Design and Realization of a 2.45 GHz Transmitter and Receiver as a Modular Unit for a MIMO SDR

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***Abstract*—This paper describes a low-cost transmitting and receiving system for wireless communication. In a first part, the design and realization of a transmitter for modulated data at 2.45 GHz carrier frequency and with frequency, amplitude and phase modulation is handled. A second part explains the design and realization of a receiving module, which filters and downconverts the signals to an intermediate frequency. The postprocessing section describes the use of a DVB-T module together with open-source software, SDR#, for the final downconversion, as well as for the demodulation and the detection of the received signals in order to reproduce the originally transmitted data. Combining all components results in a low-cost and flexible software defined radio system.**

***Index Terms*—RF-design, low-cost, transmitter, receiver, SDR#.**

I. Introduction

Nowadays, Software Defined Radio (SDR) as a receiver is used more and more, providing more flexibility, as functionality now can be adapted by means of software upgrades. As technology advances, more and more analog receiver components are replaced by software, leading to a significant cost reduction. Often the front-end filter, as well as the downconversion and sampling of the received signal are realized in hardware and the remaining part of the receiver chain is programmed in software. Different modulation techniques and implementations can hence be measured and analyzed without having to design new hardware.

In Section II the hardware and the design of the transmitter are handled. Section III deals with the choice of components and the layout of the receiver, whereas the final postprocessing and the communication between the receiver and the PC are treated in Section IV. Section V documents the measurement results, illustrating that both the designed transmitter and receiver are collaborating successfully with the software. Finally, the conclusions and future work are listed in Section VI.

II. Transmitter

Figure 1 contains the block diagram of the transmitter. The microcontroller AT89S4051 [1] stores the data, separates it in different data packets and controls the other components. The transmitter is designed to operate over the 2.35 – 2.55 GHz frequency range. Four different modulation techniques are possible: Frequency Shift Keying (FSK) by means of reconfiguring the synthesizer's PLL, Amplitude Shift Keying (ASK) and On-Off Keying (OOK) by using the amplifier and Phase Shift Keying (PSK) with a combination of the mixer and the RS-232 driver.

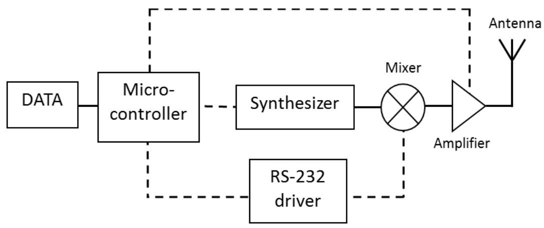

Fig. 1. The block diagram of the transmitter.

As a mixer the Mini-Circuits ADE-30+ [2] is selected, which is appropriate for the required frequency band. Here, the signal of the synthesizer is connected to the LO-port. The IF-port receives the data from the microcontroller, whereas the RF-port delivers the modulated output signal. A positive signal at the IF-port results in a signal without phase shift. In contrast, a negative signal gives a 180° phase shift of the LO-signal at the RF-port. To drive the mixer, a logic high level from the microcontroller is converted to a negative voltage and a logic low level to a positive voltage. In order to avoid extensive circuitry with positive and negative supply voltages, an RS-232 driver is selected. Here the ST3232 [3] converts the CMOS-TTL-signals of the microcontroller into positive and negative voltages, which can be handled perfectly by the mixer. The mixer in combination with the RS-232 driver hence make PSK modulation possible.

As a synthesizer a DSN-2520A-219+ [4] is used. The settling time is 0.03 ms in a frequency range of $1.12 - 2.52$ GHz, theoretically resulting in a maximal transmitted bit rate of 33.3 kbps when directly generating FSK modulation by means of the synthesizer. The reference crystal for the synthesizer is the FXO-HC736R-20 [5], operating at a frequency of 20 MHz with 25 ppm stability.

The last part before transmitting the signal over the antenna, is the amplifier. By modulating its power supply, ASK is realized. We selected the ERA-9SM+ [6], amplifying signals between DC and 8 GHz. ASK is achieved by connecting the amplifier's power supply pin to the positive supply voltage for a binary 1 and to the ground for a binary 0. The microcontroller cannot provide enough current on its IO-lines to power the amplifier directly. Therefore an analog switch ADG1419 [7] is used, switching the amplifier's supply rail, depending on a microcontroller IO-line.

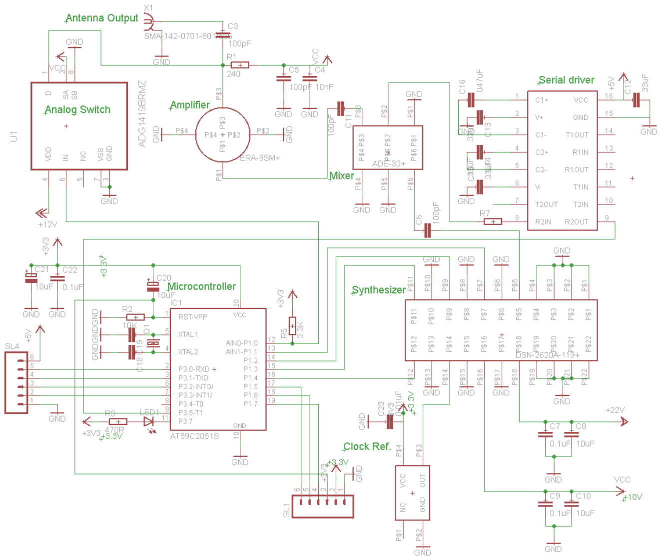

Fig. 2. Full circuit diagram of the transmitter.

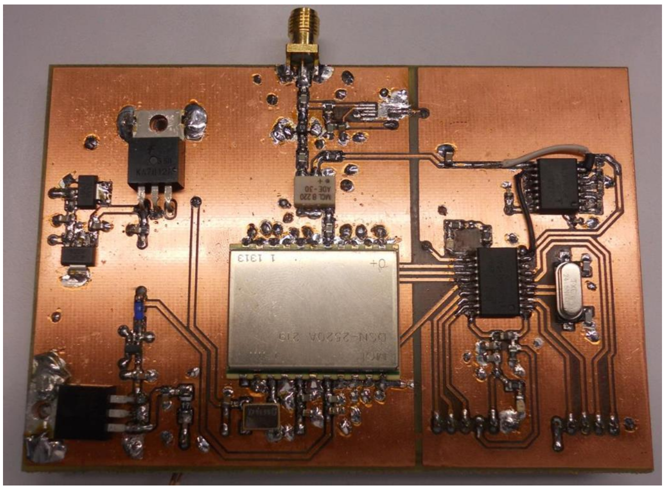

Fig. 3. The realized PCB of the transmitter.

The full circuit diagram of the transmitter can be found in Figure 2. At the top part of the figure, from left to right there's the *analog switch*, supplying the *amplifier*, which gets modulated signals from the *mixer*, which is in turn controlled by the *serial driver* in the top-right area of the diagram. At the bottom of the figure, again from left to right, there's the *microcontroller* and the *synthesizer*, which provides the RF-signal to the mixer. Underneath the synthesizer the *Clock Reference* crystal oscillator is displayed. These components are easily recognized in the photograph of the PCB in Fig. 3. The power supply regulators are located on the left side of the board.

III. Receiver

This section describes the circuit, designed to receive the signals transmitted by the transmitter of Section II. The block diagram is presented in Figure 4. The received signals are amplified in the Low Noise Amplifier (LNA) and filtered in a bandpass filter, selecting the frequency band of $2.35-2.55$ GHz. Mixing this signal with the signal of the synthesizer downconverts the signal to an intermediate frequency of 113 MHz. Using a rotary encoder, the receiving frequency of the synthesizer can be selected. Filtering and amplifying the mixed signal results in the output. The postprocessing will be explained in Section IV.

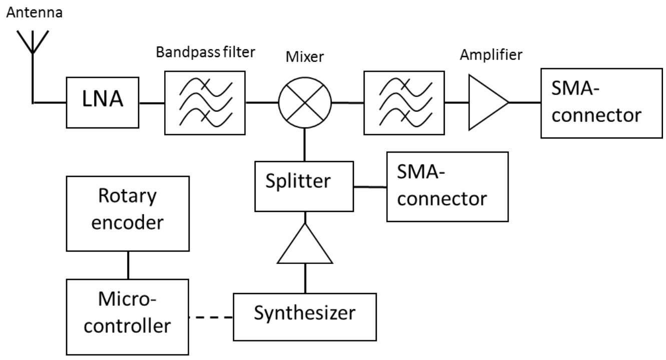

Fig. 4. The block diagram of the receiver.

As an LNA a TAMP-272LN+ [8] is chosen, with an amplification of 14 dB and a Noise Figure of 0.85 dB in the frequency band of interest. The block diagram contains two bandpass filters. The first one is BFCN-2435+ [9], which is not very sharp but has an attenuation of lower than 2 dB. For the second filter, BPF-A113+ [10] is proposed. The bandwidth is 10 MHz around the center frequency of 113 MHz. The attenuation is also limited to 2 dB. This crystal filter has a much sharper roll-off in comparison to the first filter.

The same ADE-30+ mixer as in the transmitter (see Section II) is used. In contrast, here the RF-port takes the received signals, the LO-port is connected to the synthesizer and the IF-port is the output. The synthesized signal is split by means of a BP2U+ [11], with one output to the mixer and one output reserved for future connections to another similar receiver using the same LO-signal.

Besides the attenuation of 3 dB caused by the power splitting, the additional loss is very limited, resulting in a total attenuation of about 3.4 dB. The output of the synthesizer is approximately 3.2 dBm, whereas the mixer needs 7 dBm at the LO-port. Between the synthesizer and the splitter an ERA-9SM+ amplifier [6] is placed, resulting in an amplification of 8 dB around 2.45 GHz.

As a synthesizer the DSN-2620A-119+ [12] is used, having the same reference crystal FXO-HC736R-10 [5] as for the transmitter (Section II). Also for the microcontroller the same AT89S4051 [1] is proposed. As a last step of this receiving design another amplifier is included. Now the ADL5531 [13] is selected, having an amplification of 21 dB around 113 MHz.

In Figure 5 the full circuit diagram of the receiver can be found. At the top of the figure from left to right, one can find the *LNA*, the *RF bandpass* filter, the *mixer*, the *IF*

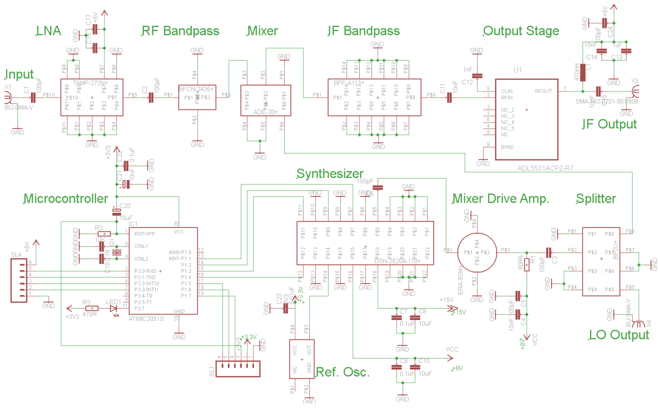

Fig. 5. Full circuit diagram of the receiver.

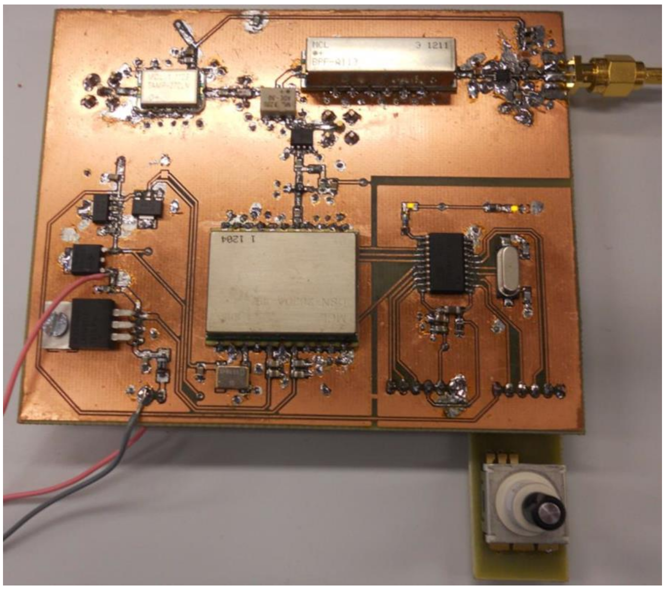

Fig. 6. The realized PCB of the receiver.

bandpass filter and the *output stage* amplifier. The components at the bottom part of the circuit provide the signal for the mixer's LO-port. From left to right, we find the *microcontroller* which configures the *synthesizer* of which the output signal is amplified by the *mixer drive amplifier* connected to the *splitter* on the right. One output from the splitter is connected to the mixer and the other output to an SMA-connector to provide a common LO-signal when combining multiple modules, such as in [14], into a MIMO (Multiple Input - Multiple Output) system.

The realized PCB of the receiver is depicted in Figure 6, with the power supply at the bottom left and the microcontroller at the bottom right of it. In between both parts the synthesizer and the reference crystal are placed. From the left to the right at the top of the figure the LNA, the RF bandpass filter, the mixer, the IF bandpass filter and the output amplifier can be seen. Figure 6 shows at the bottom right a small PCB with the rotary encoder, allowing the user to adjust the frequency of the synthesizer.

IV. Postprocessing

The previous section describes how wireless signals are received and downconverted to an intermediate frequency. In this section the final downconversion, the demodulation and the detection of the received signals in order to reproduce the originally transmitted data are described. Instead of a very expensive Analog-to-Digital Convertor (ADC), having a sampling rate of at least 226 MHz or a cheaper ADC, but with an additional downconversion, a widely available module for Digital Video Broadcasting - Terrestrial (DVB-T) is proposed. In Figure 7, a Newsky TV28T [15] is visualized. It is based on a Rafael Micro R820T [16], as a receiving module in one chip, and on a Realtek RTL2382U [17], in charge of the sampling, the downconversion, the digitizing and the USB-communication with the PC. When connecting an appropriate antenna to the USB-stick, the included software can receive TV programs on a PC.

Fig. 7. The DVB-T module for postprocessing.

If the receiver of Section III is connected to the DVB-T stick, the receiver chain is used in an alternative way, providing a low-cost SDR for the 2.45 GHz band. Further results are obtained with the alternative open-source software SDR# [18], enabling to directly read, process, demodulate and visualize signals from the DVB-T stick. With this software the receiving frequency, the sample rate (with a maximum of 3.2 Msamples/s) as well as the amplification factor can be set.

V. Measurement Results

In this section a number of measurement results are presented, illustrating the proper operation of the system. The frequency of the synthesizer at the receiver side is intended to be tuned in order to convert the frequency from the transmitter to an IF of 113 MHz. Using the software SDR# (as described in Section IV) the received 113 MHz signal will be sampled and visualized as can be seen in Figure 8. This figure shows that it is a good representation of the received signals. The scatterplot of the received data can be found in Figure 9, which gives a broad circle due to the presence of noise as well as a frequency offset between the transmitter and the receiver.

In order to demodulate the FSK data, every sample is compared with a following sample and out of the difference between these two samples the phase is obtained. A large difference in phase indicates a transition between a binary 1 and binary 0 or vice versa. This is depicted on Figure 10, showing the different packets. Here the packets are identical, because the transmitter transmits the same data in a loop.

In an additional experiment, an audio signal from a generator was digitized and transmitted. The audio signal was successfully decoded and played through the soundcard by means of a further modification of the SDR# source code.

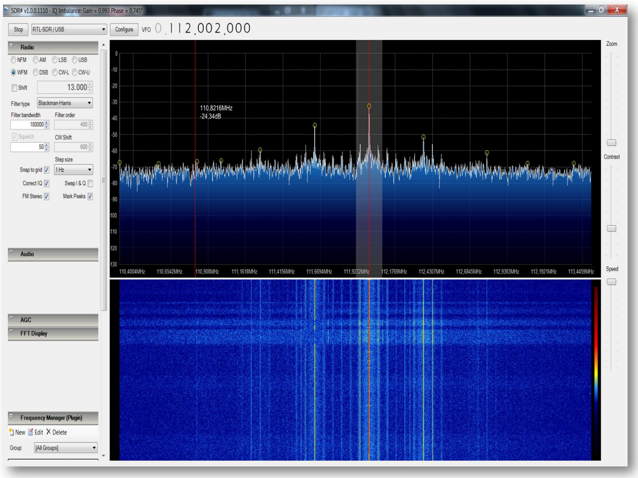

Fig. 8. Spectrum of the signals received in SDR#.

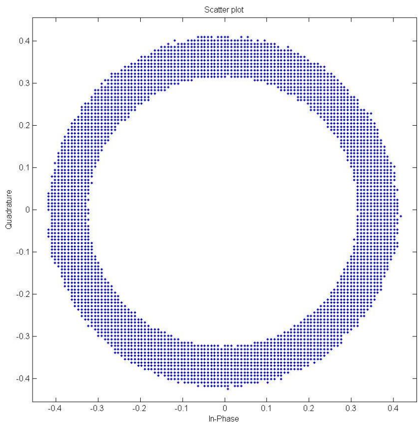

Fig. 9. Scatterplot of SDR#-data, before frequency-offset correction.

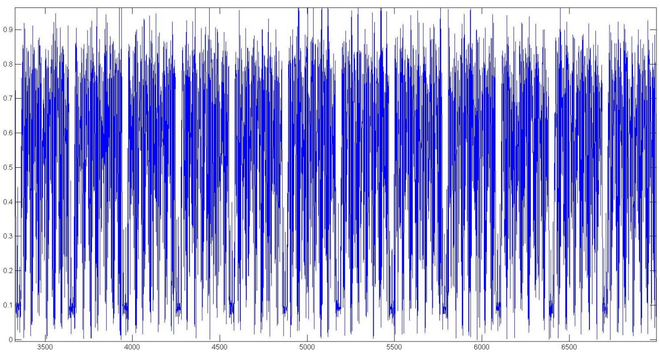

Fig. 10. The demodulated SDR#-data.

VI. Conclusions and Future Work

This paper describes the low-cost design and realization of a tunable transmitter-receiver combination, where different modulation techniques are possible. All components are selected to result in a wireless transmission between $2.35 - 2.55$ GHz. The received signal is filtered, downconverted to 113 MHz and filtered again in hardware, providing a very good selectivity and dynamic range. Using a DVB-T stick, which is compatible with the SDR# software, the received data can be stored and analyzed or processed in real time.

The receiver has been designed to allow the possible extension to more receiving modules for diversity or MIMO systems. The synthesized signal of the receiving module is split with one output directly connected to an SMA-connector. When employing additional receiver modules, the same synthesized signal can be used, reducing the complexity of these extra receiver chains. Combining multiple transmit and receive modules results in very low-cost MIMO measurement system.

Acknowledgment

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References

[1] Atmel, *8-bit Microcontroller with 2K/4K Bytes Flash*, San Jose, 2002.
[2] Mini-Circuits, *Frequency Mixer ADE-30+* [Rev. C], New York, 2013.
[3] STMicroelectronics, *ST3232* [Rev. 9], 2006.
[4] Mini-Circuits, *Frequency Synthesizer DSN-2520A-219+* [Rev. A], New York, 2013.
[5] FOXElectronics, *Model: FXO-HC73 SERIES*, Fort Myers, 2007.
[6] Mini-Circuits, *Monolithic Amplifier ERA-9SM+* [Rev. OR], New York, 2013.
[7] Analog Devices, 2.1Ω *On Resistance, 15V/+12V/5V iCMOS SPDT Switch ADG1419* [Rev. 0], Norwood, 2009.
[8] Mini-Circuits, *Low Noise Amplifier TAMP-272LN+* [Rev. B], New York, 2013.
[9] Mini-Circuits, *LTCC Bandpass Filter BFCN-2435+* [Rev. C], New York, 2013.
[10] Mini-Circuits, *Bandpass Filter BPF-A113+* [Rev. OR], New York, 2013.
[11] Mini-Circuits, *Power Splitter/Combiner BP2U+* [Rev. B], New York, 2013.
[12] Mini-Circuits, *Frequency Synthesizer DSN-2620A-119+* [Rev. OR], New York, 2013.
[13] Analog Devices, *20 MHz to 500 MHz IF Gain Block ADL5531* [Rev. A], Norwood, 2008.
[14] J. Verhaevert and P. Van Torre, *Realization and MIMO-link Measurements of a Transmit Module for Spatial Modulation*, The 9th European Conference on Antennas and Propagation (EuCAP2015), Lisbon, Portugal, 2015.
[15] Newsky Tech.Company, *Digital TV tuner support MPEG-2/4 H.264 with FM&DAB*.
[16] Rafael Micro, *R820T High Performance Low Power Advanced Digital TV Silicon Tuner Datasheet*, Chutung, 2011.
[17] Realtek, *RTL-SDR and GNU Radio with Realtek RTL2832U [Elonics E4000/Raphael Micro R820T] Software Defined Radio Receiver*.
[18] SDR#, *Software Defined Radio in C#*, http://www.sdrsharp.com/.