RF Measurements of the RFX 900 and RFX 2400 Daughter Boards with the USRP N210 driven by the GNU Radio Software

Rafik Zitouni
ECE Paris-LACSC Laboratory
37 Quai de Grenelle, 75015, Paris, France
LISSI / UPEC
120, rue Paul Armangot, 94400, Vitry S/Seine, France
Email: zitouni@ece.fr

Stefan Ataman‡ and Laurent George‡ †
‡ ECE Paris-LACSC Laboratory
37 Quai de Grenelle, 75015, Paris, France
† LIGM / UPEMLV
5, bd Descartes, 77454, Champs sur Marne, France
Email: ataman@ece.fr, lgeorge@ece.fr

***Abstract*—In this paper, we report a series of RF (Radio Frequency) measurements performed on a USRP and a GNU Radio Software Defined Radio (SDR). The RFX 900 and RFX 2400 Daughter Boards are connected to an USRP N210 platform and driven by the GNU Radio open source software. We focused on two main aspects: the output RF bandwidth and the power linearity versus the DAC value for each daughter board. The measured bandwidths of the daughter boards are found smaller than advertised while the linearity of the output power with the expected results is in good agreement only for low DAC values.**

***Index Terms*—Software Defined Radio, GNU Radio, USRP, Power linearity, radio frequency, Frequency bandwidth.**

I. INTRODUCTION

Software Defined Radio (SDR) is a combined software (SW) and hardware (HW) system, where the objective is to replace a maximum of hardware components of the communication chain by software ones. Compared to traditional wireless communication systems, the SDR offers fast and almost unlimited reconfigurability, reliability, easy expansion and low cost development. The flexibility gives rise to the cognitive radio, where the wireless network adapts to the environmental conditions and use efficiently the spectrum resources [1].

The ideal SDR architecture is achieved when the analog-to-digital (ADC) and digital-to-analog (DAC) conversions are made as close as possible to the antennas [2], eliminating the need of high-frequency radio subsystems. Subsequently, the GPP (General Purpose Processor) executes the software (SW) subsystem of the SDR, all signal processing taking place within this layer. Unfortunately, today's technology neither allows cost-effective direct ADC conversion from the antenna nor enough computing power to compute GSPS (Giga Samples-per-Second) in real-time. Therefore, the typical SDR platform available today uses HW high-frequency radio front-end, the SW part being implemented in the baseband only. The HW supporting the SDR platform is typically based on FPGAs or DSPs (Digital Signal Processors) [3].

In this work we consider a SDR comprising the GNU Radio as software and the USRP (Universal Software Radio Peripheral), designed by Ettus Research with daughter boards as hardware. The GNU Radio [4] software package provides signal processing blocks written in C++ and connected via a Python script to be executed on the host computer. The USRP handles the signal in baseband (through a FPGA) and uses the daughter boards to transpose the signal into the desired RF bands. Three USRP series have been proposed by Ettus research, which are the networked, the bus and the embedded series [5]. In the manufaturer's description, the networked series particularly N210 achieve a higher performances than the other series.

Some recent results dealing with performance evaluation of the N210 SDR are published in [6]. This work measures the frequency stability and the phase differences between two USRP N210 with SBX daughter boards. The authors concluded that the carrier frequency is sufficiently stable and the phase error can be neglected. Other performance evaluations are given in [7], where USRP 2 were used at the data packet level, where the communication delay, jitter and throughput are measured. In [8], the authors' objective is to evaluate the cooperative diversity in cellular network via USRP experimental. Their results showed the variation of the transmission power from one USRP to another. As a solution, the authors propose to calibrate manually the power, each USPR needing to be attached to a spectrum analyzer. Neither the USRP series, nor the daughter board was specified. The lack of details makes the reusability of results difficult.

However, we found no result in today's literature dealing with the true frequency bandwidth of the proposed daughter boards from Ettus Research attached to a USRP N210. Therefore, we chose two popular daughter boards – the RFX 2400 and the RFX 900 – and measured their RF output. Also, we found no reference dealing with the power linearity of this system. This motivated us in characterizing from these points of view the aforementioned daughter boards.

The remainder of this paper is organized as follows. In Section II we provide a brief overview of the experimental setup. In Section III the detailed description of the SW and

978-0-7695-5106-7/13 $26.00 © 2013 IEEE
DOI 10.1109/CyberC.2013.90

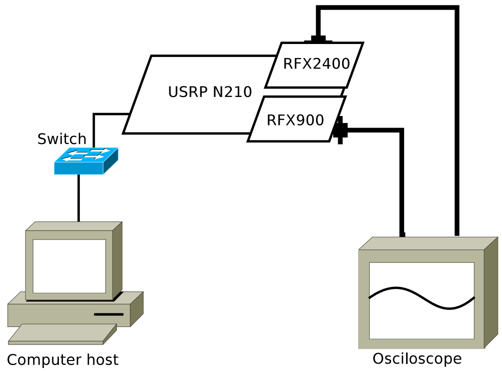

Figure 1. Experimental setup for the measurements

HW parts of the SDR are given. Measurement results are given in Section IV and finally, conclusions are drawn in Section V.

II. Experimental setup

In Fig. 1 we depict the hardware setup used in our measurements. The host computer is connected to the USPR N210 SDR via the Gigabit Ethernet Switch. The host computer uses as OS (Operating System) a Linux distribution (UBUNTU 12.04 LTS) powered by the intel Core i5-2400 CPU, clocked at 3.10 GHz and a RAM memory of 8 GB. The oscilloscope used in our measurements was a LeCroy 640 Zi [9] series oscilloscope, having an advertised input bandwidth from 400 to 4000 MHz and having a sampling rate of up to 40 GSPS. The oscilloscope was directly connected to the TX/RX terminal of the daughters boards through a high-frequency coaxial cable.

Some results could be directly measured on the oscilloscope's display (*e.g.* the average of squared samples), others were obtained after recording and storing the raw data on the oscilloscope's hard disk drive. These results were subsequently analyzed and processed using the Matlab R2012a software package from Mathworks Inc.

III. SDR description

The hardware used in our measurements is an USRP N210 from Ettus Research [5] and two daughter boards, the RFX900 and the RFX2400. The software needed to drive the system is GNU Radio [4]. In the following, we give a short description of all HW/SW components used in our experimentations.

A. The USRP N210 SDR

The USRP N210 is an enhanced version of USRP, allowing users to move additional functionality into the FPGA, increasing the maximum processing capability in both directions Tx/Rx while offering potential improvements in processing latency.

The USRP N210 provides high-bandwidth, high-dynamic range processing capability. The USRP N210 is intended for demanding communications applications requiring this type of rapid development. The product architecture includes a Spartan 3A-DSP 3400 FPGA from Xilinx, 100 MSPS (Mega Samples-Per-Second) dual ADC, 400 MS/s dual DAC and Gigabit Ethernet connectivity to stream data to and from host processors. A modular design allows the USRP N210 to operate from DC to 6 GHz, while an expansion port allows multiple USRP N210 series devices to be synchronized and used in a MIMO [5] configuration. An optional GPDSO module can also be used to discipline the USRP N210 reference clock to within 0.01 ppm of the worldwide GPS standard. The USRP N210 can stream up to 50 MS/s to and from host applications. Users can implement custom functions in the FPGA, or in the on-board 32-bit RISC softcore. The USRP N210 provides a larger FPGA than other USRP series, being able to run applications demanding additional logic, memory and DSP resources. The FPGA also offers the potential to process up to 100 MS/s in both the transmit and receive directions. The FPGA firmware can be reloaded through the Gigabit Ethernet interface.

B. The RFX900 daughter board

This transceiver daughter board is intended to operate in the 900 MHz band. It connects to all USRP SDR devices, making it a popular choice. It has a typical power output of 200 mW, and noise figure of 8 dB.

As possible applications of the product, the cellular and $902-928$ MHz ISM bands are specified.

The advertised operational bandwidth is $750-1050$ MHz in both transmit/receive (Tx/Rx) modes [5].

C. The RFX2400 daughter board

The RFX2400 is a daughter board transceiver designed for operation in the 2.4 GHz band. It connects equally with a wide range of USRP devices. The RFX2400 provides a typical power output of 50 mW, and noise figure of 8 dB. It uses independent local oscillators for the transmit and receive chains and is MIMO capable.

The advertised operational bandwidth is $2300-2900$ MHz in both Tx/Rx modes [5].

D. The GNU Radio

GNU Radio is an open source project toolkit for building software radios that run on host computers [4]. Two methods are used to control the USRP N210: the graphical GRC (GNU Radio Companion) or python flow graph scripts. The GRC is just a graphical representation of the python scripts which glued the C++ blocks.

We used two already-implemented flow graphs in our measurements: the BPSK-modulated signal and a sine wave demo. The first one is implemented in the benchmark python code `digital_bert_tx.py`. It continuously generates a scrambled bit stream, subsequently modulated using BPSK. The bit rate is 250 kbits/sec and a RRC (root-raised cosine) filter with a roll-off factor of 0.35 is used. In the second benchmark only the sinusoidal signal source is used. For both flow graphs and before the USRP-N210 sink block (in GRC), the complex stream is fed through the amplifier block `gr.multiply_const_cc`. This block multiplies the two components of the complex input by the DAC parameter (represented in floating point for more precision) that takes values in the interval $[0, 1]$.

This DAC value parameter from GNU Radio is supposed to control the output amplitude of the device, therefore we expect the relation

$$\langle P_{out} \rangle = \mathrm{DAC}^2 \cdot \mathcal{P}_0 \tag{1}$$

where $\langle \cdot \rangle$ signifies the statistical average of the output signal (since it is supposed to be ergodic) and $\mathcal{P}_0$ is a reference power level. In the new version of GNU Radio, we have $0 \leq \mathrm{DAC} \leq 1$. The central carrier frequency of each daughter board (f_0) was tuned in software according to their advertised frequency range.

IV. Measurements

All measurements have been carried out using a LeCroy WaveRunner 640 Zi oscilloscope [9]. Data was subsequently processed and displayed using the Matlab R2012a software package from Mathworks Inc.

We focused on two parameters of interest of the daughter boards: their output RF bandwidth and the average output power versus the DAC value.

The bandwidth of the daughter boards was measured by generating with GNU Radio a sinusoidal non-modulated carrier on a given frequency f_0 (set in software) and measuring the total average output power at the daughter board's Tx terminal. All reported measurements used a fixed DAC value of 1 *i.e.* the maximum power output. The measurement points swept through the advertised bandwidth, recording enough values in order to completely characterize the device's bandwidth.

We plotted our bandwidth curves in logarithmic units and set the reference power to the maximum measured value, *i.e.* the maximum output power is set to 0 dB and all the other values from our graphics are negative in dB.

The average power versus the DAC value was computed via two methods. In the first one, we created a custom function on the oscilloscope that computes the average of the squared amplitudes of the input samples *i.e.* $P_t \sim \langle v_i^2 \rangle_t$ where v_i represents the i^{th} input sample and $\langle \cdot \rangle_t$ represents time average. In order to have stable values, a supplementary meaning over 1000 oscilloscope sweeps was implemented. We used GNU Radio to generate a sinusoidal non-modulated signal and swept the DAC value from 0.1 to 1.0 in increments of 0.05 (we assumed that for $\mathrm{DAC} = 0.0$ the residual output power is small enough to be ignored), each time recording the output power at the daughter board's Tx terminal.

The second method was based on the Spectrum Analyzer software package installed on the LeCroy WaveRunner 640 Zi oscilloscope. The recorded spectral measurements were converted from dBm to linear power units and summed over a bandwidth of 2 MHz around the central frequency in the case of an unmodulated carrier and over a bandwidth of 5 MHz in

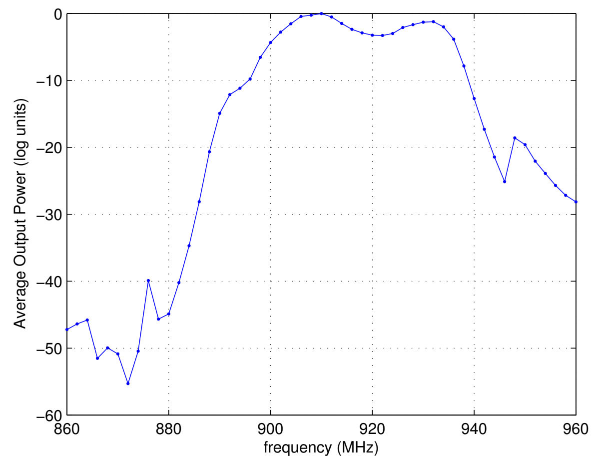

Figure 2. Measured bandwidth of the RFX900 daughter board. The reference level of 0 dB was taken at 910 MHz. Units are logarithmic (dB).

the case of BPSK modulation. Therefore, the second estimator can be written as $P_f = \sum_f 10^{P_{dBm}(f)/10}$, where $P_{dBm}(f)$ is the vector of spectral power samples given by LeCroy's Spectrum Analyzer and f sweeps all the samples from the measured bandwidth. Please note that we performed the same measurements over bandwidths of 10, 15 and 30 MHz and found no significant differences, which is expected since our signal is either a very peaked Dirac-like function (when we generate an unmodulated carrier) or has a bandwidth under 1 MHz (when using the BPSK benchmark software).

A. The RFX900 daughter board

The output power of the RFX900 daughter board was thoroughly measured in the frequency band $860 - 960$ MHz. We summarize the obtained results below.

1) Bandwidth: we measured the bandwidth of the RFX900 daughter board by the method explained previously. We set the parameter DAC at a value of 1.0 and kept it fixed throughout the measurements. The results are depicted in Fig. 2. The maximum measured value of the output was at $f = 910$ MHz, where we set our reference of 0 dB. We found the -3 dB bandwidth[1] of the RFX900 daughter board to be $B_{3dB} = 935.09 - 901.7 = 33.39$ MHz and its -10 dB bandwidth $B_{10dB} = 938.87 - 895.5 = 43.37$ MHz.

We conclude that the measured bandwidth of our RFX900 daughter board is far smaller than advertised.

2) Output power versus DAC value: For this measurement we used an unmodulated carrier frequency on four frequencies and the DAC values was modified, as explained earlier.

The average output power versus the DAC value is depicted in Fig. 3. The expected $\langle P_{out} \rangle \sim \mathrm{DAC}^2$ law is valid only for

[1]As can be seen in Fig. 2, there is a small dip below the -3 dB level in the center of the graphic, from 918.5 to 924 MHz. Nonetheless, this dip has a maximum depth of -3.285 dB at 928 MHz, therefore we will disregard it and consider the RFX900's B_{3dB} as discussed in the main text.

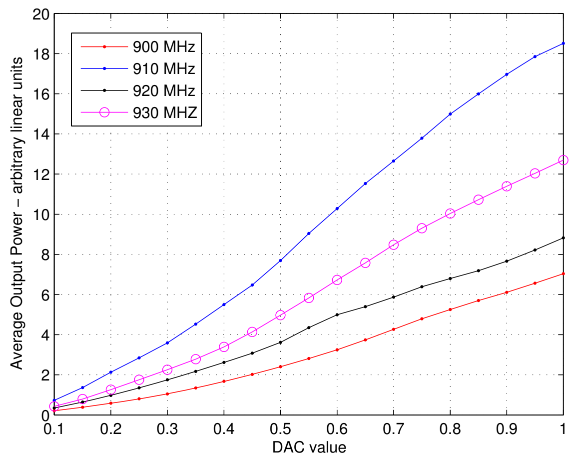

Figure 3. The average output power of RFX900 versus the DAC value at 900 MHz (unmodulated carrier).

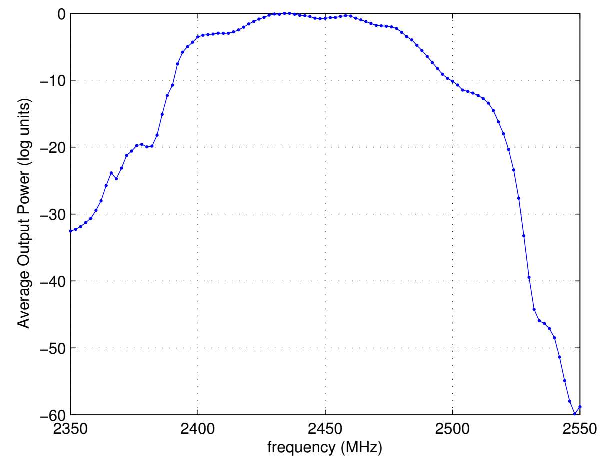

Figure 4. Measured bandwidth of the RFX2400 daughter board. The reference level of 0 dB was taken at 2434 MHz. Units are logarithmic (dB).

DAC ≤ 0.5, thereafter the average output power showing a non-quadratic behavior.

According to Fig. 2, the highest power is expected for a carrier on 910 MHz, result confirmed in Fig. 3.

B. The RFX2400

The output of RFX2400 daughter board was measured thoroughly for frequencies in the range $2350-2550$ MHz. We also measured the frequency intervals $2300-2350$ and $2550-2600$ MHz. Nonetheless, the output levels were extremely low, therefore we focused only on the frequency interval discussed in this paper.

1) Bandwidth: The same technique as before was used to carry out bandwidth measurements for the RFX2400 daughter board. In Fig. 4 we depict the measurement result using the same 0 dB convention from previous section. We found the maximum value to be at 2434 MHz.

The measured -3 dB bandwidth is $B_{3dB} = 2480.5 - 2407.6 = 72.9$ MHz. If we accept a -10 dB attenuation, the bandwidth is $2390-2499$ MHz (109 MHz) and for a -30 dB attenuation we have a bandwidth of $2359-2527$ (168 MHz).

Please note that we measured the -3 dB bandwidth of the RFX 2400 daughter board also for the case DAC $= 0.5$ and found $B_{3dB} = 2481.24 - 2399.52 = 81.72$ MHz. This bandwidth is only slightly bigger that our result for DAC $= 1.0$.

Yet again, we can confirm that for the RFX 2400, the advertised bandwidth of 600 MHz (2300 – 2900 MHz) is largely overstated.

2) Output power versus DAC value: In this measurement we used unmodulated carriers on various frequencies and we varied the DAC value from 0 to 1. In Fig. 5 we depict the average power versus the DAC value for 6 different frequencies.

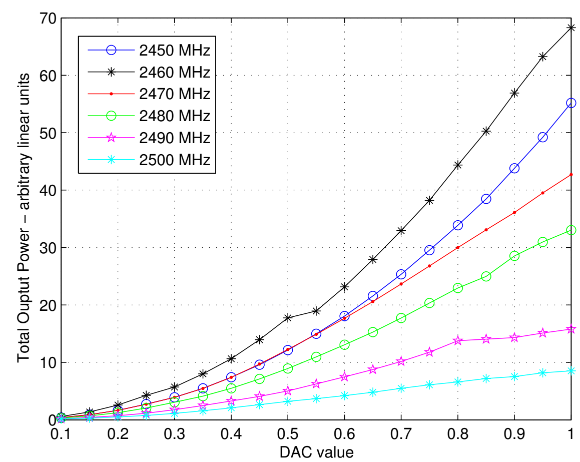

Figure 5. The average output power of the RFX2400 versus the DAC value for 6 frequencies (unmodulated carrier). The $\langle P_{out} \rangle \sim$ DAC^2 law is closely followed.

The expected $\langle P_{out} \rangle \sim$ DAC^2 law is reasonably valid throughout the whole range of the DAC parameter. Considering again the spectral power graphic results (Fig. 4) we note that the spectral amplitudes for the 6 frequencies from Fig. 5 are, in decreasing order, as follows: 2460, 2450, 2470, 2480, 2490 and 2500 MHz. This order is to be found in Fig. 5, where the curve corresponding to 2460 MHz is the top one while the one corresponding to 2500 MHz is the bottom one.

We note a major change when using instead of the unmodulated carrier frequency a BPSK modulation. In Fig. 6 we plot on the same graphic the average powers for both unmodulated and BPSK modulated signals. For a DAC value around 0.7 the $\langle P_{out} \rangle \sim$ DAC^2 law breaks down for all BPSK curves. We can explain this phenomenon by the large peak-to-average ratio of the BPSK modulation [10].

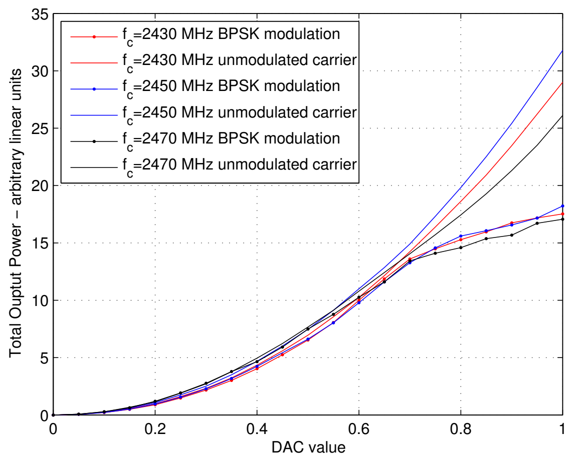

Figure 6. The average output power of the RFX2400 versus the DAC value for 3 frequencies in the cases: unmodulated carrier and BPSK transmission. The $\langle P_{out} \rangle \sim \text{DAC}^2$ law breaks down for BPSK at DAC $= 0.7$.

V. CONCLUSION

We described in this paper a series of RF measurements performed on RFX 2400 and RFX 900 daughter boards connected to the USRP N210 from Ettus Research.

We found a good overall linearity for the RFX 2400 daughter board. However, for the RFX 900 the quadratic relationship between the DAC value and the average output power breaks down if the DAC parameter has values above 0.5.

Both daughter boards exhibited a smaller than advertised bandwidth. The measured -30 dB bandwidth of the RFX 900 daughter board of around 72 MHz contrary to the 300 MHz advertised value. Also, the RFX 2400 daughter board yielded a measured -30 dB bandwidth of around 72 MHz, significantly smaller than the 600 MHz bandwidth specified by the manufacturer.

Future works will include measurements to other daughter boards and/or USRP versions (*e.g.* SBX daughter boards, E110 embedded USRP).

REFERENCES

[1] Haykin, S., *Cognitive radio: brain-empowered wireless communications*, IEEE Journal on Selected Areas in Communications, **23**, (2), 2005

[2] J. Mitola, *Software radios: Survey, critical evaluation and future directions*, IEEE Aerospace and Electronic Systems Magazine, **8**, (4), 1993

[3] M. N. O. Sadiku and C. M. Akujuobi, *Software-defined radio: a brief overview*, IEEE Potentials, **23**, (4), 2004

[4] GNU Radio, http://gnuradio.org/redmine/projects/gnuradio/wiki

[5] Ettus Research, http://www.ettus.com/product

[6] Corum, S. et al, *Evaluation of phase error in a software defined radio network testbed*, 2012 Proceedings of IEEE Southeastcon, IEEE, pp. 1–4, 2012

[7] Puschmann, André and Kalil, Mohamed A. and Andreas Mitschele-Thiel, *Implementation and evaluation of a practical SDR testbed*, Proceedings of the 4th International Conference on Cognitive Radio and Advanced Spectrum Management - CogART '11, ACM Press, pp. 1–5, 2011

[8] Bradford, Glenn J. and Laneman, J. Nicholas, *An experimental framework for the evaluation of cooperative diversity*, 2009 43rd Annual Conference on Information Sciences and Systems, IEEE, pp. 641–645, 2009

[9] Teledyne LeCroy, http://teledynelecroy.com/oscilloscope

[10] S. Haykin, M. Moher, *Analog & Digital Communications*, 2nd ed. Wiley, 2007