Facultad de Ingeniería
ISSN: 0121-1129
revista.ingenieria@uptc.edu.co
Universidad Pedagógica y Tecnológica de Colombia
Colombia

Machado-Fernández, José Raúl
Software Defined Radio: Basic Principles and Applications
Facultad de Ingeniería, vol. 24, núm. 38, enero-junio, 2015, pp. 79-96
Universidad Pedagógica y Tecnológica de Colombia
Tunja, Colombia

ISSN 0121-1129
eISSN 2357-5328

Software Defined Radio: Basic Principles and Applications

Software Defined Radio: Principios y aplicaciones básicas

Software Defined Radio: Princípios e Aplicações básicas

Fecha de Recepción: 29 de Septiembre de 2014
Fecha de Aceptación: 15 de Noviembre de 2014

José Raúl Machado-Fernández*

Abstract

The author makes a review of the SDR (Software Defined Radio) technology, including hardware schemes and application fields. A low performance device is presented and several tests are executed with it using free software. With the acquired experience, SDR employment opportunities are identified for low-cost solutions that can solve significant problems. In addition, a list of the most important frameworks related to the technology developed in the last years is offered, recommending the use of three of them.

Keywords: Software Defined Radio (SDR), radiofrequencies receiver, radiofrequencies transmitter, radio development frameworks, superheterodyne receiver, SDR hardware devices, SDR-Sharp, RTLSDR-Scanner.

Resumen

El autor realiza una revisión de la tecnología Radio Definido por Software (SDR, Software Defined Radio) incluyendo esquemas de hardware y campos de aplicación. Un dispositivo de desempeño modesto es presentado y varias pruebas son ejecutadas con él usando software de distribución gratuita. Con la experiencia adquirida, son identificadas oportunidades de empleo de SDR en soluciones de bajo costo que pueden resolver problemas significativos. Además, se ofrece una lista de las librerías más importantes relacionadas con la tecnología en los últimos años, recomendando el uso de tres de ellas.

Palabras Clave: Software Defined Radio (SDR), receptor de radiofrecuencias, transmisor de radio frecuencias, librerías de desarrollo de radio, receptor superheterodino, dispositivos de hardware SDR, SDR-Sharp, RTLSDR-Scanner.

* Instituto Superior Politécnico José Antonio Echevarría (ISPJAE) (La Habana, Cuba). m4ch4do@hispavista.com

Resumo

O autor realiza uma revisão da tecnologia Rádio Definido por Software (SDR, Software Defined Radio) incluindo esquemas de hardware e campos de aplicação. Um dispositivo de desempenho modesto é apresentado e várias provas são executadas com ele usando software de distribuição gratuita. Com a experiência adquirida, são identificadas oportunidades de emprego de SDR em soluções de baixo custo que possam resolver problemas significativos. Ademais, se oferece uma lista das bibliotecas mais importantes relacionadas com a tecnologia nos últimos anos, sendo recomendado o uso de três delas.

Palavras Chave: Software Defined Radio (SDR), receptor de radiofrequências, transmissor de radiofrequências, bibliotecas de desenvolvimento de rádio, receptor super-heteródino, dispositivos de hardware SDR, SDR-Sharp, RTLSDR-Scanner.

I. Introduction

From the first wireless transmissions around 1890 [1-3], radio transmission techniques have continually evolved, providing users the possibility to stay connected with increasing transmission rates [4]. The triumphant radio era came first, in the mid-1930, at a time when limited band widths were used for analog voice communications. Then, came the golden era of broadcast transmission in the 50s [5] with analogic television broadcasts that consumed more bandwidth but provided a rich customer experience. As computers became smaller and more powerful, reaching the 60s, they began to be useful as a communication media for long distances, using both wired connectivity via ARPANET[6] (which became later the Internet) and wireless satellite ALOHANET [7].

Cell phones also emerged around this time[8], allowing users to establish wireless voice communications from any public place or vehicle, although the original mobiles were hard to operate and to travel with, given their volume and weight. Many modern phones are now almost portable computers, providing access to both cellular networks and the Internet, and achieving wireless communications at speeds that were unimaginable a generation ago.

To the continuous progress in communications, it follows the advent of WLAN (Wireless Local Area Networks) that were originated in 1985 controlled by the United States Federal Communications Commission (FCC). The organization put together the not licensed spectrum in three different regions to be used in the following applications: Industry (902-928 MHz), Science (2400-2483.5 MHz) and Medicine (5725-5850 MHz)[9]. However, the original IEEE standard for WLANs was not published until 1997[10]. Taking advantage of these freedoms in the spectrum, protocols such as WiFi and Bluetooth proliferated and are now a vital part of any corporative network.

Despite the growth achieved by multiple technologies, an interesting and potentially problematic issue common to all mentioned devices is that their radios and protocols are mostly hardware based. Therefore, reprogramming or reconfiguration options are minimal, at least regarding radio functions. This lack of flexibility is disturbing in the sense that if an error occurs in the hardware, firmware, or software then generally there is no reasonable way to correct the problem: the built-in vulnerabilities are not easy to remove. In fact, these devices are commonly limited in their functionality to the hardware components and cannot be reconfigured to perform other wireless protocols beyond what the hardware itself provides [11]. Precisely, the Software Defined Radio, subject of this article, aims to provide a solution to many of the problems described along with many other benefits.

A. Software Defined Radio

The Software Defined Radio (SDR) is a design paradigm for wireless communications devices. Its creator, Joseph Mitola, defined the term in the early90s as an identifier of a class of radios that could be reprogrammed and reconfigured through software[12]. Mitola envisioned an ideal Software Defined Radio, whose physical components were only an antenna and an Analog Digital Converter (ADC) on the receiver side. Likewise, the transmitter would have a Digital Analog Converter (DAC) and a transmitting antenna. The rest of the functions would be handled by reprogrammable processors.

As the idea conceived in the 90sis still not achievable, and a sit will not be likely for some time, the term SDR is used to describe a viable device that is primarily defined by software, but includes significant hardware components. Even with these components, the SDR receiver is quite different from a traditional receiver.

B. Motivation and Objectives

SDR has evolved, like most technologies, from military to civilian environments. The first operational SDR, known as Speakeasy [13] was developed by the United States' Navy between 1991 and 1995.Unfortunately, the application could not be used with other than the hardware for which it was conceived. Also, another negative issue was the fact that the device fully occupied the backside of a transport vehicle. His younger brother, Speakeasy II [14], achieved much greater success mainly due to advances in electronics, wireless communications circuits, and reusable and modular programming techniques.

A long way has been traveled from that first moment to the present. Today, both SDR software [14, 15] and hardware [16] are available at very low prices (in fact, most software implementations are free), which invites to consider the introduction of the paradigm in radio solutions. Thus, the author establishes as the article's objective to make a review of SDR technology, including hardware designs and application fields. In addition, he will show the operation of a software defined radio device, identifying employment opportunities at very low cost solutions that can solve latent problems in common radio environments.

II. SDR Hardware

In this section, a theoretical review of hardware differences between traditional and SDR receivers is performed at first, explaining also how the software defined transmission takes place. Finally, a SDR device is shown setting the ground for the discussion of the technology's applications in section 3.

A. Traditional Receiver

A traditional or typical receiver, besides the classic demodulation, performs three other operations: (1) carrier frequency tuning to select the desired signal, (2) filter to separate it from others received, and (3) amplification to compensate transmission losses. Moreover, an amplification step is commonly placed before the demodulation block to carry the signal to an acceptable level for the demodulator circuitry [17].

Most traditional receivers have used conventional heterodyne schemes for almost a century. The superheterodyne internals blocks are shown in Fig. 1 [18]. A basic understanding of the structure is necessary to distinguish this conception from the new SDR receiver.

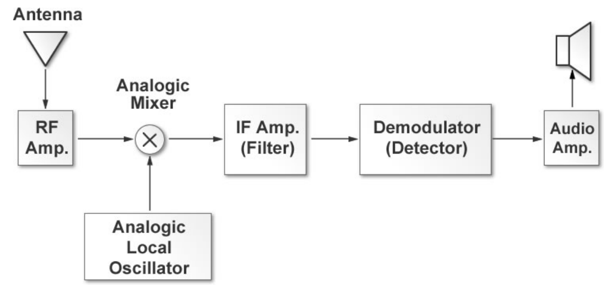

Fig. 1. Superheterodyne Receiver's Internal Blocks.

In the previous scheme, after the signal enters through the antenna, it is typically amplified by an RF stage that operates only in the frequencies of interest region. Then, the signal is passed to the mixer which receives the local oscillator contribution by its other input. The local oscillator's frequency is set by the radio's tuning control [18]. The mixer is in charge of translating the signal to the Intermediate Frequency (IF).

Typically, the oscillator's frequency is set to a value that ensures that its difference from the desired signal's frequency is equal to the IF. For example, if someone would like to receive a FM station at 100.7MHz and the IF were 10.7MHz, the local oscillator should be placed at 90MHz.The operation is known as downconversion.

The next stage is a bandpass filter that attenuates every signal except a specific portion of the spectrum. The bandwidth of this stage limits the band width of the signal that's being received. Common center frequencies for the IF stage are 455 kHz and 10.7 MHz for commercial AM and FM respectively. Likewise, for commercial FM, the bandwidth is approximately 100 kHz and for AM is above 5 kHz, consistent with the channel spacing that's 200kHz for AM and 10 kHz for FM [19].

At the end, the demodulator recovers the original modulating signal from the IF amplifier's output employing one of several alternatives. For example, for AM an envelope detector is used, and for FM a frequencies discriminator [20]. Further processing of the signal depends on the purpose for which the receiver is intended. In a common home radio, the demodulated output is passed to an audio amplifier that is connected to a speaker.

B. SDR Receiver

Fig. 2 shows the block diagram of a SDR receiver. At first, the RF tuner converts the analog signal to IF, performing the same operation that the first three blocks of the superheterodyne receiver. Up to this point the two schemes converge [21].

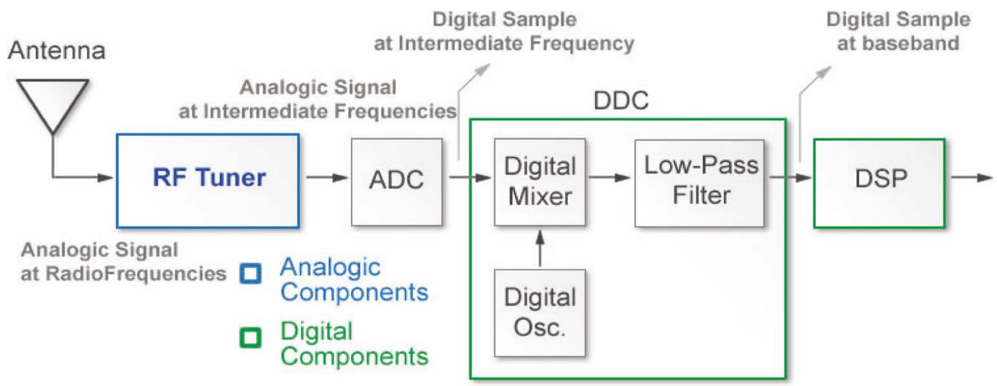

Fig. 2. Block Diagram of the SDR Receiver.

Next, the IF signal is passed to the ADC converter in charge of changing the signal's domain, offering digital samples at its output. The samples are feed to the following stage's input which is a Digital Down Converter (DDC). The DDC is commonly a monolithic chip and it stands as the key part of the SDR system. It consists of three main components: (1) a digital mixer, (2) a digital local oscillator, and (3) a Finite Impulse Response (FIR) low-pass filter.

The components operation is similar to their analog counterparts. The digital mixer and the local oscillator shift the IF digital samples to baseband, while the FIR low-pass filter limits the bandwidth of the final signal [21]. For the implementation of each of its parts, the DDC includes a high number of multipliers, adders and shift registers.

Observe that the signals are transferred to their baseband equivalent at the digital mixer's output by the disintegration into the I and Q counter phase components [20]. If the tuning of the digital local oscillator is modified, the desired signal can be shifted away or towards the point where it reaches 0Hz. This variation, together with the bandwidth adjustment of the low-pass filter, defines which part of the reception is treated as a useful signal.

Another procedure, known as decimation, is commonly performed for reducing the sampling frequency or sample rate. Thus, the new sampling frequency in baseband results from the division of the original sampling frequency by an N factor, called decimation factor. The final sample rate can be as little as twice the highest frequency component of the useful signal, as proposed by the well-known Nyquist theorem [22]. Furthermore, practical approaches have shown that reduction can be applied up to an extra 20% without significantly affecting the quality of the result [19]. This can be expressed numerically as is done in equation 1.

$$f_{b2}=0.8fb=fs/N \quad (1)$$

Where f_b is the frequency at baseband, fs is the sampling frequency, N is the decimator factor and f_{b2} is the new calculated baseband frequency after the decimation is applied.

Finally, the baseband samples are passed to the Digital Signal Processing (DSP) block, where task such as demodulating and decoding are performed, among others.

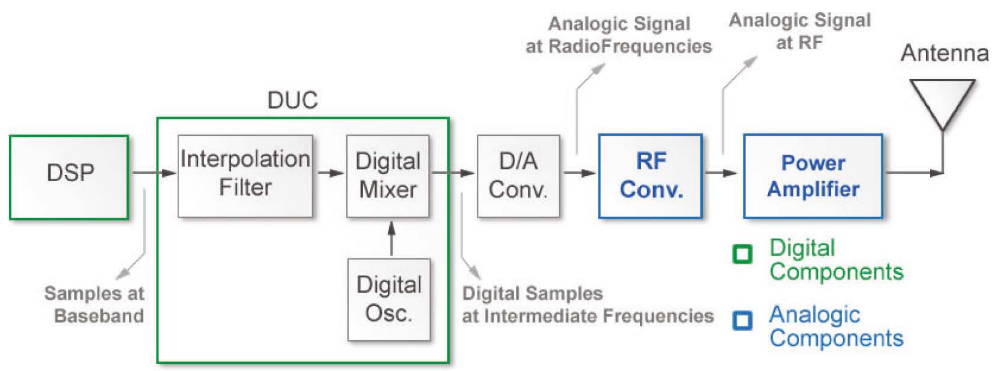

Fig. 3. Block Diagram of a SDR transmitter

The PDS block can be implemented in an FPGA if the system is to be adapted to a specific application. However, PDS stages are commonly found within a general purpose computer in the form of specialized software if versatility is to be added to the solution.

C. SDR Transmitter

Although the most common SDR devices are receivers, the technology also includes transmission schemes. The price of a SDR receiver can be as low as 20 USD [16], while the cost of SDR transmitters/receivers typically exceeds 300 USD [23]. The SDR transmitter's structure is explained below.

SDR transmitters receive a baseband signal as an input, typically generated by a DSP step as it is shown in Fig. 3.

The first block is a Digital Up Converter (DUC) which transfers the baseband signal to IF. The DAC that follows transform the samples to the analog domain. Next, the RF converter shifts the signal towards higher frequencies. Finally, the signal is amplified and directed to the antenna.

Table 1

Most relevant SDR Devices in the Market.

Commercial Name	Min. Freq. (MHz)	Max. Freq. (MHz)	Band-width	Resolu-tion of the ADC	Transmit?	Price
RTL-SDR 2831	24	1766	3,2	8	No	10-20
Funcube Pro	64	1700	0,096	16	No	150
Funcube Pro+	410	2050	0,192	16	No	200
HackRF	30	600	20	8	Yes	300
BladeRF	300	3800	40	12	Yes	400-650
USRP 1	10	6000	64	12	Yes	700
MatchStiq	300	3800	28	12	Yes	4500

Within the DUC, the Interpolation Filter is responsible for raising the baseband signal's sample rate to match the operating frequency of the components that follow. Therefore, it performs the Decimator's opposite operation in the receiver's architecture. Then, the digital mixer and the local oscillator shift the samples to IF, the shift being controlled by the local oscillator.

D. RTL2831 Device

Once explained the structure of the SDR receiver and transmitter, it's now the turn to introduce a SDR device. Later, in the section 3.3, some tests are carried out exploiting its functionalities using free software.

As one of the cheapest offers in the market, RTL2831SDR receiver from Teratec manufacturer is an excellent choice for a first approach to the technology. It operates in the VHF and UHF bands, allowing the exploration of a considerable part of the spectrum used for national broadcasts in various applications. It delivers to the DSP stage a spectral width of 3,2 MHz at real time operation.

Although it comes equipped with a quite small antenna (customizable from 9 to 32cm), the RTL2831 can be connected to other antennas with a better performance, adapted to the bands of intended operation. Moreover, the device has an USB 2.0 port for communicating with the computer, consistent with the spectral width that it handles. Devices able to monitor higher band-widths are commonly connected through a traditional network cable.

A small list of the most popular SDR devices in the market is offered as a valuable reference in table 1 [23]. Note that RTL2831 is the cheaper device.

III. SDR Software

While the hardware components are essentials in the SDR conception, the definition of the paradigm it-self points out the necessity of complementary dedicated software. In this section, a description of the main software tools that allows the SDR signal manipulation is offered.

Fig. 4. RTL2831 SDR Device.

A. SDR Frameworks

In order to operate a SDR device, from a personal computer or from an FPGA running Digital Signal Processing, software is needed for enabling the interaction. However, before developing software, a framework must be created providing low-level interface functions. Several attempts have been made since1980. Most major efforts are listed below.

- The Software Radio (1980-1985) [24]
- National Instruments – LabVIEW (1986 - present) [25]
- US Military – SPEAKKeasy I (1992-1995) [13]
- Massachusetts Institute of Technology – SpectrumWare (1994-1999) [26]
- US Military – SPEAKeasy II (1995-1997) [27]
- US Military – Joint Tactical Radio System (1997- present) [28]
- Trinity College – IRIS (1999 - present) [29]
- Vanu Software Radio (2001- present) [30]
- GNU Radio (2001 - present) [31]
- Flex-Radio SDR-1000 (2002-present) [11]
- Tsao, SDR Framework (2002) [32]
- Universidad de Kansas – Agile Radio (2003) [33]

- California Institute of Technology – CallRadio (2005 - present) [34]
- Rice – WARP (2006 - present) [35]
- High Performance SDR (2006 - present) [36]
- Virginia Tech – Open Source SCA Implementation (2006 - present) [37]
- Lyrtech – Small Form Factor SDR (2007 - present) [38]
- Virginia Tech – Cognitive Engine (2007 - present) [39]
- HYDRA (2007) [40]
- P-HAL (2008 - present) [41]
- Microsoft – SORA (2009 - present) [42]
- Karlsruhe Institute of Technology – MATLAB / Simulink/ USRP (2009) [43]
- MathWorks – MATLAB / Simulink / USRP (2011 - present) [44]

Though the above list is not complete, it illustrates the increasing popularity of the SDR technology. Projects grouped by year are show in Fig. 5. Obviously, the number of emerging frameworks has increased since 2000.

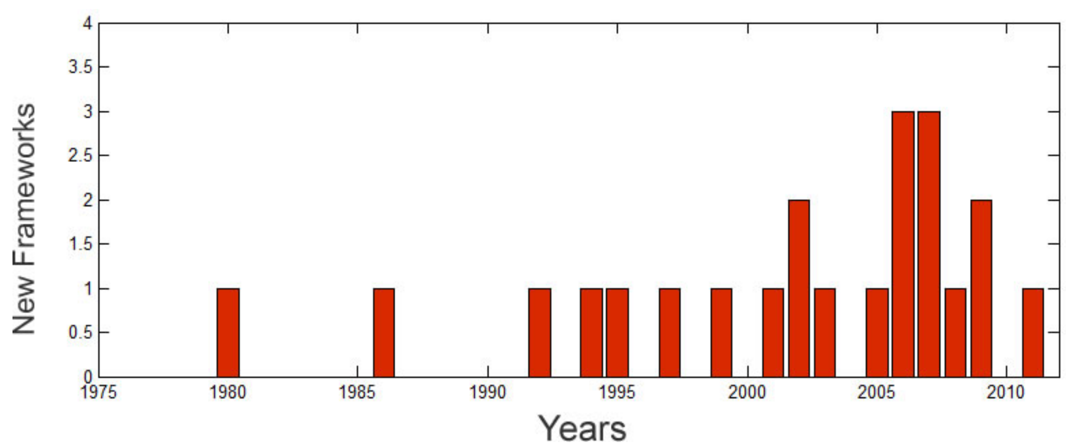

Fig. 5. Amount of Frameworks implemented by year.

Among the published list, there are three libraries that stand out for its frequent use in a great amount of the current research papers. The first of them appear in 2001 and it was designed exclusively for Linux operative system, but its popularity [45-47] has extended its usage also to Windows: GNU Radio2001.The other two operate exclusively on Windows and are based on MATLAB mathematical software: Karlsruhe Institute of Technology-MATLAB/Simulink/USRP2009 and MathWorks-MATLAB/Simulink/USRP2011. Precisely together with GNURadio, MATLAB is the most used support in SDR investigations [48-50]. The Success of GNU Radio and MATLAB mainly reside in the fact that they provide easy to handle tools for the manipulation of signals.

The duration over time of the above mentioned SDR frameworks is illustrated in Fig. 6. As it can be seen, there is a growing tendency to stability in new projects.

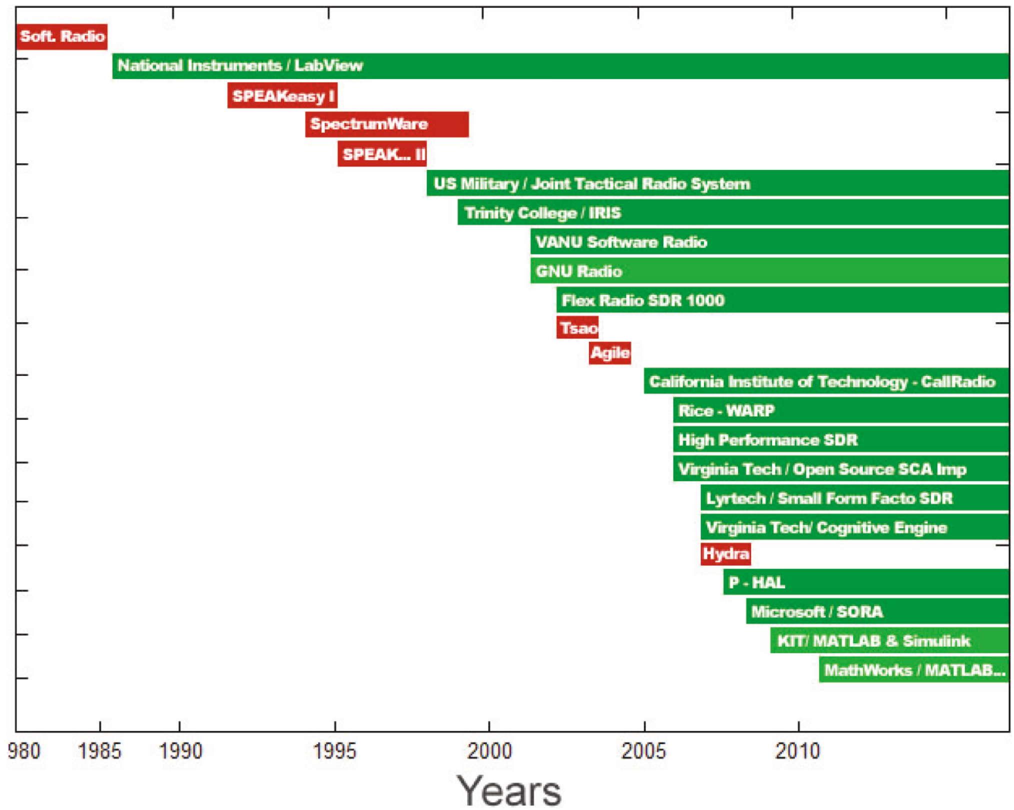

Fig. 6. Time Duration of SDR framework projects.

B. SDR Uses

Once the SDR device is in communication with the personal computer, one can start looking for uses of the technology, offering specific solutions. The concept of unified platform and the ability to correct errors in real time are the classic applications of SDR. However, studies have identified other significant applications, such as: Dynamic Spectrum Positioning, Opportunity Driven Multiple Access (ODMA), Spectrum Regulation and Cost Reduction (some SDR implementations are more cheaper than its analog counterpart) [51].

A little beyond its traditional applications, the SDR philosophy begins to dawn on high-impact areas within telecommunications. This is the case of Driver Assistance [52], GPS signals' Reception [53], HF Propagation Analysis [54], Interpretation of Cellular Technology Emissions [55-57] particularly the OFDM modulation [58], and the Identification of Radio Frequency Emissions [59].

In other visionary fields, SDR experiments have provided encouraging results that motivate to continue the investigations. Potential applications are being found in areas as diverse as prototypes development [60], microscopic investigations of the strength of the magnetic resonance [61], aviation tests [62], evaluation of multi-path communications [40], broadcast transmissions in multi-media mobile environments [63], cooperative wireless networks diversity [64], crossings prototypes between wireless networks layer, quantum optical communications and particularly in cognitive radio research [65-68].

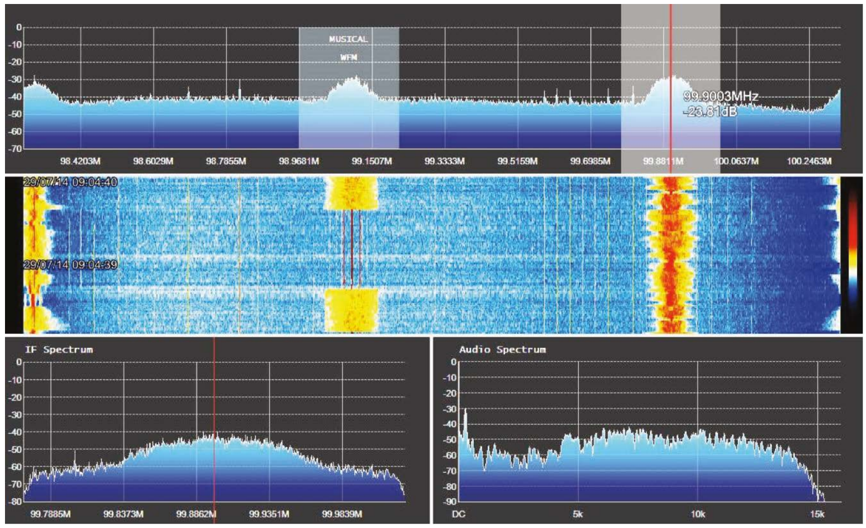

Fig. 7. Real time spectrum visualization

C. Employment Opportunities

Many of the applications previously described are only available to large corporations and universities with high amounts of money dedicated to research. However, there are some low-cost solutions that can be achieved with the RTL2831 or another similar device using free software. In this section, several free downloaded softwares are presented, together with some solutions that can be materialized or studied with them. Every one of the provided figures was obtained by running the softwares on Windows 7 and 8.

1) SDR-Sharp

The first software is called SDR-Sharp [14] and displays in real time all the readings that is capable to generate the SDR device, which it translates to 3.2 MHz in the case of the Teratec RTL2831. As shown in Fig. 7, it offers of 4 main windows to the user. The top one shows the spectrum displayed in real time, in which three FM radio stations are visible in the selected example. The next window, known as waterfall chart, illustrates the signal´s time behavior showing the most intense emissions in warmer colors. The two lower windows are in charge of plotting the selected bandwidth inside the full spectrum displayed in the top window. To the left, the IF spectrum can be perceived. To the right, the frequency distribution of the voice demodulated signal is illustrated. In addition, the transmission's acoustic content can be heard if a speaker is connected to the computer. Obviously, in the example above, the demodulation scheme used a FM demodulator. In addition, the software allows demodulation of the AM (Amplitude Modulation), CW (Continuous Wave), USB (Upper Side Band), LSB (Lower Side Band) and DSB (Double Side Band) signals.

Understanding how SDR-Sharp works, some applications can be identified. They are shown below:

- Cheap Radio Receiver: A general purpose computer may become a cheap radio receiver if a SDR device is connected to it. SDR-Sharp works well on single core 2GHz computers with at least 1GBof RAM. However, there are some operations that consume more resources.

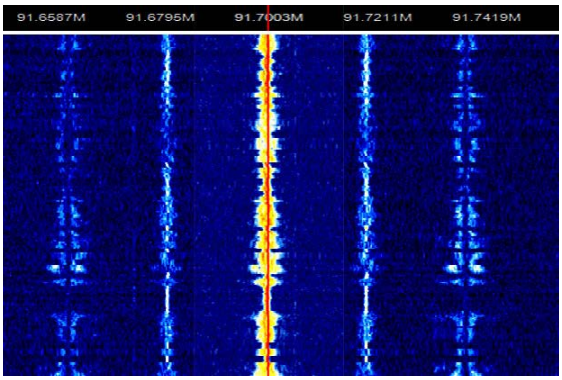

Fig. 8. Interference generated by an RF transmission.

- Interference Detection: Not all emissions are kept within the frequency region specifically conceive for them. Some devices let escape signals, resulting from undesired intermodulation, which can interfere with other radio users. As it is visible in Fig. 8, SDR-Sharp is a very useful tool when is necessary to detect an interference.
- Spectrum Relocation: A SDR receiver allows exploring a wide range of frequencies so that not used or not assigned spaces can be found, as well as frequencies with very low access. This type of studies allows for transmission relocation, optimizing the consumed bandwidth.
- Spectrum Regulation and Automatic Transmission's Identification: Unfortunately, radio users do not always maintain discipline. Sometimes emissions occur in unauthorized bands. Real time monitoring is achievable trough SDR-Sharp. In addition, such a versatile tool induces the implementation of Systems for Automatic Transmission's Identification. Emissions can be distinguished not only by its bandwidth, but by its cyclic variation and specific characteristics such as the tail's shape of the signal. Note that the automatic identification cannot be executed directly with SDR-Sharp. New software needs to be created.

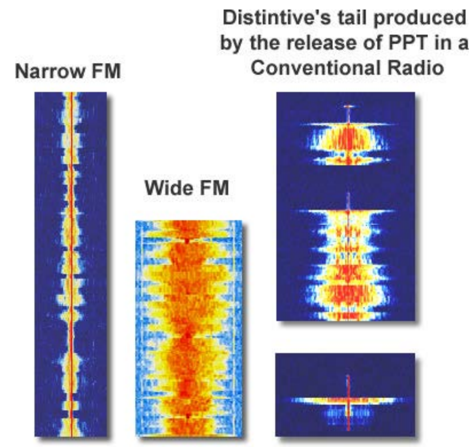

Fig. 9. RF transmissions distinctive features.

- Checking Repeaters Systems: If the power receiver from several repeaters is periodically measured in a common geographic point, damage, interference or disruptions can be detected. Similarly, if a SDR transmitter was available, or a conventional radio device with a similar functionality, low rate or probably down sites availability could be checked. Furthermore, with the employment of frameworks as the mentioned above it's possible to automate the process.

2) RTLSDR Scanner

Another very useful software is RTLSDR Scanner [15] which has the characteristic of being cross platform as it has been tested on Windows 7 and 8, Ubuntu 12 and 13 and Macintosh Systems like Leopard and Mountain Lion. In short, the application is a spectrum analyzer that performs consecutive scans and allows to gather data and to make comparisons. Unlike SDR-Sharp, it does not operate at real time.

Fig. 10 shows a measurement made with RTLSDR Scanner. In it, the computation of the received power's average after performing several scans over a1 MHz bandwidth is revealed. Note that a specific area may be selected if the user wishes to obtain numerical values for the Maximum Power, Low Power and Average Value.

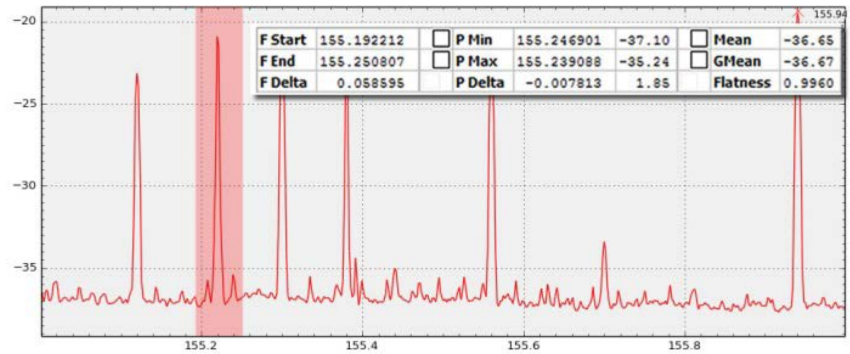

Fig. 10. Spectrum Analyzing with RTLSDR Scanner.

The plotted results can be saved in different formats and comparisons can be performed over them to analyze the measurements. One of the comparisons is shown in Fig. 11 where data from consecutive scans is plotted. The colored area represents the signal's variation. For example, the peak to the extreme left is colored, which means that the maximum is not constant but appears at intervals in this area. By contrast, the peak to the extreme right is not colored, indicating that the local maximum hasn't fall throughout the all observation period.

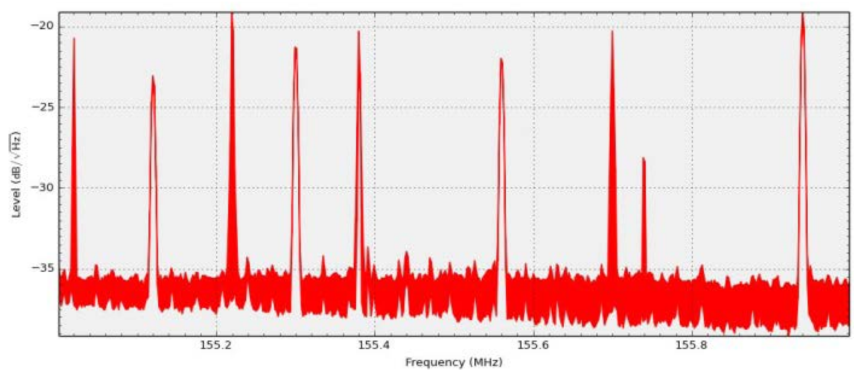

Fig. 11. Plotting the difference between consecutives scans.

Taking advantage of the benefits offered by RTLSDR Scanner, some applications can be identified. They are show below:

- Measurement of the repeaters' electrical parameters: RTLSDR Scanner allows checking if the signal parameters offered by manufacturers are actually implemented by their equipment. Transmitted power and frequency deviation can be easily checked, as well as the appearance of harmonics frequency bands near to the one intended for the communication.
- Noise Characterization by Bands: By exploring the spectrum, qualified personal may analyze the noise level of each band obtaining as a result the possibility of making adjustments in the propagation calculation methods.
- Spectrum Intruders Identification: Scanning silence zones, unauthorized transmissions can be detected.

3) SDR for Android

One of the platforms for which SDR applications have been developed is Android. The software SDR Touch turns the phone in to a SDR receiver whose range fluctuates between 50MHz and 2 GHz in AM, FM and SSB depending on the used hardware [69]. There is also another software called Pocket HAM Bands Transceiver who allows the remote listening of SDR receivers.

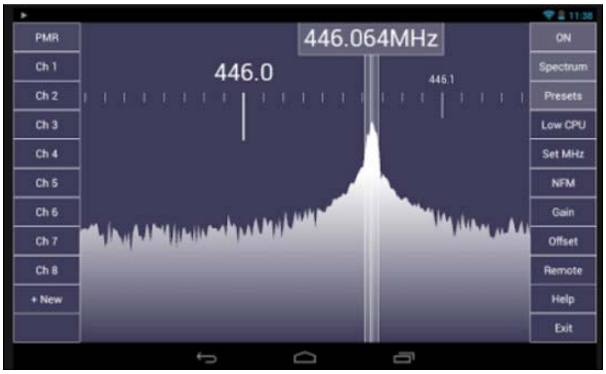

Fig. 12. SDR Touch Visual Interface.

4) SDR in the Web

SDR's perspectives in the future are many and varied, but its application is particularly important when Internet connected systems are brought into consideration. From this point of view, there are two fundamental approaches:

1. Transmission over Internet of own SDR signals.
2. Free access to foreigners SDR in remote locations.

For the transmission of a local own signal (approach 1) the software rtl_tcp may be used. With two PCs, a hub and SDR RTL 2831 the possibility to visualize data received through the network was verified. However, when a laptop was added as a third active element, the disadvantage of the scheme became evident: only one remote host can receive the signal at a given time. There are two solutions to the problem:

- Place several SDR devices in a centralized server so each remote may have access to a different one. This can be made because of the low prices of the SDR hardware available on the market. However, note that the alternative requires some centralized service that should act as a judge and rule the access to various devices connected.
- Establish a Linux server responsible for handling requests to a single device. This application already exists.

Both options are viable, being the selection conditioned by the necessities of each particular user. However, if the conditions are given, the second-one is recommended over the first.

Regarding the free access to foreigners SDR in remote locations (approach 2), it needs to be let clear that this alternative is equally or more valuable than the previous. Worldwide, there are a lot of SDR devices ruled by amateur users and nonprofit associations. The geographical location of all 79 stations is provided in Fig. 13 [70].

As the reader may notice, the majority of the receivers are located in Europe, although there are stations in all continents. The operating bands and the signal's quality offered by the deployed devices differ from one location to another, understandable fact if the spontaneous nature of the network is considered. However, by accessing several terminals, multiple bands can be covered, especially in high density areas.

Fig. 13. SDR Receivers around the world

The SDR Internet transmission possibilities shown above leads to consider the following applications of the technology:

- Estimation of Wireless Transmission Losses: Providing centralized control of several SDR devices deployed at strategic locations enables the comparison of received signals, which allows the estimation of path loss and the validation of the coverage computations made with specialized software like RadioMobile [71].
- SDR as a service: The Corporation that achieves deploying a large SDR network will be able to provide access to the receivers as a service to third parties with specific interests.

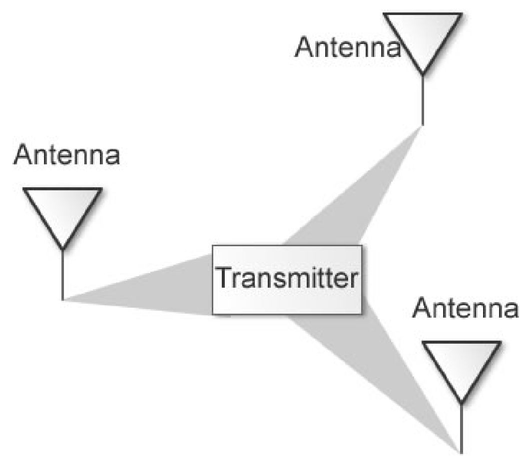

Fig. 14. Location of unknown transmitters from at least three different locations.

- Radiogoniometry: Location of emission's source using information supplied by several receivers located at distant positions. If at least three of them are used, the location of a radiofrequency source can be accurately determined. However, the application is not directly usable with the software presented.
- Improvement of Shortwave Communications: Using remote SDR receivers, shortwave transmissions can be heard even from distant countries. Thus, HF communication reception quality may be improved through Internet.
- Spectrum Exploring: The listen to specific bands in remote locations can be useful for many organizations.

IV. Conclusions

SDR technology has many applications in radio environments and is becoming increasingly popular among all type of users. While the first projects were unstable, there are currently a lot of frameworks that allow the manipulation of radio signals only with a personal computer and an inexpensive SDR device such as the Teratec RTL2831U. The applications are multiple. Besides providing a very cheap radio receiver, SDR devices can be combined with free software to facilitate examination of the spectrum, detection of interferences, assigning of frequency distributions in an efficient manner, testing repeater systems' operation and measuring their electrical parameters, identifying spectrum intruders and characterization of noise by bands and regions of the world.

In addition, SDR versatility envisions its possible application in the improvement of shortwave communications. Similarly, the continued growth of the SDR with worldwide available receiving points announces the formation, in a not too distant future, of a vast network through which it will be possible to listen to radio broadcast on any part of the world by using Internet.

References

[1] P. K. Bondyopadhyay and G. Marconi, "The Father of Long Distance Radio Communication - An Engineer's Tribute", *Proceedings of the 25th European Microwave Conference,* vol. 2, pp. 879-885, 1995.

[2] O. U. Press, *A Tower in Babel: A History of Broadcasting in the United States to 1933* ,1966.

[3] J. J. Green, "The Apparatus for Wireless Telegraphy", *American Electrician,* pp. 344-346, 1899.

[4] D. Raychaudhuri and N. B. Mandayam", Frontiers of Wireless and Mobile Communications", *Proceedings of the IEEE,* 2012.

[5] O. U. Press, "The Image Empire: A History of Broadcasting in the United States from 1953", 1970.

[6] L. Kleinrock, "An Early History of the Internet", *IEEE Communications Magazine,* vol. 48, pp. 26-36, 2010.

[7] N. Abramson, "Development of the ALOHANET", *IEEE Transactions on Information Theory,* vol. 31, pp. 119-123, 1985.

[8] R. Frenkiel, "Creating Cellular: A history of the AMPS project (1971-1983)", *IEEE Communications Magazine,* pp. 14-24, 2010.

[9] U. F. C. Commission, "Authorization of Spread Spectrum Systems Under Parts 15 and 90 of the FCC Rules and Regulations", *General Docket,* pp. 81-413, 1985.

[10] IEEE, "802.11 IEEE Standard for Information Technology. Telecommunications and Information Exchange Between Systems, Local and Metropolitan Area Networks. Specic Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specications", 1997.

[11] G. Youngblood, "A Software-Defined Radio for the Masses, Part 1", *QEX: A Forum for Communications Experimenters,* 2002.

[12] J. Mitola III, "Software Radios. Survey, Critical Evaluation and Future Directions", *IEEE National Telesystems Conference,* pp. 13-15, 1992.

[13] R. J. Lackey and D. W. Upmal, "Speakeasy: the Military Software Radio", *IEEE*

Communications Magazine, vol. 33, pp. 56-61, 1995.
[14] (August 2014). *SDR-Sharp Oficial Web Site*. Available: http://sdrsharp.com/
[15] (August 2014). *RTLSDR Scanner GitHub reference*. Available: http://github.com/EarToEarOak/RTLSDR-Scanner
[16] (August 2014). *Amazon. Venta de Hardware SDR*. Available: http://www.amazon.com/Terratec-Receiver-Low-Cost-Software-Defined/product-reviews/B00CRDF5WQ
[17] A. B. Carlson, *Communications Systems An Introduction to signals and Noise*, 4th ed.: McGraw-Hill Higher Education, 2002.
[18] J. D. Gibson, *The Communications Handbook*, 2 ed.: CRC PRESS, 2002.
[19] R. H. Hosking, *Software Defined Radio Handbook (Notes Gathering)*, 8 ed., 2010.
[20] J. B. Anderson and J. Rolf, *Understanding Information Transmission*: IEEE Press, 2005.
[21] V. Giannini, J. Craninckx, and A. Baschirotto, "Baseband Analog Circuits for Software Defined Radio", ed: Springer, 2008.
[22] B. Sklar, *Digital Communicatinos Fundamentals and Applications*, 2 ed.: Prentice Hall, 2001.
[23] (August 2014). *Comparisons with other Wideband Commercial Software Defined Radios*. Available: http://www.rtl-sdr.com/about-rtl-sdr/
[24] G. D. Space Systems Technology Group, "New Research Lab Leads to Unique Radio Receiver", *E-Systems Team magazine,* vol. 5, pp. 6-7, 1985.
[25] (April 2012). *National Instruments Corporation History, accessed* Available: http://www.ni.com/company/history.htm
[26] "Design and Implementation of Software Radios Using a General Purpose Processor", Ph.D., Massachusetts Institute of Technology, Cambridge, MA, USA, 1999.
[27] R. Vidano, "SPEAKeasy II : an IPT Approach to Software Programmable Radio Development", *MILCOM 97 Proceedings,* vol. 3, pp. 1212-1215, 1997.
[28] (1997, April 2012). *Mission Needs Statement (NMS) for the Joint Tactical Radio (JTR)*.
[29] P. Mackenzie, L. Doyle, K. Nolan, and D. O'Mahony, "An Architecture for the Development of Software Radios on General Purpose Processors", *Proceedings of the Irish Signals and Systems Conference,* pp. 275-280, 2002.
[30] V. G. Bose, "A Software Driven Approach to SDR Design", *COTS Journal,* 2004.
[31] (April 2012). *GNU Radio Wikipedia Entry*. Available: http://en.wikipedia.org/wiki/Gnu
[32] S.-L. Tsao, C. C. Lin, C. L. Chiu, H.-L. Chou, and M. C. Wang, "Design and Implementation of Software Framework for Software Defined Radio System", *Proceedings of the 56th IEEE Vehicular Technology Conference,* vol. 4, pp. 2395-2399, 2002.
[33] G. J. Minden, J. B. Evans, and J. A. Roberts, "Agile Radio Systems and National Radio Networking Research Testbed", *SensorNet Architecture Forum, Lawrence, KS, USA,* 2003.
[34] (April 2012). *Calradio User Guide*. Available: http://calradio.calit2.net/calradio1a.htm
[35] P. Murphy, A. Sabharwal, and B. Aazhang, "Design of WARP: A Flexible Wireless Open-Access Research Platform", *Proceedings of 14th European Signal Processing Conference,* 2006.
[36] (April 2012). *High Performance Software Defined Radio Website.* Available: http://openhpsdr.org/history.php
[37] J. A. DePries, "A Practical Approach to Rapid Prototyping of SCA Waveforms", Master, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, 2006.
[38] (February 2007). *Lyrtech SFF SDR Development Platform Technical Specs, Technical Report*. Available: http://www.lyrtech.com/publications/sff_sdr_dev_platform_en.pdf
[39] T. W. Rondeau, "Application of Articial Intelligence to Wireless Communications", Ph.D., Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 2007.
[40] K. Mandke, S. H. Choi, G. Kim, R. Grant, R. Daniels, W. Kim, R. W. Heath, and S. M. Nettles, "Early Results on Hydra: A Flexible MAC/PHY Multihop Testbed", *Proceedings of the 65th IEEE Vehicular Technology Conference,* pp. 1896-1900, 2007.
[41] I. G. Miguelez, "A Software Framework for Software Radio", Master, Universidad Politécnica de Cataluña, Barcelona, España, 2008.
[42] K. Tan, J. Zhang, J. Fang, H. Liu, Y. Ye, S. Wang, Y. Zhang, H. Wu, W. Wang, and G. M. Voelker,

"Sora: High-Performance Software Radio Using General-Purpose Multi-Core Processors", *6th USENIX Symposium on Networked Systems Design and Implementation,* 2009.

[43] (2009, April 2012). *Native Interface between MATLAB / Simulink and USRP*.

[44] (April 2012). *MATLAB and Simulink Support Package for USRP Hardware*

Available: http://www.mathworks.com/matlabcentral/linkexchange/links/2973-matlab-and-simulink-support-package-for-usrp-hardware

[45] D. Valerio, "Open Source Software-Defined Radio: A survey on GNUradio and its applications", *Technical Report, Donaucitystrasse 1, 1220 Vienna, AUSTRIA,* 2008.

[46] D. C. Tucker and G. A. Tagliarini, "Prototyping with gnu radio and the usrp - where to begin", *SOUTHEASTCON'09. IEEE,* pp. 50–54, 2009.

[47] S. J. Olivieri, "Modular FPGA-Based Software Defined Radio for CubeStats", Master, Worcester Polytechnic Institute, 2011.

[48] R. Sivappagari and C. Mohan, "Software Defined Radio using Digital Modulation Techniques - A MATLAB SIMULINK Approach", *Proceedings of International Academic Conference on Electrical, Electronics and Computer Engineering,* 2013.

[49] K. J. T. Hazim Salah Abdulsatar, Ali Hashim Jryian, "Low power Transceiver Structure for Wireless and Mobile Systems Based SDR Technology Using MATLAB and System Generator", *International Journal of Engineering and Advanced Technology (IJEAT),* vol. 3, 2013.

[50] Z. Feng, "A Software Defined Radio Implementation Using MATLAB", Graduated, 2013.

[51] S. Gultchev, K. Moessner, and D. Thilakawardana, *Evaluation of Software Defined Radio Technology,* Centre for Communication System Research, University of Surrey, 2005.

[52] N. Haziza, M. Kassab, and R. Knopp, "Multi-technology vehicular cooperative system based on Software Defined Radio (SDR)", Communication Technologies for Vehicles, pp 84-95, Springer, 2012.

[53] J. Seo, Y.-H. Chen, and D. S. De Lorenzo, "A Real-Time Capable Software-Defined Receiver Using GPU for Adaptive Anti-Jam GPS Sensors", *Sensors Journal,* 2011.

[54] P. B. Nagaraju, E. Koski, and T. Melodia, "A Software Defined Radio Ionospheric Chirpsounder for HF Propagation Analysis", 2009.

[55] H.-S. Yoo, B. Park, and S.-H. Kim, "Seamless Vertical Handover in Software Defined Radio Terminal", *International Journal of Control and Automation,* vol. 2, 2009.

[56] M. Zahangir Alam and M. Abdus Sobhan, "Design of Future Software Defined Radio (SDR) for All-IP Heterogeneous Network", *Recent Patents on Signal Processing,* vol. 2, pp. 12-21, 2010.

[57] P. Vinayakray Jani, "Algorithm Driven System Selection with Reconfigurable Software Defined Radio in Mobile Devices", *International Journal of Wireless & Mobile Networks,* vol. 2, 2010.

[58] A. Technologies, "Creating and Analyzing Custom OFDM Waveforms for Software-Defined Radio (SDR) Application Brief", 2010.

[59] M. Islam, M. A. Hannan, S. A. Samad, and A. Hussain, "Software Defined Radio for RFID Application", *Proceedings of the World Congress on Engineering and Computer Science 2009,* vol. 1, 2009.

[60] M. L. Dickens, B. P. Dunn, and J. N. Laneman, "Design and Implementation of a Portable Software Radio", *IEEE Communications Magazine,* vol. 46, pp. 58-66, 2008.

[61] J. P. Jacky, J. L. Garbini, M. Ettus, and J. A. Sidles, "Digital Control of Force Microscope Cantilevers Using a Field Programmable Gate Array", *Review of Scientic Instruments,* vol. 79, 2008.

[62] E. Matlis, T. Corket, and S. Gogineni, "Plasma Anemometer for Hypersonic Mach Number Experiments", *Instrumentation in Aerospace Simulation Facilities,* pp. 245-256, 2005.

[63] R. Farrell, M. Sanchez, and G. Corley, "Software-Defined Radio Demonstrators: An Example and Future Trends", *International Journal of Digital Multimedia Broadcasting,* vol. 12, 2009.

[64] G. J. Bradford, "A Framework for Implementation and Evaluation of Cooperative Diversity in Software-Defined Radio", Master, University of Notre Dame, 2008.

[65] J. G. Q. Maguire, “Cognitive Radio: Making Software Radios More Personal”, *IEEE Personal Communications,* vol. 6, pp. 13-18, 1999.

[66] N. M. Josuttis, *The C++ Standard Library - A Tutorial and Reference*, 2 ed.: Addison-Wesley Professional, 2012.

[67] N. Savage, “Special Reports on Emerging Technologies: Cognitive Radio”, *MIT Technology Review,* 2006.

[68] J. E. G. Minden, L. Searl,, “Cognitive Radios for Dynamic Spectrum Access: An Agile Radio for Wireless Innovation”, *IEEE Communications Magazine,* vol. 45, pp. 113-121, 2007.

[69] (August 2014). *Recopilación de Apps SDR para Androide*. Available: http://www.radioclubfene.net/index.php/hf-vhf-uhf-shf/59-recopilacion-de-apps-de-radio-para-android

[70] (August 2014). *Web SDR around the World*. Available: http://websdr.org/

[71] (August 2014). *Radio Mobile Oficial Website*. Available: http://www.cplus.org/english1.html