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Keywords: Software Defined Radio, Real-Time Implementation, Wireless Communications.

Abstract: With the advent of GNU Radio, a revolution in the SDR technologies is foreseen that will greatly reduce development and deployment costs in terms of hardware as well as manpower. The availability of the Universal Software Radio Peripheral (USRP) and the USRP2, an extremely low-cost, mid-performance, real-time capable system equipped with a great variety of pluggable radiofrequency front-ends covering any frequency band from 50 MHz to 2.9 GHz and from 4.9 GHz to 5.9 GHz leads to a unique device all over the world. Furthermore, such hardware is complemented with the GNU Radio software, an open-source, flexible, sophisticated and powerful software toolkit specifically designed for SDR-based implementations and digital signal processing carried out in general-purpose processor. In conjunction, the GNU Radio software together with the USRP and, especially, the USRP2, constitute a new paradigm to be taken into account when SDR systems are to be developed.

1. INTRODUCTION

Software-Defined Radio (SDR) is defined by the SDR Forum as a “radio in which some or all of the physical layer functions are software-defined” (SDR Forum, 2010). Only radiofrequency (RF) and signal rate conversion operations are somehow implemented in hardware, while the remaining radio functionalities are implemented in software. SDR technologies are particularly suitable for implementing the multi-standard wireless communications equipments demanded by the Next Generation Mobile Networks (NGMN) alliance (NGMN, 2010).

Figure 1: Block diagram of the main components of an SDR system.

Figure 1 shows a block diagram containing the basic components of an SDR system. On the right-hand side the baseband processing system is shown, which is in charge of carrying out all digital signal processing operations. Depending on the requirements of the SDR system, the hardware utilized can vary from ordinary general-purpose processor to real-time processors like Digital Signal Processors (DSPs) and Field Programmable Gate Arrays (FPGAs), and even application-specific integrated circuits (ASICs). In order to reduce the transfer rate between the DSP software and the Analog-to-Digital (A/D) and the Digital-to-Analog (D/A) conversion section, a digital front-end is included, which mainly carries out sample rate conversion operations (i.e., digital up and down conversions). Finally, flexible and user-configurable RF front-ends are utilized to be able to intercommunicate at different RF bands.

However, the commercial success of SDR solutions has been obstructed by the high cost and low flexibility of the currently available programmable devices (mainly those based on DSPs and/or FPGAs) (Hunt Engineering, 2010; Innovative Integration 2010; Lyrtech, 2010; Nallatech, 2010; National Instruments, 2010; Pentek, 2010; Signalion, 2010; Sundance, 2010). With the advent of GNU Radio (GNU Radio, 2010), a revolution in SDR technologies is foreseen that will greatly reduce development and deployment costs in terms of both hardware and manpower. This paradigm change is evidenced by the large number of GNU
Radio solutions that have been recently developed (CGRAN, 2010): GPS receiver, 802.11a/b/g/p and 802.15.4 applications, RDS FM receiver, RFID solutions, etc.

GNU Radio is a free and open software toolkit for the development of SDR technologies. GNU Radio provides the necessary blocks for implementing reconfigurable software radios using the Universal Software Radio Peripheral (USRP) hardware. The USRP (and its successor, the USRP2) is a low-cost external digital front-end and radiofrequency (RF) hardware manufactured by Ettus Research LLC (Ettus, 2010). It contains a programmable signal rate conversion before the digital front-end in order to reduce the required transfer rate with the host PC. RF front-ends are available as pluggable daughterboards. Consequently, the same motherboard can be used with a great variety of daughterboards, each one designed to operate in specific RF bands.

The GNU Radio and the USRP (including the USRP2) work with the following operating systems: any GNU/Linux distribution (with a 2.6 kernel version), on the Mac OS X (either in the Power PC or the x86 architectures), on the Microsoft systems (including Windows 2000, XP, Vista, and 7) and, finally, on FreeBSD and NetBSD UNIX systems. Given that, first, the price of the USRP and the USRP2 is, respectively, 700 USD and 1400 USD; second, the price of the majority of the daughterbords range from 275 USD to 450 USD; and, third, the GNU Radio software is available for free, the total cost of GNU Radio solutions is very attractive, especially when compared to the cost of commercial solutions offered by companies like Lyrtech, Nallatech, National Instruments, or Sundance among others. The cost of such commercial solutions increases by a factor of ten or even more. Furthermore, commercial solutions are not based on free hardware designs and free software (GNU, 2010; GPL, 2010) and, thus, there are additional expenses for the software licenses.

In this paper, we provide a detailed overview of the GNU Radio hardware and software. More specifically, we focus our analysis on the USRP and the recently launched USRP2 hardware. We also stress the applicability of the USRP2 to the implementation of multiple-antenna, real-time, high-performance, broadband wireless communications systems at a low-cost. Finally, we also emphasize the opportunities provided by the GNU Radio hardware – including both USRP versions – as well as its main limitations.

2. GNU RADIO OVERVIEW

GNU Radio is a free software framework for developing SDR applications (GNU Radio, 2010), providing signal processing blocks as well as drivers to interact with the hardware. GNU Radio defines an application development model based on a set of blocks (the signal processing operations) connected on a flow graph basis. The blocks are implemented in highly optimized C++, specifically suitable for the x86 architecture that is, by far, the majority in the general-purpose processor industry. Such blocks are interconnected between them by means of Python, a high-level language suitable for purposes like this. With the above-mentioned approach, it turns out that it is very easy to translate a typical description of a wireless communications system into a design suitable for the GNU Radio framework.

Although the GNU Radio software perspective is very interesting, in this paper we focus on the hardware side. From now on, we elaborate on the Universal Software Radio Peripheral (USRP) and its successor, the USRP2.

3. THE USRP

Generally and simply speaking, the USRP (see Figure 2) is a low-cost piece of hardware that converts the analogue signals received by the antennas into discrete-time signals that are fed into an ordinary host to be processed by means of a general-purpose processor. Figure 3 shows a block diagram of the USRP hardware.
Basically, the USRP consists of a motherboard plus up to four RF front-ends referred to as daughterboards (more on this in Section 5). The motherboard contains the following basic elements:

- A Cypress FX2 Universal Serial Bus (USB) controller (Keil, 2010) which handles the data transport between the host and the USRP motherboard.
- An Altera Cyclone EP1C12 FPGA (Altera, 2010) that carries out the data routing between the USB controller and the CODEC section. It also implements some digital signal processing operations for the user-selectable sample rate conversion and digital mixing to baseband at the receiver side.
- For the CODEC section, the USRP incorporates two Analog Devices AD9862 mixed-signal front-end processors (CODEC) directly attached to the FPGA (AD9862, 2010). The only transmit signal processing blocks included in the FPGA are the Cascaded Integrator-Comb (CIC) interpolators (Hogenauer, 1981). The USRP allows the interpolator output to be routed to any of the four CODEC inputs. The remaining steps to be performed at the transmitter (namely, the digital up conversion and the complex quadrature modulation) are carried out inside the AD9862. At the receiver side, however, only a half-band filter decimating by two is implemented inside the AD9862. The complex quadrature demodulation as well as the digital down conversion is carried out inside the FPGA.

The default firmware included with the GNU Radio software configures the D/A converters to 128 Msample/s, while the A/D converters sample at 64 Msample/s. Given that the USB can sustain a rate equal to 32 MB/s and that complex baseband signals take four bytes for each complex-valued sample, it results in a maximum bandwidth of 8 MHz shared among all transmit and receive paths. Finally, Ettus declares a Spurious-Free Dynamic Range (SFDR) equal to 85 dB for the A/D converters and equal to 83 dB for the D/A converters.

### 4. THE USRP2

The USRP2 (see Figure 4) is the successor of the USRP, offering improved versions for the CODEC, the FPGA, and the data transfer system with the host, which is carried out through a Gigabit Ethernet connection (see Figure 5). Contrarily to the USRP, interpolation and decimation filters as well as digital mixing are all implemented in the Xilinx Spartan 3 FPGA, while the CODEC consists of an Analog Devices AD9777 dual D/A converter (AD9777, 2010) plus a Linear Technologies LTC2284 dual A/D converter (LTC2284, 2010), resulting in two D/A converters and two A/D converters, both configured to sample at 100 Msample/s, dealing with intermediate frequency (IF) signals. Additionally, the AD9777 implements a four-time interpolation filter in the analogue domain, simplifying the requirements for the analogue reconstruction filters and improving the signal quality at the TX side. The motherboard also...
incorporates a CPLD for loading the FPGA firmware from an ordinary Secure Digital (SD) card.

Figure 5: USRP2 block diagram. D/A, A/D converters as well as data path assume complex-valued signals.

The USRP2 is specified to be able to manage 50 MHz of bandwidth shared between the transmitter and the receiver sections with full-duplex operation, becoming the broadband wireless device with the lowest cost per bandwidth unit available in the market. However, it features a single CODEC, which led to the incorporation of mechanisms to coherently synchronize various USRP2 units by incorporating a user-configurable clock distribution system. Particularly, the USRP2 also includes a specific Multiple-Input Multiple-Output (MIMO) expansion port allowing coherent synchronization of two or four USRP2 units.

However, what makes the USRP2 a unique device from the SDR point of view is the possibility of attaching to it a high-performance FPGA (e.g., a Xilinx Virtex 5 by means of the Rocket I/O connection) utilizing a 2.2 Gbit/s high-speed Serializer/Deserializer (SerDes), which provides a tremendous increase in bandwidth with respect to previously available technologies. This opens the door for SDR-based, real-time, high-performance, multiple-antenna, broadband wireless communications systems at a low-cost.

Finally, Ettus declares a SFDR of 88 dB for the A/D converters and at least 80 dB for the D/A converters.

5. RF DAUGHTERBOARDS

Ettus Research LLC provides three different sets of pluggable RF daughterboards. The first set is constituted by the so-called BasicTX, BasicRX, LFTX and LFRX, which permits direct access to the CODEC inputs and outputs (through coaxial cables), thus allowing connection with RF front-ends different than those provided by Ettus. The second set consists of a Very High Frequency (VHF)/Ultra High Frequency (UHF) receiver based on an analogue TV tuner, referred to as TVRX. Such set is completed with the DBSRX, an 800 MHz to 2.4 GHz receiver covering many frequency bands of interest such as, for example, Global Positioning System (GPS) and Galileo, Digital Enhanced Cordless Telecommunications (DECT) as well as some astronomy bands. Finally, the third set is formed by the so-called transceiver daughterboards, namely: WBX, RFX400, RFX900, RFX1200, RFX1800, RFX2200, RFX2400, and XCVR2450, covering the frequency bands from 50 MHz to 2.9 GHz and from 4.9 GHz to 5.9 GHz.

Table 1: RF transceiver daughterboards.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Frequency range (MHz)</th>
<th>TX power (dBm)</th>
<th>Price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBX</td>
<td>50 - 2200</td>
<td>20</td>
<td>450</td>
</tr>
<tr>
<td>RFX900</td>
<td>750 - 1050</td>
<td>23</td>
<td>275</td>
</tr>
<tr>
<td>RFX1200</td>
<td>1150 - 1450</td>
<td>23</td>
<td>275</td>
</tr>
<tr>
<td>RFX1800</td>
<td>1500 - 2100</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>RFX2200</td>
<td>2000 - 2400</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>RFX2400</td>
<td>2300 - 2900</td>
<td>17</td>
<td>275</td>
</tr>
<tr>
<td>XCVR2450</td>
<td>2400 - 2500 / 4900 - 5900</td>
<td>20</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 1 shows the main features exhibited by the transceiver daughterboards as well as their prices according to the official pricelist available at the Ettus webpage in June 2010. All transceiver daughterboards are MIMO capable and completely reconfigurable by software. They also incorporate a TX/RX switch, built-in Receive Signal Strength (RSS) measurement capability, 70 dB automatic gain controller (AGC), adjustable TX power and, finally, some of them can operate in a full-duplex way.
6. USRP VS USRP2

The USRP2 offers a considerable improvement with respect to the previous USRP. Hereafter, we stress the most significant differences:

**Connection to the Host**

The first difference is found in the interconnection mechanism with the host. In theory, the USRP2 can sustain up to 200 MB/s (50 mega complex sample/s) instead of the 32 MB/s sustained by the USB 2.0 in the USRP. However, different tests reported that only 100 MB/s can be sustained (without underruns), leading to a maximum bandwidth of 25 MHz. As an additional advantage, the Ethernet cable can be much longer than the equivalent USB 2.0 cable, thus distances longer than two meters from the host are possible.

**CODEC**

The USRP CODEC is based on the AD9862, while the URSP2 CODEC utilizes the AD9777 and the LTC2284, both offering more resolution bits and higher sampling rate. However, the sampling rate at the D/A converters is higher in the USRP1, but the AD9777 is capable of sampling up to 160 MHz and, together with its internal interpolation filter, generating a 320 Msample/s signal.

**MIMO Capabilities**

The USRP2 is ready to be coherently synchronized with other USRP2 units. The user can choose, by software, between an external reference and the internal one (generated utilizing a VXCO), which is also better than that included in the USRP. Both the USRP and the USRP2 support two TX/RX antennas in a MIMO system. However, the USRP2 is already prepared to construct a system with a greater number of antennas, keeping it coherently synchronized. According to Ettus specification, the USRP2 can form an eight-antenna coherent system (employing a four-way MIMO link device).

**Real-time Capabilities**

Last, but not least, the USRP2 includes the SerDes high-speed interconnection mechanism to be able to attach another high-performance FPGA system to the USRP2 FPGA, thus opening the door for the integration of the URP2 into high-performance, real-time SDR wireless communications systems. Note that here are no real-time capabilities with the USRP.

7. ADVANTAGES AND LIMITATIONS OF GNU RADIO

The main advantages offered by GNU Radio are summarized below:

- **Low-cost solution.** Compared to commercial solutions, GNU Radio is a free software platform and you only pay for the hardware manufacturing expenses.
- **Low-cost software implementation.** GNU Radio platform provides the engineer a very flexible and sophisticated SDR programming environment.
- **Some parts of the hardware designs are open,** thus easing customization to meet specific requirements.
- **GNU Radio is platform-independent.** The only requirement is a USB library (for the USRP) and it is available for the most used operating systems.
- **The available set of pluggable daughterboards covers the RF bands ranging from 50 MHz to 2.9 GHz, and from 4.9 GHz to 5.9 GHz.**
- **Both URSP and USRP2 incorporate mechanisms to provide a common reference signal to be able to synchronize several units.**

However, besides the above-mentioned advantages, GNU Radio also presents some drawbacks:

- **Although Ettus claims that the USRP and the USRP2 are open design hardware, the sources of the hardware design are not available, neither from the Ettus, nor from the GNU Radio webpages. Instead, only the schematics are distributed, and they are generated with gEDA (gEDA, 2010), while the PCB layouts, designed with PADS (PADS, 2010), are not shared. Consequently, the software does follow the free source model, but the hardware design does not (at least not completely).**
- **GNU Radio is a sophisticated programming environment.** However, a great amount of people specialist on digital signal processing is familiarized neither with C++ nor with Python, thus the knowledge curve has a greater slope than in the case of well-known tools like MATLAB (Mathworks, 2010).
- **The first-generation USRP hardware employs a low-cost USB-based solution to solve the interconnection with the host.** Consequently, the maximum sustainable sample rate is reduced to
8 Msample/s shared among all antennas. The USRP2 overcomes such limitation by replacing the USB connection with a Gigabit Ethernet.

- The USRP offers very limited possibilities for real-time implementations. However, the USRP2 incorporates a SerDes connection that solves this problem.

With respect to the SDR development, the GNU Radio together with the USRP2 constitutes a very economical solution in terms of costs and manpower. The availability of extremely low-cost hardware capable of handling signals with 25 MHz of bandwidth at any RF carrier from 50 MHz to 5.9 GHz constitutes by itself a unique solution all over the world. Furthermore, the integration of the interface and configuration of such hardware in the GNU Radio software, supported in the most used platforms, and available as open source constitutes the ideal complement for the hardware, making possible to transmit signals from an ordinary host and/or acquire them at low-cost and with very little time and effort.

The advent of the USRP2 and its connectivity with high-performance, real-time solutions such as, for example, the Xilinx Virtex 5, leads to a superb solution even for replacing current, expensive, real-time hardware products.

8. CONCLUSIONS

In this work we presented the GNU Radio software as well as the USRP and the USRP2 hardware platforms manufactured by Ettus Research LLC as a solution to be taken into account when SDR-based wireless communications systems are being devised. We introduced the main idea of GNU Radio and described in detail the USRP, the USRP2 and the broad set of pluggable RF daughterboards available. Next we compared the USRP with the USRP2, arriving at the conclusion that the USRP2 is a much more suitable device for high-performance SDR systems. Finally, we described the main advantages as well as the main limitations exhibited by GNU Radio when it is combined with the USRP and/or the USRP2.

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