base application interfaces, base device interfaces, framework control interfaces, framework services interfaces and domain profile. The SCA CF interfaces are defined in CORBA's Interface Description Language (IDL). A simplified diagram of their relationships is shown in the following figure.

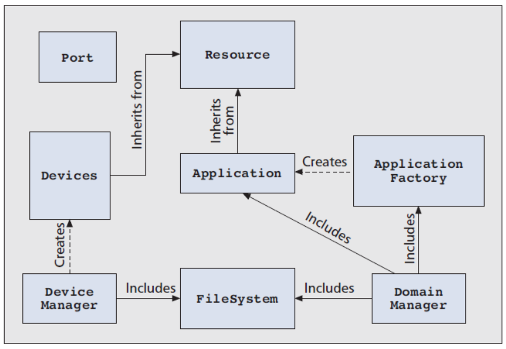


Figure 29.Simplified SCA CF IDL Rrelationship
Source: "Understanding the Software Communications Architecture" [27].

Base Application Interfaces	
In the SCA, all waveform components are required to implement the base application interfaces. At the highest level of these interfaces is the *Resource* interface, which provides a common interface for the control and configuration of software components. This interface enables component control and inherits from the following base interfaces.	
LifeCycle	Is used to initialize or release the resource.
TestableObject	Provides resources with built-in test capabilities.
PropertySet	Provides operations to configure and query resource properties.
PortSupplier	Provides an operation to get a port object reference.
Port	Is used to connect *Resource* components. Enables components to exchange data. Ports are classified into *Uses* ports (clients) and *Provides* ports (servers). The Port interface also provides components with the connect and disconnect functionalities necessary to assemble waveforms.
ResourceFactory	Optional interface modelled after the Factory design pattern, and used to create and tear down resources.

Base Device Interfaces	
The device-related interfaces allow interaction with physical hardware devices by providing a proxy to the rest of the framework. This abstraction allows non- CORBA-enabled elements to interact with other components and the rest of the framework. Device-related interfaces include:	
Device	Provides a logical representation of hardware devices. It inherits from the *Resource* interface, extending it to provide status and capacity management (allocate and deallocate capacities). An ASIC or a dedicated piece of hardware is a typical example of physical hardware represented by this interface.
LoadableDevice	Extends the functionality of *Device*. It adds loading and unloading capabilities that modify the runtime behaviour of the physical device. FPGAs and DSPs are typical examples of hardware components represented with this interface.

ExecutableDevice	Extends the *LoadableDevice* interface by allowing it to execute and terminate resources. A typical example of a device represented by this interface is a GPP, although any processor with multithread capabilities can be represented by this interface.
AggregateDevice	Is used to represent composite devices, which can be made of multiple logical devices but display a single interface to the domain.

Framework Control Interfaces	
These interfaces provide management and control capability to the CF over the whole radio domain. These interfaces allow consistent deployment, configuration, and management of waveforms and platforms.	
ApplicationFactory	Used to create instances of a specific waveform. It obtains assembly instructions from the *Domain Profile*. These instructions include a list of the components that make up a waveform, their location, and their respective connections. It finds suitable *Devices* based on available capacity, launches the components, establishes the respective connections, and performs initial configuration and initialization
Application	After creating an application, *ApplicationFactory* returns an instance of the *Application* interface. This interface provides a container for all resources in a waveform, enabling waveform configuration and status inquiries in a single interface. This interface is also in charge of terminating the application, releasing all the resources used and returning the allocated capacities to host devices.
DeviceManager	Used to manage a set of logical devices and services. Usually, this interface is used to represent a CORBA-enabled board. When instantiated, *DeviceManager* creates a file system for the board it represents and launches all of the logical devices under its control. *DeviceManager* also obtains the location of *DomainManager* and registers itself as part of the radio domain.
DomainManager	The *DomainManager* interface controls and maintains the overall state of the radio. It creates a *FileManager* that will contain the *FileSystem(s)* of every *DeviceManager* registered under its domain. At instantiation, *DomainManager* also sets up the naming context for the radio in the CORBA naming service. *DomainManager* provides registration interfaces for *DeviceManagers*, *Devices, Applications, and Services*, manages access to registered device managers and installed applications, and provides the user interface.

Figure30 provides a graphical description of the simplified operation of *ApplicationFactory*.

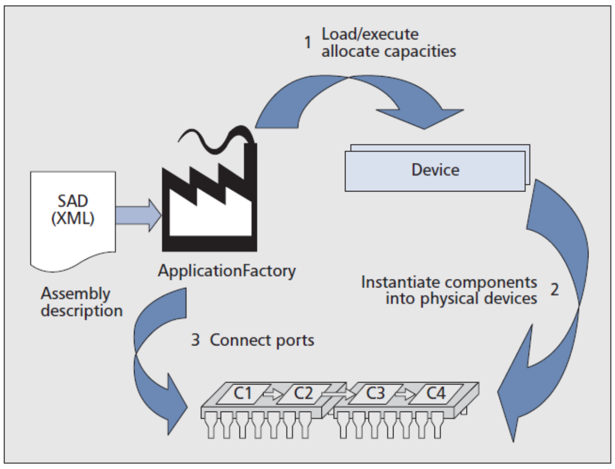

1 Load/execute allocate capacities
Device
SAD (XML)
ApplicationFactory
Assembly description
Instantiate components into physical devices 2
3 Connect ports
C1
C2
C3
C4

Figure 30.Application Factory behaviour
Source: "Understanding the Software Communications Architecture" [27].

Framework Services Interfaces	
These interfaces are used to perform all file-related operations. These interfaces allow files to be accessed across distributed SCA platforms.	
File	Provides access to individual files and their basic operations (e.g., read, write, close) within the radio's domain.
FileSystem	Allows remote access to physical file systems, and the creation, deletion, copying, and so on of files. Typically, a *FileSystem* is limited to one piece of hardware or a single OS.
FileManager	Allows the management of multiple distributed *FileSystems*. It can be seen as a root file system that mounts and unmounts other file systems.

Domain Profile
Includes in a set of files all the information concerning applications and platforms within the SCA. These files describe the interfaces, capacity models, properties, inter-dependencies, interconnections, and logical location of each and every component within the domain. These descriptions are provided in Extensible Markup Language (XML).

A visual description of the relationships among *Domain Profile* descriptors is shown in the following figure.

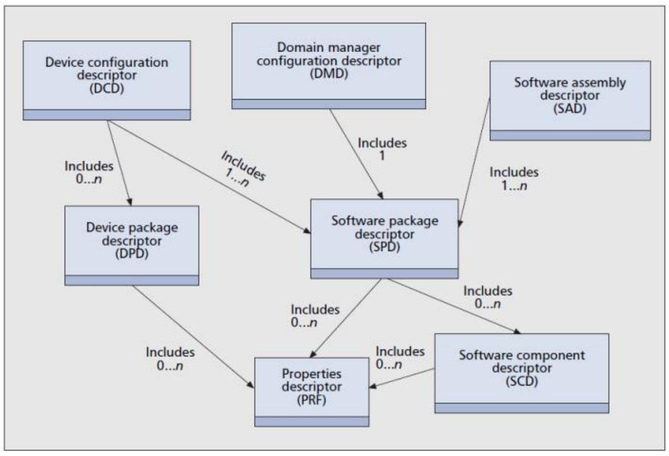

Device configuration descriptor (DCD)
Domain manager configuration descriptor (DMD)
Software assembly descriptor (SAD)
Includes 0...n
Includes 1...n
Includes 1
Includes 1...n
Device package descriptor (DPD)
Software package descriptor (SPD)
Includes 0...n
Includes 0...n
Includes 0...n
Includes 0...n
Properties descriptor (PRF)
Software component descriptor (SCD)

Figure 31.XML Domain Profile Relationship
Source: "Understanding the Software Communications Architecture" [27].

Software Package Descriptor (SPD) files describes software components and their implementations. The interfaces provided and used by each component are described in the Software Component Descriptor (SCD), and a reference to this file is included in the SPD. The particular properties of each component are described in the PRF. A property is the representation of any physical or logical characteristic.

Waveforms are described by a Software Assembly Descriptor (SAD) file, which includes a list of the components, specific deployment requirements and configurations, and connections between them. The SAD file references an SPD for each of the components in the waveform.

Platform characteristics are described by the Device Package Descriptor (DPD) and Device Configuration Descriptor (DCD); both are also known as the *Device Profile*. Each hardware component is described by a DPD and an SPD addressing its hardware and logical representations, respectively. The DPD also references a PRF, which describes the properties of the device being deployed such as serial number, processor type, and allocation capacities. The DCD contains a list of the devices initially deployed at start-up by the *DeviceManager* and the required information to locate the *DomainManager*.

6.2.4. THE GENERAL WAVEFORM DEVELOPMENT FLOW OF SDR

The guiding principle in designing the SDR is as follow: "develop once, run anywhere" [46].

This is different from the traditional method in which all development must start anew each time the function changes. In order to obey the aforementioned rules and improve the portability and reusability of waveform software, a special flow should be followed when one develops the waveform application.

6.2.4.1. THE EARLY WAVEFORM DEVELOPMENT FLOW

Before the appearance of visual integrated development environment (IDE), the development of SDR waveform which conforms to the SCA specification is finished through writing different kinds of code manually. The detailed flow is shown as *Figure32* and we can see every step involves writing code manually. This flow requires a thorough mastery on the SCA specification and is very complicated and fallible. Because of the appearance of IDE for waveform development, this flow is outdated now.

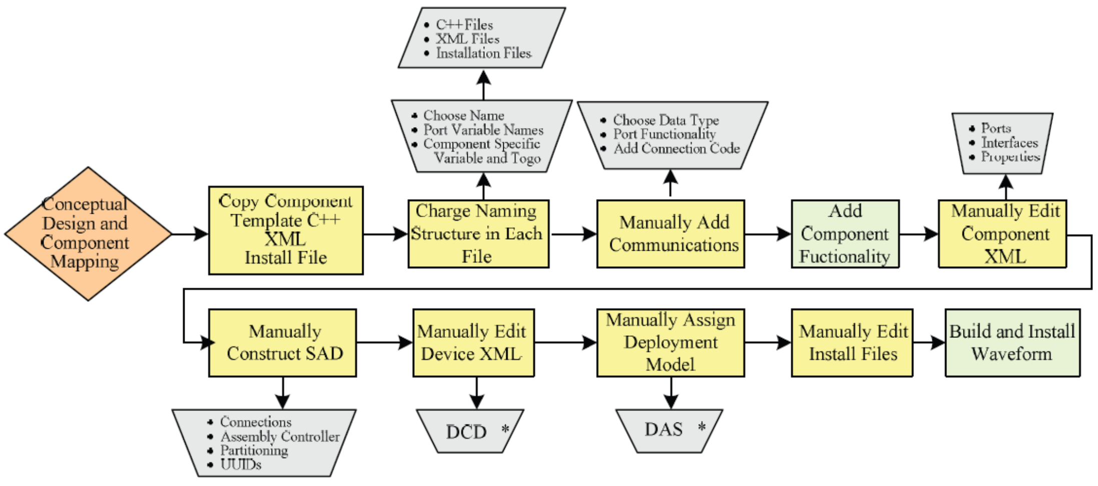

C++Files
XML Files
Installation Files
Choose Name
Port Variable Names
Component Specific Variable and Togo
Choose Data Type
Port Functionality
Add Connection Code
Ports
Interfaces
Properties
Conceptual Design and Component Mapping
Copy Component Template C++ XML Install File
Charge Naming Structure in Each File
Manually Add Communications
Add Component Fuctionality
Manually Edit Component XML
Manually Construct SAD
Manually Edit Device XML
Manually Assign Deployment Model
Manually Edit Install Files
Build and Install Waveform
Connections
Assembly Controller
Partitioning
UUIDs
DCD *
DAS *

Figure 32.The flow of manual developing the SDR waveform
Source: "The general Waveform Development Flow of Software Defined Radio" [39].

6.2.4.2. The General Waveform Development Flow of SDR in IDE

Aiming at those shortcomings in the traditional flow and in order to satisfy the requirements on portability, the Object Management Group (OMG) proposed a new method for waveform development. This method is the famous Model Driven Architecture (MDA).

These IDEs can automatically generate many skeleton and code which were written manually before. This is helpful for reducing mistake, improving the efficiency of waveform development and improving the compatibility with SCA specification. The general waveform development flow of SDR based on IDE is shown in *Figure33*.

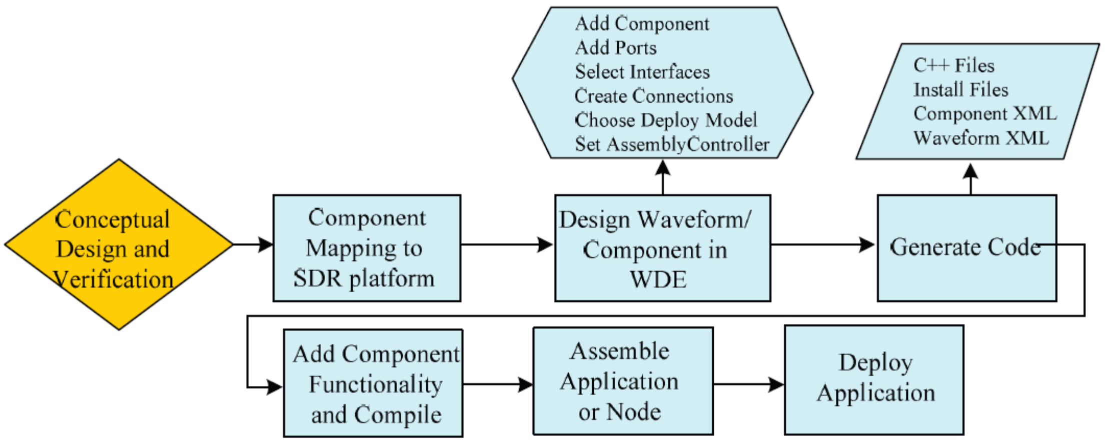


Figure 33.The general waveform development flow of SDR in IDE
Source: "The general Waveform Development Flow of Software Defined Radio" [46].

As shown in *Figure33*, the general waveform development flow based on IDE can automatically generate all kinds of files defined in the *Domain Profile* and the skeleton code of the waveform application. The remainder work is adding the necessary code which performs digital processing manually. The every step in *Figure33* is explained as follow.

- SDR waveform components mapping to SDR platform

The mapping from SDR waveform components to SDR platform means the assignment of waveform components on the processing elements in the SDR platform according to function requirement and computation burden. The processing elements in SDR platform include four categories: GPP, DSP, FPGA and ASIC. Generally speaking, the high speed waveform components will be arranged on the FPGA or ASIC, and the low speed components could be arranged on the GPP.

- SDR waveform component modelling

Those components such as *Resource, Device, Adapter, DeviceManager* and *AssemblyController* are the basic elements composing the SDR waveform. The concept of component modelling in IDE means the determination of input/output port and their types and the accession of corresponding properties and description. The sketch map of component modelling is shown in *Figure34*.

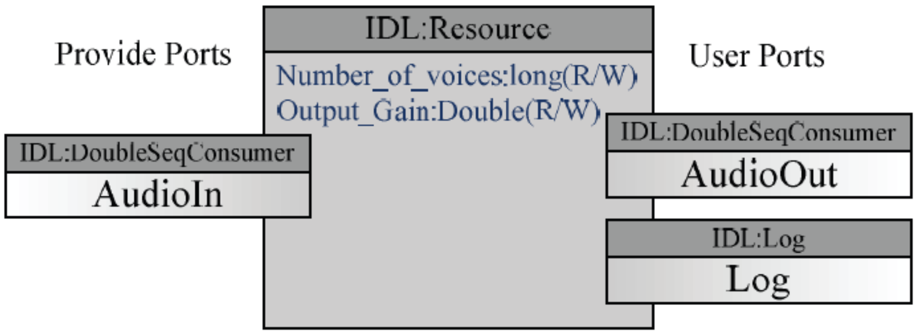


Figure 34.SDR Waveform component modelling in IDE
Source: "The general Waveform Development Flow of Software Defined Radio" [46].

When creating the *Resource* or *Device component*, we should use as little granularity as possible to model them and this is helpful for the reuse and portability of waveform. At the same time we must notice that the property and port modelling is different from the component modelling. Some property, port and interface can be created through reusing *ComponentTypes*, but others need be imported using the interfaces defined using CORBA IDL.

- The skeleton code generation, arithmetic integration and compilation of SDR waveform component

The next step after component modelling is the skeleton code generation using the function provided by IDE. The code can deal with the problem of lifecycle in CORBA/SCA and it needs no incorporation when the model is modified or the code is regenerated. Because these skeletons are empty, the code fulfilling the signal processing function should be added (called arithmetic integration) and compiled according to the prospective operating environment.

- The assembly of SDR waveform application and node

As mentioned before, the waveform application of SDR is the combination of different components which implement different function. So the SCA application or node is defined as the assembly of separate components. The model of assembly provides the following information: the types of components which are used in the assembly, the number of component instantiation of each type and the instantiation of interconnection between ports of specified component, etc. In IDE the assembly of a waveform application or node only needs a simple paradigm blocking plan. The components can be dragged into an assemble placement. This method can realize reengineering and verify the existent assembly to indicate or resolve the possible problems. It also provides the real-time model verification and a packaging property to create a document from all SCA production.

- The installation, deployment and test of the application

The waveform application must be installed before it can be used. Similar to the Personal Computer (PC) world, the installation of an application means the copy of all files into target platform. In order to use an application, we must deploy it onto the hardware platform. Through deployment the independent components will be loaded on the appropriate devices and then be instantiated. The connection will be established and the application will be configured to the default state. Once an application is expanded, we can monitor and control it through user interface. In the IDE such as SCARI Suite, we can install, deploy and control an application through *RadioManager*. After the installation and deployment, the system should be tested to determine whether it can implement the desired function.

6.2.5. SOFTWARE RADIO DOWNLOAD

The increased amount of software installed in wireless devices includes both application software and operational software, such as radio software used to implement software defined radio capabilities [47].

Application software is the software that resides at and deals with the highest layer in the communications protocol stack. Application software is usually directly executable by the device user to satisfy a specific need.

The operational software is all the software other than application software. It includes the operating system, drivers, radio software and middleware. All the software needs to support the applications on the wireless device.

Radio software is the primary software within a wireless device; it is coupled with the radio hardware to derive the overall radio functionality. Ancillary software (e.g., control) that may be needed as a consequence of the primary software is an inherent part of this definition. Radio software includes reconfiguration data and reconfiguration executable code.

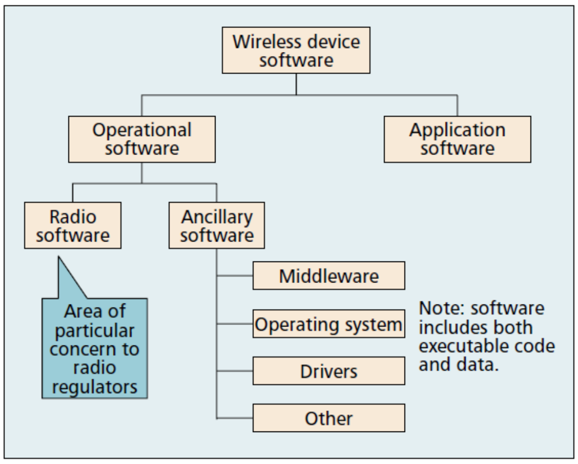


Figure 35.Software/Firmware categories in commercial wireless terminals
Source: "Radio Software Download for Commercial Wireless Reconfigurable Devices" [47].

6.2.5.1. Software Radio Download Requirements

The requirements for radio software download can be broadly divided into general requirements, requirements related to each individual step in the download process, SDR device requirements, and requirements for the network that supports radio software downloads. A critical general requirement is that any downloaded radio software installed on an SDR device must not malfunction or cause the SDR device to emit undesirable radio frequency waves. It is also required that billing, licensing, ownership, and maintenance agreements be in place between the SDR device user and the service provider, network operator, equipment and software manufacturer, and software vendor prior to the download and installation of a radio software module.

The process of downloading radio software to an SDR device can be broken down into several individual steps such as discovery of the need for download, initiation of download, download setup, mutual authentication, authorization, capability exchange, download acceptance exchange, protection (encryption), software download, installation, in situ testing, nonrepudiation, reset and recovery, and termination.

Appendix IV illustrates the download process steps and outlines the major requirements.

A crucial requirement for reconfigurable SDR devices that support radio software download is a Reconfiguration Manager (RM) that oversees the processes of radio software download, installation, reconfiguration, in situ testing, and recovery. Such an RM is required to reside on the SDR device in a secure software area that is not subject to reconfiguration, and is responsible for enabling full or partial reconfiguration of all protocol stack layers of the SDR device, controlling and managing reconfiguration processes at the SDR device, ensuring that the anticipated configuration adheres to the given radio access system standards, and communicating with any RM entities residing on the network side to coordinate radio software download and reconfiguration.

SDR devices are required to perform mode monitoring and service discovery to seek alternative modes of operation and services, and select the most appropriate mode of operation for the desired service, including software radio download. SDR devices also need to be equipped with sufficient additional memory space beyond that required for normal modes of operation to support all of the above-mentioned functions. Additional memory is no longer considered to be an impediment to the implementation of SDR capabilities. A network supporting radio software downloads needs to meet certain specific requirements. The architecture of such a network needs to also support reconfiguration management (RM) functionalities. These network RM functionalities are responsible for maintaining a database of current configurations and capabilities of SDR devices in the network, scheduling radio software downloads to SDR devices, supporting efficient downloads to a large number of SDR devices, maintaining and coordinating access to software repositories of third-party vendor and original equipment manufacturer (OEM) software modules, communicating with local RMs residing on each SDR device to coordinate radio software download, reconfiguration, mode identification, mode monitoring, mode negotiation, and mode switching. An operator needs to forecast and provision sufficient network and radio resources to support radio-software-download-related traffic in addition to regular user traffic.

6.2.5.2. Differences in download requirements

A major difference, between radio software download and other downloads is that a Regulatory Agency (RA) might impose certain obligations on the process of radio software download to address specific radio-related concerns.

For example, it is a regulatory requirement that in general the device must provide some means of indicating its current “type approval” or “conformance acceptance,” often a physical label attached to the device [47]. However, the specific need with SDR is that the indications must be associated with the radio configuration that is downloaded. This is because the radio characteristic of the device is changed after a download and reconfiguration. Consequently, the currently accepted practice of a physical label becomes untenable. Therefore, download and device management may need to include how an electronic variant (proposed in some regulatory jurisdictions) of this labeling might be accommodated and how the device could provide information as to its current version/variants. This criterion is beyond that typically needed in the application download regime.

Another RA-related requirement is that the radio must not be able to operate with an unapproved configuration. Therefore, a security mechanism must be built into the radio to prevent malicious or accidental reconfiguration.

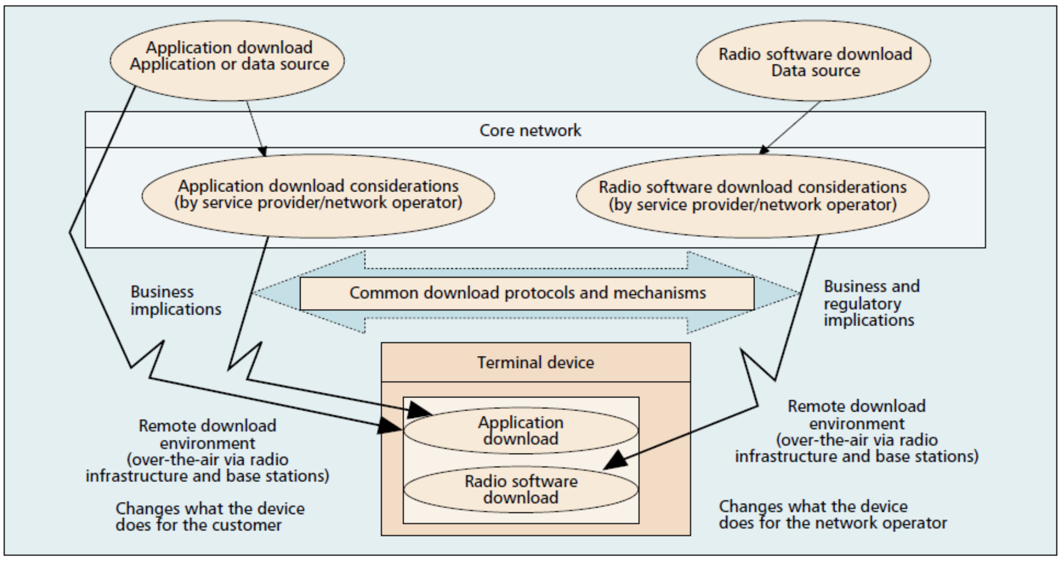


Figure 36.Download to a terminal device
Source: “Radio Software Download for Commercial Wireless Reconfigurable Devices” [40].

There are other differences, although lesser ones. For example, in radio software download, stronger authentication may be required. Verification of a downloaded module may need different techniques than other downloads. Further to the point, referring to *Figure36* is a difference in philosophy that provides an overarching difference between application and radio software downloads. In the application arena, the failure of the application (e.g., a game) may result in disappointment of the customer with no additional harm done. In the radio software arena, failure of the radio software (e.g., frequency selection and modulation) may result in a customer having a non-functional radio device or, worse, a device that functions inappropriately and disturbs other users or radio services. The mechanisms to download may be the same; the specifics and scope can vary to satisfy the imposed criteria.

6.2.6. STANDARDIZATION

It is essential to analyse which are the appropriate elements to be standardized and which industry for are the relevant parties to address these aspects. Is it the architecture, protocol, interfaces, management? For operational software download, particularly in an OTA environment, it is evident that certain elements should be standardized. The released standards and ongoing work on the download of applications certainly provides guidance for the download of operational software, including radio software. As has been pointed out, operational software is a close relative of application software, and consequently can and should build on the foundation work done on applications software.

It is desirable that any OTA download be independent of the radio interface technology and the core network to the greatest extent possible.

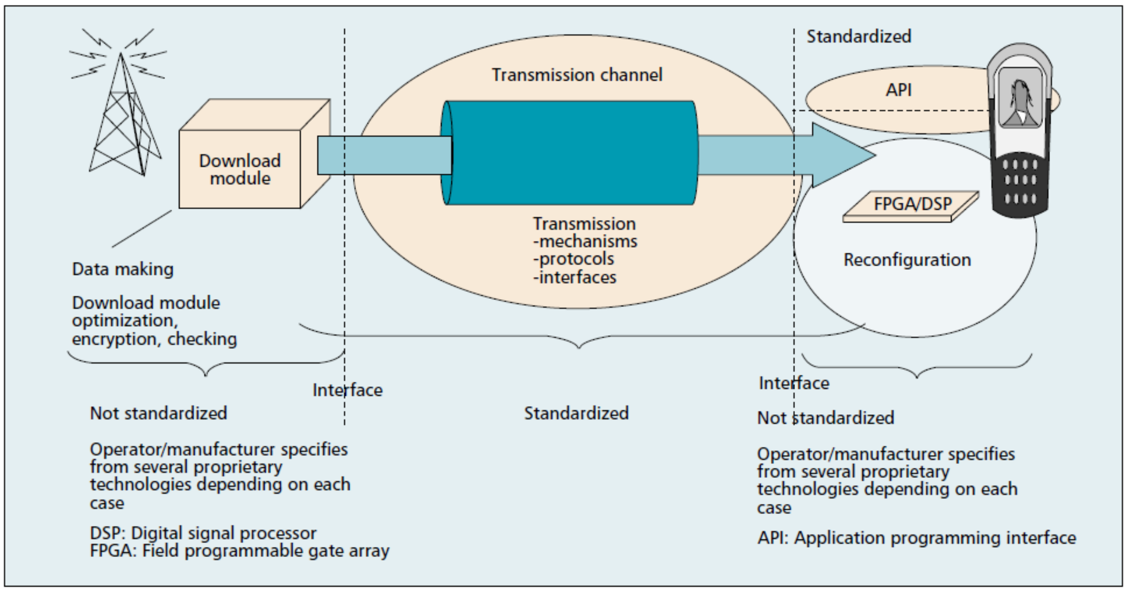

Standardized
Transmission channel
API
Download module
FPGA/DSP
Transmission
-mechanisms
-protocols
-interfaces
Reconfiguration
Data making
Download module optimization, encryption, checking
Interface
Not standardized
Operator/manufacturer specifies from several proprietary technologies depending on each case
DSP: Digital signal processor
FPGA: Field programmable gate array
Standardized
Interface
Not standardized
Operator/manufacturer specifies from several proprietary technologies depending on each case
API: Application programming interface

Figure 37.Which part should be standardized and which not?
Source: Panasonic Technologies [47].

Sufficient standardization is required to ensure adherence to the protocols and procedures, perhaps down to the level of a standardized “sandbox” (partitioned memory/code) in a device where the transition takes place between the standardized world and the internal proprietary regime.

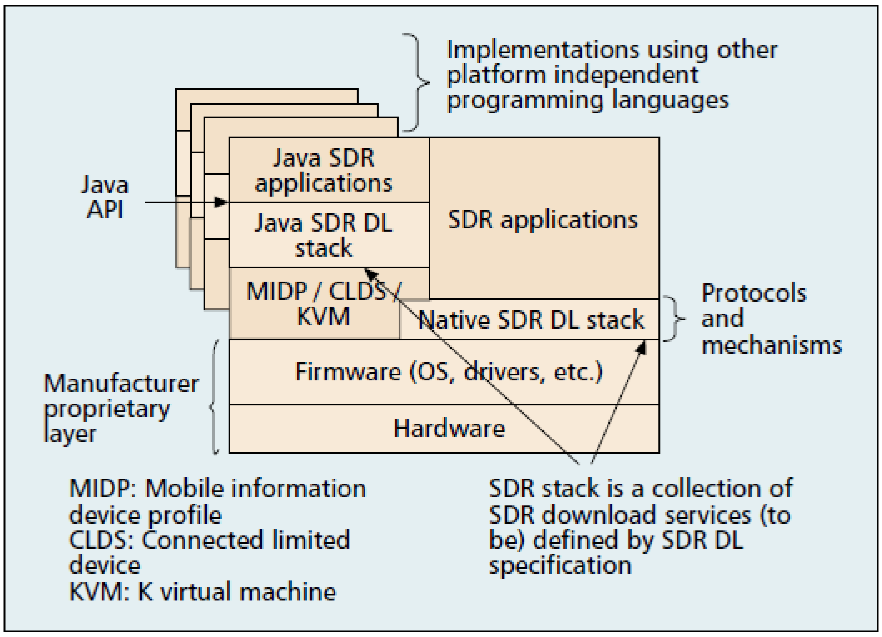

Implementations using other platform independent programming languages
Java API
Java SDR applications
Java SDR DL stack
SDR applications
MIDP / CLDS / KVM
Native SDR DL stack
Protocols and mechanisms
Manufacturer proprietary layer
Firmware (OS, drivers, etc.)
Hardware
MIDP: Mobile information device profile
CLDS: Connected limited device
KVM: K virtual machine
SDR stack is a collection of SDR download services (to be) defined by SDR DL specification

Figure 38.Possible SDR download hardware and software stack
Source: Panasonic Technologies [47].

6.2.7. Libraries

The reusability of software is one of the main targets of SDR. The SDR software framework can be shared by different system. But the software modules for different standard are different [48]. The new air-interface standards typically rely on well-understood protocols of predecessor systems. Cost intensive re-engineering of software can be avoided and software can be re-used if designed in a suitable way. Modular software design entails several advantages. On the one hand, portability of dedicated functionality is supported. Using well defined interfaces, the same module can operate within different systems. On the other hand software-upgrades are easily facilitated, as the respective modules can be changed individually.

In the multi-standard SDR BB, the reusability of protocol software is reached through library definition.

Through identification of commonalities and difference of different standards, protocol libraries can be defined as common library, dedicated library. For BB part, the software modules mainly focuses on the development of base band signal processing which basically performs chip- and symbol- rate processing in both downlink and uplink, as well as frame protocol terminations, and so on. The comprehensive software modules for base band signal processing, which will be used in multi-standard environment, have to be clarified into three libraries (pools), as depicted in *Figure39*, in whatever downlink and uplink:

- Dedicated system libraries

These libraries consist of the unique functions in the specific air interface environment, identified by different standards, for example, UMTS-FDD and HSDPA, e.g. 16QAM modulation scheme for HSDPA, and 1st interleaving function for UMTS-FDD, etc. They have to be downloaded immediately to the unique hardware accordingly. Making the connections of the specific building blocks is necessary before the radio link in the air interface protocol required is really set up.

- Common system libraries

When different standards are operated simultaneously, the components in these libraries will help to build up the common functional blocks in the processing chain, for example HSDPA and UMTS-FDD, which includes CRC attachment, spreading, QPSK, TPC, TFCI, Pilot bits, etc. All these elements will be downloaded during the radio link setup procedure.

- Common algorithm libraries

Generally, they consist of basic functions that are widely used in scientific and Telecom areas, such as Filtering function, Complex/Real FTT, function, Matrix function, Windowing function, Logical functions, Simple functions, Vector Math functions, etc., particularly for DSP implementations.

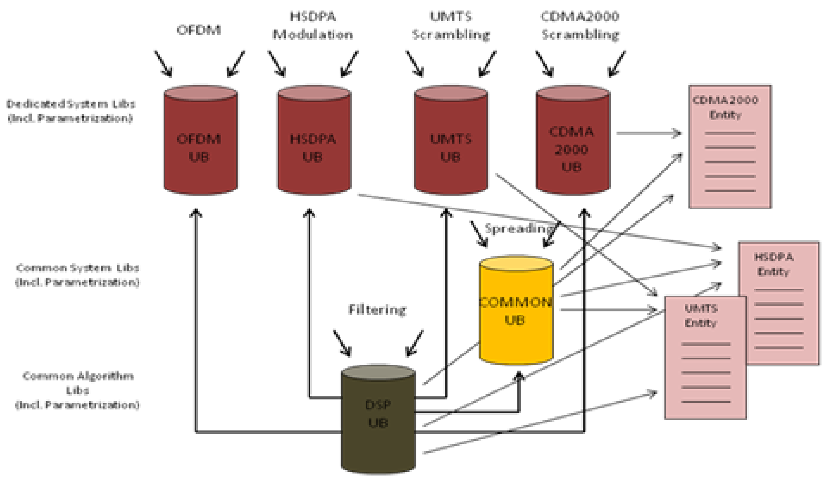


Figure 39.Hirarchical SDR Library Concept

Source:"A multi-standard SDR Base Band Platform [48]"

6.3. KEY FEATURES IN NEW MOBILE PHONES DESIGN

6.3.1. USER'S CENTRIC METHODOLOGY

User's perspective refers taking the user as its departing point. Users are the main actors on the stage of the wireless world and are unaware of and indifferent about the technology to use in order to obtain a desired service.

The user centric approach can result in a beneficial method for identifying innovation topics at "all" the different protocols layers and avoiding a potential mismatch in terms of service provisioning and user expectations.

If it is considered the users requirements as secondary with respect to the technological issues, the risk is to face an unanticipated failure. Thus, it becomes crucial to understand the users and their expectations and needs, and to consider them as the cornerstone in the design of new services in order to turn the new technology into a big success. Besides, it has also to be taken in consideration that novel technologies may have a significant impact on the user's behaviour and, consequently, their usage may change the emerging product. So, understanding users in general means understanding how they change as the society around them changes and, specifically, how they change through the interaction with the products that are introduced. In particular, if technological developers start from understanding human's needs, they are more likely to accelerate the evolutionary development of useful technology.

The methodology proposed in [49] is a top down approach that focuses on a user-centric vision of the wireless world and consists of the following four steps. First of all it is necessary to consider the user as a socio-cultural person with subjective preferences and motivations, cultural background, customs and habits. This leads to the identification of the user's functional needs and expectations in terms of series and products. Then it is necessary to make a reflection about the functional needs and expectations derived from the previous step in everyday life situations, where new services are significant assets for the user. In this way, fundamental but exemplary user scenarios are derived from sketches of people's everyday life. Following it can be extrapolated the key features of new services from the user scenarios. Finally comes the identification of the real technical step-up of new services with respect to old ones by mapping the key features described in the previous step into advanced in terms of system designs, services, and devices.

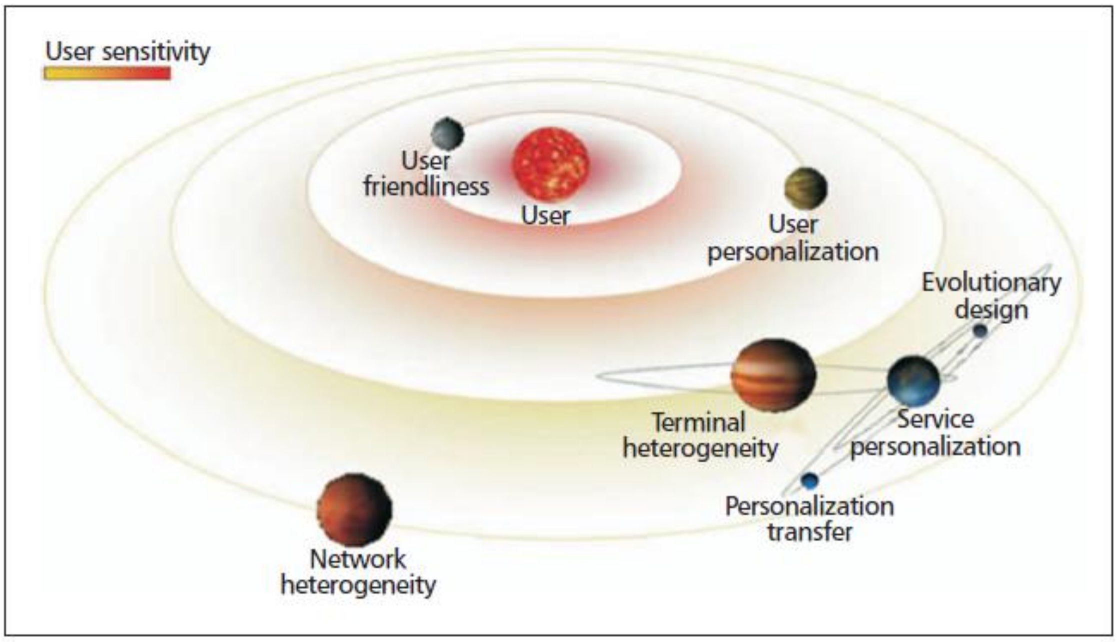


Figure 40.The user centric system
Source: "Defining 4G Technology from the User's Perspective" [49].

As shows the *Figure40* the user is located on the center of the system and the different key features defining new services rotate around him on orbits with a distance dependent on a user-sensitive scale.

Therefore, the further the planet is from the center of the system, the less sensitive to it the user is. The decrease of user-sensitivity leads to a translation towards the “techno-centric” system, where network heterogeneity has a much stronger impact than user friendliness. Furthermore, this kind of representation also shows the independency between key features, for example, service personalization is a satellite of terminal heterogeneity. The “user-centric” system demonstrates that it is mandatory in the design of 4G to focus on the upper layers (maximum user-sensitivity) before improving or developing the lower ones. If a device is not user friendly, for example, the user cannot exploit it and have access to other features, such as user personalization.

Some important traits are:

- User friendliness and user personalization

User friendliness exemplifies and minimizes the interaction between applications and users thanks to a well-designed transparency that allows the users and the terminals to naturally interact.

User personalization refers to the way users can configure the operational mode of their device and preselect the content of the services chosen according to their preferences. Since every new technology is designed keeping in mind the principal aim to penetrate the mass market and to have a strongly impact on people’s life, the new concepts introduced are based on the assumption that each user wants to be considered as a distinct, valued customer who demands special treatment for his or her exclusive needs.

- Terminal heterogeneity and network heterogeneity

Terminal heterogeneity refers to the different types of terminals in terms of display size, energy consumption, portability/weight, complexity, and so forth.

Network heterogeneity is related to the increasing heterogeneity of wireless networks due to the proliferation in the number of access technologies available. These heterogeneous wireless access networks typically differ in terms of coverage, data rate, latency, and loss rate. Therefore, each of them is practically designed to support a different set of specific services and devices. Hence, new technologies will encompass various types of terminals, which may have to provide common services independently of their capabilities. Therefore, tailoring content for end-user devices will be necessary in order to optimize the services presentation.

6.3.2. Radio Spectrum Sensing

Radio spectrum is a scarce resource and is regulated under the responsibility of local administration. Today's technology can only operate on certain frequencies. Frequencies are classified under licensed band or unlicensed band. Spectrum usage is one of the key issues in communication system challenges [7]. It is observed by empirical study that good quality spectrum is even underutilized. Hence the problem is more a spectrum management policy issue than a physical scarcity. The static allocation of spectrum results in deficiency of spectrum utilization. The spectrum efficiency can be improved with idea of dynamic spectrum allocation. The technology which promises to implement dynamic spectrum allocation is cognitive radio network. The idea of cognitive radio is based on effective spectrum utilization. The spectrum is allocated to primary user or licensed user. When primary user is not utilizing the allocated band, secondary user can claim for the band without interfering to primary user. The cognitive radio should sense the spectrum and allocate it to secondary use when it is empty. So basically, cognitive radio has to deal with spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing. Cognitive radio technology integrates radio technology and network technology.

The dynamic spectrum allocation is achieved through spectrum sensing. One of the primary requirements of cognitive radio networks is their ability to scan the entire spectral band for the presence/absence of primary users. This process is called spectrum sensing and is performed either locally by a secondary user or collectively by a group of secondary users. The spectrum sensing is challenging goal in cognitive radio. In wireless communication spectrum is occupied in multidimensions, in form of time domain allocation, frequency domain allocation and code spectrum allocation. Spectrum sensing can be achieved in two flavors: Horizontal spectrum sensing and Vertical spectrum sensing. Horizontal spectrum sensing assigns equal regulatory status to all users (both primary and secondary). Vertical sensing distinguishes between rights of primary user and secondary users. Secondary user will access the spectrum without affecting to primary users. Cognitive radio follows principle of vertical sharing. The requirement of vertical sharing is that secondary user should not interfere with primary user. This interference analysis is one of the design parameter of cognitive radio. This is done with respect to power control, modulation strategy, higher layer protocol etc. Practically interference is handled in two ways: interference control and interference avoidance. Interference avoidance is worst case design issue. Interference control means controlling the transmitted power from secondary user below threshold. This threshold is selected such that it should not affect primary user. But this approach fails with incorrect threshold value selection. The shadowing effect on primary user can result into interference with secondary user. The SNR required for estimating threshold should be carefully chosen. But low SNR could cause interference from secondary user. Interference avoidance approach allows secondary user to share the band only if primary user is not utilizing it. As soon as primary user want to utilize band, secondary user should vacant it. This requires continuous sensing of spectrum from secondary user to detect presence/absence of primary user. Sensing accuracy and reliability is limited due by electromagnetic signal attenuation which is result of path loss and fading. Commonly consider spectrum sensing metrics are bandwidth, resolution, real time capability.

- Individual Sensing

There are lots of sensing algorithms studied in literature for cognitive radio. The broad classification of these algorithms based on prior information is knowledge of transmitted signal and noise, knowledge of environmental noise, and without prior knowledge of signal and noise.

The spectrum sensing techniques are energy detection, matched filter, cyclostationary, wavelet matching, eigenvalue based and other multiple approaches. Out of which energy detection tech is adapted in many of research environment due to its simplicity and ease in design.

The mentioned approaches are individual sensing approach followed by secondary user. The secondary user can share their information among themselves and can take decision about spectrum utilization. This is known as cooperative sensing. The cooperative sensing overcomes problem of individual sensing such as hidden user terminal, low SNR detection. Tradeoff for selecting spectrum sensing method based on characteristic of primary user, accuracy, sensing duration requirement, computational complexity and network requirements [7]. The characteristic of primary user is based on use of technology. The technology may be fixed frequency and spread spectrum. Primary users that use spread spectrum are difficult to detect. The issues to be considered while spectrum sensing is as follows: Measuring which frequencies are being used, when they are used, determine location of transmitter and receiver and determining signal modulation.

In energy detection algorithm, also known as radiometry signal is detected by comparing output of energy detector with threshold. It performs non coherent detection. Match filter is optimum method for detection of primary user when transmitted signal is known. Cyclostationary stationary detection method is augmented with energy detection. The cyclostationary method makes use of periodicity characteristic of modulated signal. This periodicity of modulated signal results from sine wave carriers, pulse trains, repeated spreading sequence. Cyclostationary analysis estimate relation between widely dispersed spectral components due to spectral redundancy cause caused by periodicity. The other category of sensing algorithm which mainly concentrates on noise information covers Eigen value algorithm, correlation function algorithm [7]. Most of the above mentioned techniques suffer from noise uncertainty and channel fading variation, for this blind spectrum sensing technique is solution.

- Cooperative sensing

The cooperative sensing technique come up with idea of sharing information among the secondary users and takes decision based on collective information. Cooperative sensing relies on variability of signal strength at various locations. The cooperative sensing address question like how secondary user of cognitive radio should cooperate and what is overhead associated with cooperation. Cooperative sensing techniques follows one of the two approach centralized network or distributed approach. This is also known as data fusion or decision fusion respectively. In centralized network on in data fusion each secondary user obtains information about spectrum and sends it to access point which act as central unit. This raw data from every secondary user is processed at access point and based on that decision will be taken. The drawback of this approach is costly set up for transmission of raw data from individual secondary user to access point. In distributed or decision fusion technique, secondary user processed data at his terminal and then processed data is send to access point. Access point has to take decision based on fusion rules. Cooperative sensing reduces probability of misdetection and false alarm consideration and also reduces sensing time. Cooperative sensing address issues like hidden user problem, noise uncertainty, fading and shadowing. There are issues need to be addressed with reference to cooperative sensing like how to combine results of various secondary users which may have different sensing time and sensitivities. To resolve this issue there is need to have separate control channel. But this dedicated channel shares bandwidth when multiple cognitive radio groups are active simultaneously.

The design requirements for cognitive radio uses mathematical formulation which either follows artificial intelligence approach or machine learning approach.

6.3.3. Front-end challenges

It is necessary to take into account the front-end design of such a system. From the technical point of view, the front-end also is part of an SDR solution, even if it is not software. Radio or communication standards operate in different frequency bands and require dedicated input frequencies and bandwidths to the front-end. The vision is to have a wideband front-end and sample the complete bandwidth of several tenths of MHz with one ADC, and perform all post processing like channel selection and filtering in DSP engines. Within commercial boundaries this is simply not suitable because sampling of a broad signal bandwidth requires higher interface bandwidth, and the processing workload may exceed the platform capability.

A second more realistic approach is to build front ends, which can be switched to different input frequencies. This is possible, and there are several front-end architectures that can be configured in a wide range.

The other aspect is the sampling frequency. It has to be high enough to fulfill the Nyquist Criteria. The tendency to build wideband front-ends can be seen through modern technologies, which allow for a bandwidth increase of multiple tens of MHz for commercial applications. Commercial applications in this context means that the chipset has to be at a competitive price point for high volume production, and the power consumption has to be as low as possible.

For mobile applications, the power is one of the key parameters. As the power consumption of an ADC is directly related to the sampling frequency and resolution, the wideband system architecture needs to be compared with narrow band architectures. If the ADC is not on the same silicon as the digital baseband processing, an interface with enough bandwidth must exist to send the data from the ADC to the processing unit. In the case of commercial standard components, the input interface could easily be the bottleneck of the overall system. The conclusion of this challenge is that the components of the overall system architecture with tuner, ADC and baseband processing, must fit together. There are several chipsets existing on the market that fulfill the requirements of such a multi-standard terminal, but the components cannot be mixed arbitrarily.

6.3.4. Power consumption

Power is a major consideration in the design of every subsystem of an SDR, especially since they tend to consume more power than hardware radios. As an example, the Radio Frequency (RF) front end must have sufficient transmit power for the radio's intended range, typically in the order of 5-10 km, depending on the link. Also, for radios running on batteries, the power consumption of the RF front end, modem and the crypto processing subsystems directly impacts the operational lifetime of the radio. In addition, the ability to dissipate the heat generated by the modem has a direct impact on the radio lifetime, and even potentially on the number of channels that can be processed concurrently in a chassis.

Hence, reducing the power of an SDR has numerous benefits that can even include reduced operational expenses from having to purchase fewer spare batteries. Here, the focus will be on a holistic approach to reducing the power consumption of the modem of an SDR in order to capture some of those benefits.

6.3.4.1. The Hardware Approach to Reducing Power

The first place most people look to reduce power consumption in the modem is in the processing hardware, which is typically comprised of a Field-programmable Gate Array (FPGA), Digital Signal Processor (DSP) and General-purpose Processor (GPP). It is important to distinguish between two sources of power consumption in any hardware device, static and dynamic. Static power consumption is the inherent power consumed by a device that is on but not active, and it is dominated by the current leakage of the transistors. Dynamic power, on the other hand, is the power consumed by active usage of the device, which is affected by a number of variables including supply voltages, number of accesses to external memory, data bandwidth, etc. It is important to monitor both types of power consumption, particularly in the case of a radio that has a duty cycle that typically involves more receiving than transmitting. In the case of GPPs and even DSPs, power management features such as frequency scaling, voltage scaling and power down modes have become increasingly common.

Static Power	Triple Oxide Power Gating	Power Gating Floorplanning Partial Reconfiguration
Dynamic Power	Processor Integration Dedicated IP Blocks Clock Gating	Low Frequency Operation Parallelization Clock Gating Floorplanning

Table 16.A holistic approach to reducing power in SDRs would ideally multiple techniques from each quadrant
Source: [50].

There are numerous methods that can be used to reduce static or dynamic power consumption in an FPGA, many of which are not mutually exclusive. Some methods of reducing static power consumption include triple oxide and power gating.

With triple oxide, silicon vendors coat transistors with an oxide to reduce leakage; the thicker the coating, the less leakage. The trade-off is performance. It has been common to use thin oxide in the core where performance is required, and use thick oxide for the I/Os to drive higher voltages. The addition of a medium oxide can significantly reduce leakage where maximum performance is not required, such as configuration SRAMs.

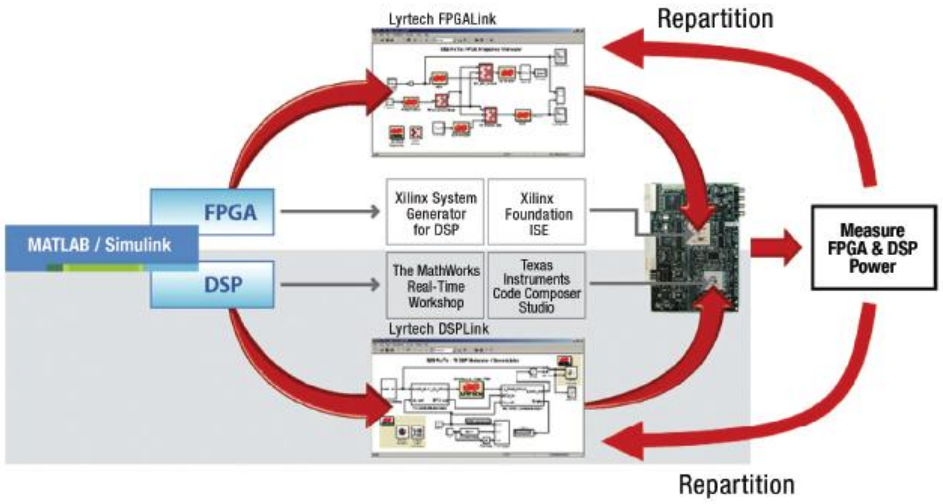


Figure 41.Model-based design flow with power measurements can simplify waveform partitioning decisions.
Source: [50].

Power gating involves the usage of transistors to reduce standby leakage when an FPGA block is not being utilized. An example of this technique can be seen in low-power sleep modes. For example, if all the blocks in an FPGA are power gated, the device consumes very little static power. The trade-off, in this case, is a loss of the configuration of the FPGA such that the device has to be completely reconfigured during the wake-up process, which can take milliseconds. On the other hand, if all blocks are power gated except those with configurations (i.e., configuration memories), then the state of the FPGA is retained. Although the wake-up time is significantly decreased, the power saving is not as significant as when all blocks are power gated.

Dynamic power consumption is the other part of the power equation. Methods of reducing dynamic power consumption include processor integration, dedicated IP blocks and clock gating.

Processor integration is a classic value proposition for platform FPGAs with embedded GPPs and DSP engines. By using an embedded GPP, rather than a discrete GPP, power savings are derived by not having to drive data from the FPGA to the GPP across external I/O lines, which can typically consume a significant amount of power.

Having dedicated IP blocks to perform certain common functions can significantly reduce dynamic power without a major impact on flexibility. An example is having a dedicated DSP engine in an FPGA to perform multiply-accumulates. This dedicated IP block can perform that function at much higher performance and up to 85% lower power than logic.

The clock gating technique uses circuitry to disable clocks of FPGA blocks that are not in use, thereby reducing the power consumption in that block to the amount of leakage current.

Since it is important to reduce both static and dynamic power, the most powerful approaches to lowering power from a hardware perspective impact both. One of the best examples is lowering the core voltage. Processing devices tend to benefit from lower voltages as they move to the next process node (i.e., from 90 to 65 nanometers). As an example, the core voltage of a 65 nm Virtex-5 FPGA is 1.0V, 17% lower than the 90 nm Virtex-4 FPGA at 1.2V and 33% lower than the 130 nm Virtex-II FPGA at 1.5V. This is one benefit to using the most current devices. Lower core voltage has a significant impact on both static and dynamic power, since leakage scales exponentially with voltage and dynamic power scales quadratically. As a result, Virtex-5 devices average over 30% lower static and dynamic power than Virtex-4 FPGAs.

To truly optimize SDRs for power consumption one needs to take a more holistic approach, combining both hardware and programming techniques. An inefficiently implemented waveform can have a tremendous negative impact on an SDR's power consumption regardless of how well the hardware is designed. There are many techniques that one can use to implement a waveform more efficiently in an FPGA, including parallelizing the algorithm, low frequency operation, floorplanning for power and partial reconfiguration.

With parallelizing the algorithm, it is well documented that the parallelism offered by FPGAs allows for much higher performance signal processing than is possible from sequential processors such as DSPs or GPPs. Since parallel processing can perform tasks at much lower clock frequencies than required by sequential processors, FPGAs can actually be more energy efficient than processors when parallelizing the algorithm.

With low frequency operation, many military waveforms can benefit from running at lower frequency to reduce power consumption. It is common for waveforms to be running in an FPGA at less than 200 MHz, well below the maximum frequency.

Some of the techniques described above, such as clock gating, can be much more effective with some careful floorplanning of the design. For example, to truly take advantage of clock gating, one would want the portions of a design utilizing the same clock that could be gated located in the same area, perhaps in a quadrant of the device. Commercially available tools such as the Xilinx PlanAhead design and analysis tool significantly ease floorplanning with a Graphical User Interface (GUI).

Partial Reconfiguration (PR) allows a designer to time multiplex the resources within an FPGA. Without PR, one would have to reload the entire FPGA to support a new waveform mode, thereby temporarily losing the comms link, or have all modes loaded concurrently in a large FPGA even though only one mode is being used at a time. PR allows support for multi-mode waveforms without having all the modes loaded into the FPGA concurrently, thus enabling the same functionality with a smaller, lower power FPGA. Efficiently using PR also benefits from floorplanning. Similar to low core voltage, PR can impact both static and dynamic power, whereas the techniques above only affect dynamic power.

Given the numerous approaches to reducing power in an SDR, many of which can be combined, it would seem that there could be little chance to determine the ideal power-optimized waveform implementation. Add to the mix that many waveform components like Forward Error Correction (FEC) can often be efficiently implemented in either an FPGA or DSP. It is often not clear how best to partition a waveform between hardware and software to maximize energy efficiency. While there is no magic bullet, no tool that can assess all the various options and permutations to definitively identify the optimal solution, there must be a better way than sheer guesswork by using published datasheet numbers and spreadsheet-based power estimators.

A far superior approach would be to have access to an SDR that could serve as a testbed for power-optimized designs. Having such a testbed would allow a designer or system architect to empirically test and weigh the trade-offs associated with a specific hardware and software design for power. The designer could not only compare the relative merits of some of the techniques discussed above, but could also iteratively develop and partition a waveform between an FPGA and DSP/GPP with relative ease, while taking power measurements on each modem processing device.

Such an SDR testbed with power monitoring is available today through the collaboration between Xilinx, Texas Instruments and Lyrtech. The Small Form Factor SDR Development Platform combines a Virtex-4 FPGA with a DM6446 DSP/GPP to empower designing for low power.

CONCLUSIONS

In the last few years the mobile and wireless networks have made an incredible growth. First generation mobile telephones were developed around the world using different incompatible analog technologies. Second generation used digital technology and it was still primary meant for voice communications, not data. Then, third generations appeared and allowed high speeds of transmission and were particularly useful for data services. During the evolution from 2G to 3G, a range of wireless systems were developed. The increasing growth of user demand, the limitations of the third generation and the emergence of new mobile broadband technologies on the market have brought researchers and industries to a thorough reflection on the fourth generation. This technology give users faster access to the Internet than most previous third generation networks, and it also offers new user options such as the ability to access high-definition (HD) video, high-quality voice, and high-data-rate wireless channels via mobile devices. With a higher data rate and broader bandwidth capability, the increasing complexities of mobile terminals and a desire to generate multiple versions with increasing features for handsets have led to the consideration of Software Defined Radio based approach in the wireless industry.

The term "Software Defined Radio" was coined in 1991 by Joseph Mitola, who published the first paper on the topic in 1992. Software Defined Radios have their origins in the defense sector and one of the first public software radio initiatives was a U.S. military project. A Software Defined Radio is a radio communication system where components that have been typically implemented in hardware are instead implemented by means of software on an embedded computing device.

The most widely used software architecture for SDR is the Software Communications Architecture (SCA). The SCA is an open architecture framework that tells designers how elements of hardware and software are to operate in harmony within a software defined radio. The SCA is a distributed system architecture, allowing the various parts of applications to run on different processing elements. The communication between the components, and between components and devices, is based on using the Common Object Request Broker Architecture (CORBA) middleware.

SDR is a rapidly evolving technology that is receiving widespread popularity in the commercial wireless communication industry. It facilitates implementation of multi-band and multi-standard wireless communications systems. Mobile operators, manufacturers and subscribers will all benefit from the vastly improved communications available through SDR.

With the SDR technology, mobile operators will be able to upgrade their network systems to the latest version without any hardware change, hence decreasing total cost of ownership. They can roll out new services tailored to the various tiers of users on a common hardware platform. The deployment of SDR equipment can help operators transit from "network providers" to "service providers", which will create a substantial new source of revenue. Moreover, the SDR equipment offers improved time to market, significantly reducing the operators' investment risks.

From the manufacturers' perspective, the SDR technology is adopted to remove the development gap among different technologies, which can lower the R&D cost and shorten the time to market for new products and services. As the SDR-based air interfaces and frequency bands accommodate multiple and evolving technical standards, the SDR platform addresses a wide range of market requirements. The SDR products are modularized and enable "soft" update of new services, features and security mechanisms. With the SDR technology, the manufacturers can enhance product integrity, continuity and stability.

For subscribers, the SDR terminal means a single platform for multiple technical standards that allows customization and access to a variety of new features and services with an easy upgrade path. Subscribers can use the SDR terminals to seamlessly roam across operator boundaries and achieve true mobility. The SDR technology increases the lifetime of a terminal investment and provides insurance against obsolescence.

The next step after SDR is Cognitive Radio (CR). The main advantage for using CR would be because spectrum is over-allocated but under-utilized. There are lots of white spaces in the spectrum that could be utilized by devices intelligently of their own. Cognitive Radios are defines as a radio that can autonomously change its parameters based on interaction with, and possibly learning of, the environment in which operates. Through appropriate radio resource management, such a cognitive radio should make flexible and efficient use of network/spectrum resources.

Following the changes of mobile and wireless networks, the software development of consumer electronics industry also has gone through a substantial transition in the last 15 years. In the beginning the industry used to have a vertically structure but with the introduction of more functionalities, the structure of consumer electronics industry started to change and more de-verticalization structures appeared.

Initially the size of the software was limited, so it could be developed by vertically integrated companies, and enabled them to use the system resources most efficiently. With the introduction of feature phones, the players used components from other consumer electronics firms but no major architectural changes were required. A major shift occurred when functionality from PDAs was incorporated, thereby requiring general purpose operating systems, which required large development investments. Several software platforms entered the market with the aim to create an ecosystem for the mobile phone handset. However, none of these attempts have gained industry wide option and no high degree of modularization was attained. This led to the challenge to use different suppliers while assuring optimal resource utilization and, furthermore, an increase in the time needed for software integration was noted.

The supply chain is the dominant industry structure at this moment in the time, although some players use a more vertically integrated approach. The need to ensure optimal resource utilization, the ability to serve multiple customers and the lack of industry-wide standards prevents the development of handsets from becoming more ecosystem-centric. The supply chain industry structure is likely to remain the dominant structure since no industry wide standardization may be expected due to the speed of innovation and the fear that a dominant player may take most of the revenues. For the development of downloadable applications, close ecosystems have been created because this functionality has no hard performance requirements nor does optimal resource utilization need to be guaranteed.

In a vertically integrated structure there are more control and better resource utilization. Thus, a company that uses a more vertically approach has control over the architecture and its constituent components and can guarantee the product quality more easily. Moreover, it has the freedom to innovate more freely. Anderson identified that for the entry-levels devices, which contain little variability, vertically integrate firms offers better possibilities to obtain the lowest costs because increased resource efficiency. Andserson and Constrantinou argued that a more integrated approach might be more suited for high-end and new-to-market products. For this product range, bringing novel functionality to the market is more important than the higher development costs since the sales price is much higher than the manufacturing costs.

In a supply chain or ecosystem centric approach it is more difficult to change the system architecture. Modular and layering introduces inefficiency in the implementation, constrain innovation and impose the requirements backwards compatibility.

Specialized firms are used to develop part of the system. In this way the total development cost are reduced because an individual firm does not have to invest in developing the entire software stack. Hence, the customers can have more variability using components from different suppliers or by enabling third parties and customers to develop the functionality they need. On the other hand, the time to achieve the system integration is higher and the cooperation with suppliers leads to additional interaction costs. It is not so easy to innovate and there is the fear that some firms may be able to take a dominant position and create a monopoly. This is often possible for a firm that develops the middleware or the spanning layer.

Actually, there are no so many companies that dedicate its efforts in software radio and less in software radio for the commercial domain. If a telecommunications company decides that it wants to work with this kind of software it has to take into account some of the arguments discussed before. First of all the company need to develop the software and this means a big inversion of money and time in the beginning. Once the software is developed is necessary to adapt it to the hardware because, as it is known, software design is always ahead of hardware. The good point is that when the software is developed this doesn't need any effort in maintenance or management. It can be said that the telecommunications companies that would be able to implement the software technology would be the "small ones". In a "big company" the software is designed by specialized third parties but in a small company is this one that produces all the steps to develop the product or system.

What about mobile phones? Can you imagine keeping the same cell phone as you switch from one service provider to another to take advantage of deals and new phone service options? Software Defined Radio can make that possible.

Traditional radio chips are hard wired to communicate using one specific protocol. For example, a typical cell phone has several different chips to handle a variety of radio communications: one to talk to cell phone towers, another to contact WiFi base stations, a third to receive GPS signals, and a fourth to communicate with Bluetooth devices. In contrast, SDR hardware works with raw electromagnetic signals, relying on software to implement specific applications.

This makes software defined radio devices tremendously versatile. With the right software, a single software defined radio chip could perform the functions of all of those special purpose radio chips in your cell phone and many others besides. It could record FM radio and digital television signals, read EFID chips, track ship locations, or do radio astronomy. In principle it could perform all of these functions simultaneously. Software defined radio hardware also enables rapid prototyping of new communications protocols.

Software defined radio will make it possible to use the electromagnetic spectrum in fundamentally new ways. Most radio standards today are designed to use a fixed, narrow frequency band. In contrast, SDR devices can tune into many different frequencies simultaneously, making possible communications schemes that wouldn't be feasible with conventional radio gear. Most significantly, the widespread adoption of SDR hardware could undermine the FCC's control over the electromagnetic spectrum itself. Right now, the FCC largely focuses on limiting the transmission frequencies of radio hardware. But this regulatory approach is likely to work poorly for SDR devices that aren't confined to any specific frequency.

A fundamental challenge with SDR is how to achieve sufficient computational capacity, in particular for processing wide-band high bit rate waveforms, within acceptable size and weight factors, within unit cost, and acceptable power consumption. The power consumption must be below certain limits to keep the battery discharge time within acceptable limits, and with the smallest handheld units it will also be an issue of not causing the surface temperature of the device to become unpleasantly high for the user. Although traditionally the focus has been on reducing the power consumption of the SDR hardware, it is clear that software also has a major impact on power consumption. As such, a holistic approach to reducing the power of SDRs is required.

To make a good design of software defined radio devices it is important to keep in mind a user’s perspective. The user centric approach can result in a beneficial method for identifying innovation topics at all the different protocols layers and avoiding a potential mismatch in terms of service provisioning and user expectations.

It is necessary to take into account the front end design of such a system. From the technical point of view, the front-end also is part of an SDR solution, even if it is not software. Radio or communication standards operate in different frequency bands and require dedicated input frequencies and widths to the front-end.

Nowadays there are some organizations that focus their efforts in the design and implementation of SDR. GNU Radio, Virginia Tech OSSIE and High Performance SDR are some of them.

To finish just say that expects envision a future in which every home has a software defined radio device. Right now, most people probably could not imagine why they’d want software defined radio hardware in their homes. But people said the same thing about microcomputers in the 1970s.

ABBREVIATIONS

1G	First Generation
2G	Second Generation
2.5G	2.5 Generation
2.75G	2.75 Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
3.5G	3.5 Generation
4G	Fourth Generation
ADC	Analog to Digital Converters
ALOE	Abstraction Layer and Operating Environment
AMPS	Advanced Mobile Phone System
API	Applications Program Interface
BOM	Bill of Material
CDMA	Code Division Multiple Access
CF	Core Framework
CIC	Cascaded Integrator-Comb
COCOMO	Constructive Cost Model
CORBA	Common Object Request Broker Architecture
COTS	Commercial Of-The-Shelf
CR	Cognitive Radio
DAC	Digital to Analog Converters
DCD	Device Configuration Descriptor
DDC	Digital Down Converters
DFS	Dynamic Frequency Selection
DPD	Device Package Descriptor
DRA	Dynamically Reconfigurable Area
DSP	Digital Signal Processors
DUC	Digital Up Converters
EDGE	Enhanced Data GSM Environment
EGPRS	Enhanced GPRS
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FPGA	Field Programmable Gate Array
GIOP	General Inter-ORB Protocol
GSM	Global System for Mobile Communications
GPP	General Purpose Processor
GPRS	General Packet Radio Service
GUI	Graphical User Interface
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HS – DSCH	High Speed Downlink Shared Channel

IDE	Integrated Development Environment
IDL	Interface Description Language
IIOP	Internet Inter-ORB Protocol
IMT-SC	IMT Single Carrier
IP	Internet Protocol
ITU	International Telecommunication Union
JTAC	Japanese Total Access Communication
LTE	Long Term Evolution
MDA	Model Driven Architecture
MIMO	Multiple Input Multiple Output
MMT	Mobile Multi-Standard Terminals
MPMB	Multiprotocol Multiband
NMT	Nordic Mobile Telephone
OE	Operating Environment
OEF	OSSIE Eclipse Feature
OFDM	Orthogonal Frequency Division Multiplexing
OMG	Object Management Group
ORB	Object Request Broker
OSI	Open System Interconnection
OWD	OSSIE Waveform Developer
PC	Personal Computer
PDA	Personal Digital Assistant
PE	Processing Elements
PGA	Programmable Gain Amplifier
PR	Partial Reconfiguration
RA	Regulatory Agency
RAT	Radio Access Technology
RF	Radio Frequency
RM	Reconfiguration Manager
SAD	Software Assembly Descriptor
SAW	Surface Acoustic Wave
SCA	Software Communications Architecture
SCD	Software Component Descriptor
SDR	Software Defined Radio
SE	Software Engineering
SISO	Single Input Single Output
SLOC	Source Lines of Code
SNR	Signal to Noise Ratio
SPD	Software Package Descriptor
SSN	Software Supply Networks
SWL	Short Wave Listeners
TACS	Total Access Communication System
TCP	Transmission Control Protocol
TDMA	Time division Multiple Access
TPC	Transmit Power Controls
UHF	Ultra High Frequency

UMTS	Universal Mobile Telecommunications System
USR	Ultimate Software Radio
USRP	Universal Software Radio Peripheral
VHE	Virtual Home Environment
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

APPENDIX

APPENDIX I

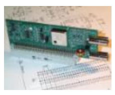
ATLAS	The Atlas is a passive backplane that all other modules plug into. The circuit board has provision for up to six DIN41612 connectors at 0.8 inch spacing. An ATX 20 pin power connector is fitted to the board so that 12v, 5v, 3.3v etc. supplies from a standard PC power supply can be used for power. Since such power supplies are in plentiful supply, both new and surplus, this neatly solves the power supply requirements. The DIN connector spacing and board size have been chosen such that the backplane can fit into a standard PC enclosure.
MAGISTER	Magister is an FPGA based interface controller card that provides a high-speed USB 2.0 interface for the Atlas bus, as well as limited additional I/O lines intended for radio control. The USB interface uses a Cypress FX2 chip, supporting full duplex USB communications at > 30MB/s.
MERCURY	Perhaps the most exciting of all the modules, the Mercury board enables direct sampling of the 0-65MHz spectrum. Based on a Linear Technology LTC2208 130MSPS 16-bit A/D converter the board downsamples in its own Altera Cyclone III FPGA to 250 kSPS or less for transfer over the Atlas bus to the USB interface on the OZY board.
FILTERS	ALEXIARES is a combination RF Preselector for use with Mercury or any other SDR, as well as a transmitter low pass filter bank for a transmitter such as Penelope, and optionally, with an associated RF power amplifier up to 100 watts peak. As a receiver preselector, the purpose of ALEX is to reduce the level of out-of-band signals at the input of a receiver, and importantly, to suppress any signals at the sampling image or alias frequencies. See Anie for ideas on a tunable preselector. As a transmitter low pass filter, ALEX will suppress the harmonic energy typically generated by an RF power amplifier, as well as the images or aliases that appear at the sampling clock frequency (122.8 MHz) plus/minus the operating frequency. The transmit low pass filters will also be used for additional MERCURY receiver input band limiting.
PENELOPE	The Penelope digital up converter (DUC) is a 1/2-watt transmitter/exciter board. It makes a good companion to the Mercury HF direct sampling receiver board. When connected to the Atlas (bus) it will process the I and Q signal from the personal computer.
POWER AMPLIFIER	PennyWhistle is a compact RF power amplifier stage that can be used with Penelope and Alex to make a complete 16 to 20 Watt transmitter. Since any higher power HPSDR amplifier does not appear to be close in time, this amplifier can quickly and inexpensively be used to get an HPSDR on the air, either barefoot, or as a driver for a larger linear. It covers the same 160 Meter through 6 Meter bands as the rest of HPSDR.
CRYSTAL CONTROL 	Excalibur is a small accessory card for the Atlas bus that enables the use of an external 10 MHz frequency reference for locking the frequency of an HPSDR radio to the same accuracy of the standard, or GPS disciplined oscillator. It also provides an optional TCXO frequency reference for the HPSDR, that is much better than the on board 10 MHz oscillators, although not as good as an external standard or GPS-DO.
SOUND	The Janus module is a very high performance, dual, full duplex, audio frequency A/D and D/A converter board (soundcard). The A/D sample rate options are 48, 96 or 192kHz and the D/As are fixed at 48kHz. While the M-Audio Delta 44 has become the de-facto standard for A/D sound cards for use with a SDR, there are a number of advantages to rolling your own. These include having complete control of any software drivers needed to communicate with the A/D chips as well as optimization of sampling rates and bit depths for individual signals. It's also possible to cost effectively develop a board which approaches the performance of professional high end sound cards.
POWER SUPPLY	"LPU" is the project-name for a simple HPSDR power supply. Although power supplies are widely available, the LPU will provide a convenient low-noise solution until the more complex Demeter power supply is completed. The LPU (as well as Demeter) are specifically designed for the HPSDR project. With the approaching release of Mercury, this is the last hardware part of a basic functional HPSDR transceiver.

Table 17.Basic features of the main parts of the HPSDR system
Source: [43].

APPENDIX II

WINDOWS	PowerSDR is the Microsoft Windows based client software created by Flexradio to operate their software defined radios. It has been adapted (primarily by Bill Tracey, KD5TFD and Doug Wigley, W5WC) to work with the HPSDR Mercury, Penelope, Ozy, Magister, and Excalibur boards. Features of the software also support the Antenna Switch, Alexiares, and the Hercules 100 Watt Amplifier.
MACINTOSH	Heterodyne is a native Mac implementation of a receiver for OpenHPSDR hardware by Jeremy McDermond (NH6Z).
LINUX	GHPSDR is a software defined radio client written specifically for HPSDR by John Melton, G0ORX/N6LYT. The software is being developed on the Ubuntu version of Linux (specifically version 9.04). This code has been compiled and runs on MacOS as well.
SVN	The software is available from SVN and includes a precompiled executable in the bin directory. There are now a compiled version of the 64-bit Linux version, 32-bit Linux version and the MacOS version.

Table 18.HPSDR Software
Source: [43].

APPENDIX III

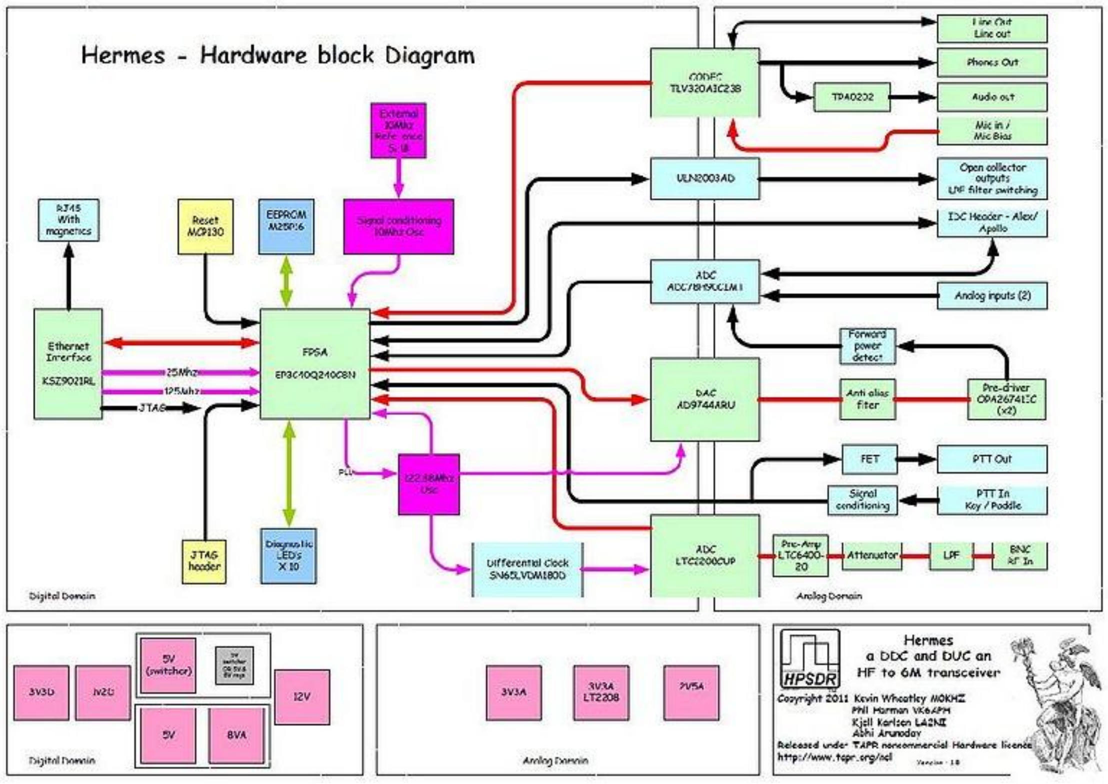


Figure 42. Hermes hardware block diagram
Source: [43].

APPENDIX IV

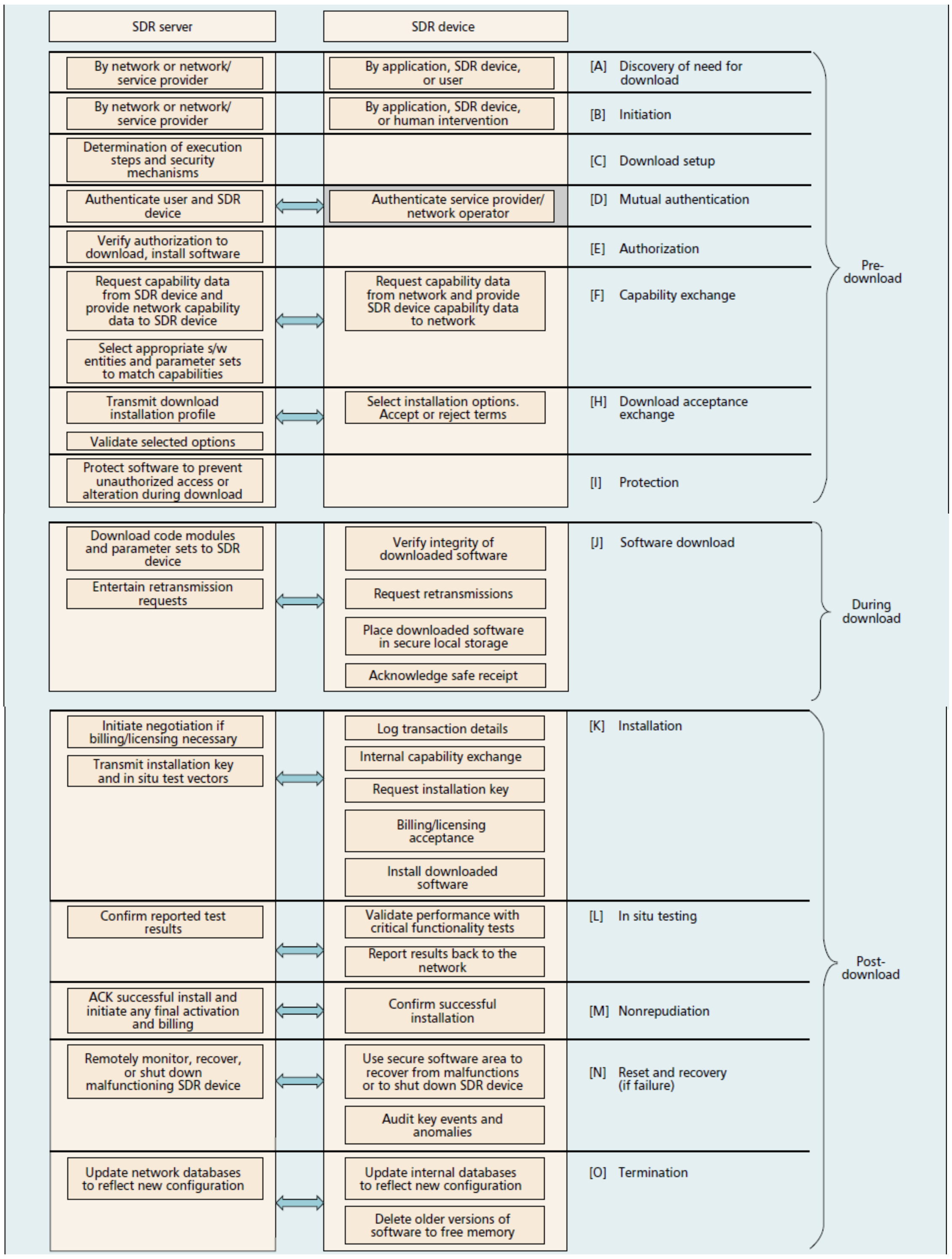

SDR server
SDR device
By network or network/ service provider
By application, SDR device, or user
[A] Discovery of need for download
By network or network/ service provider
By application, SDR device, or human intervention
[B] Initiation
Determination of execution steps and security mechanisms
[C] Download setup
Authenticate user and SDR device
Authenticate service provider/ network operator
[D] Mutual authentication
Verify authorization to download, install software
[E] Authorization
Request capability data from SDR device and provide network capability data to SDR device
Select appropriate s/w entities and parameter sets to match capabilities
Request capability data from network and provide SDR device capability data to network
[F] Capability exchange
Transmit download installation profile
Validate selected options
Select installation options. Accept or reject terms
[H] Download acceptance exchange
Protect software to prevent unauthorized access or alteration during download
[I] Protection
Pre-download
Download code modules and parameter sets to SDR device
Entertain retransmission requests
Verify integrity of downloaded software
Request retransmissions
Place downloaded software in secure local storage
Acknowledge safe receipt
[J] Software download
During download
Initiate negotiation if billing/licensing necessary
Transmit installation key and in situ test vectors
Log transaction details
Internal capability exchange
Request installation key
Billing/licensing acceptance
Install downloaded software
[K] Installation
Confirm reported test results
Validate performance with critical functionality tests
Report results back to the network
[L] In situ testing
ACK successful install and initiate any final activation and billing
Confirm successful installation
[M] Nonrepudiation
Remotely monitor, recover, or shut down malfunctioning SDR device
Use secure software area to recover from malfunctions or to shut down SDR device
Audit key events and anomalies
[N] Reset and recovery (if failure)
Update network databases to reflect new configuration
Update internal databases to reflect new configuration
Delete older versions of software to free memory
[O] Termination
Post-download

Figure 43.Download process steps

Source: "Radio Software Download for Commercial Wireless Reconfigurable Devices" [47].

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