# Detailed Investigation of Ultra-Wideband Impulse Radio Communication Systems with LeCroy Oscilloscopes

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## I. Overview

Target of the work is the evaluation of the potential of impulse radio (IR) communication systems with respect to commercial usage. Therefore a reconfigurable ultra-wideband (UWB) software defined radio (SDR) transmitter has been developed and the concept is presented in this application note. Besides common SDR concepts the developed IR transceiver employs first order bandpass (BP) sampling at a conversion frequency which is four times the sampling frequency. Hence signals can be directly generated in the radio frequency (RF) band avoiding any non–ideal mixer stages. Furthermore the requirements of the digital signal processing is significantly reduced. The transmitter consists basically of a field programmable gate array (FPGA) and a high speed digital to analog converter (DAC) with 12 bit resolution. This design allows full flexibility and can be adaptively reconfigured in terms of modulation schemes, data rates, and channel equalization. The reconfigurable design will be used for an extensive performance analysis with respect to different modulation schemes, modulation techniques and bitrates required by a various number of applications.

## II. Introduction to IR UWB Transceivers

Since the approval of the UWB frequency band by the Federal Communications Commission (FCC) [1], the UWB technology has gained enormous research interest. However most commercially available systems are based on the multiband orthogonal frequency division multiplexing (OFDM) [2] or direct sequence spread spectrum (DSSS) [3]. Only a few companies like Time domain [4] or Decawave [5] provide IR UWB systems commercially (see Fig. 1). The main reason is that the transceiver architectures are still too expensive for low cost applications.

Nevertheless IR components and systems are still one of the current research topics [6], [7]. This is due to the fact, that IR systems have some significant benefits compared to common transceiver structures. As signal energy is spread over a wide bandwidth, transmissions are noise–like and thus signals cause less interference and are very difficult to detect or intercept. Furthermore flexible data rates from 100 kbit/s up to 500 Mbit/s can be achieved. Concerning future transceiver designs the mitigation of the power budget is vitally important. As the entire IR system can be completely turned off between two transmitted impulses, the expensive baseline power consumption of the system can be significantly reduced compared to common transceiver architectures.

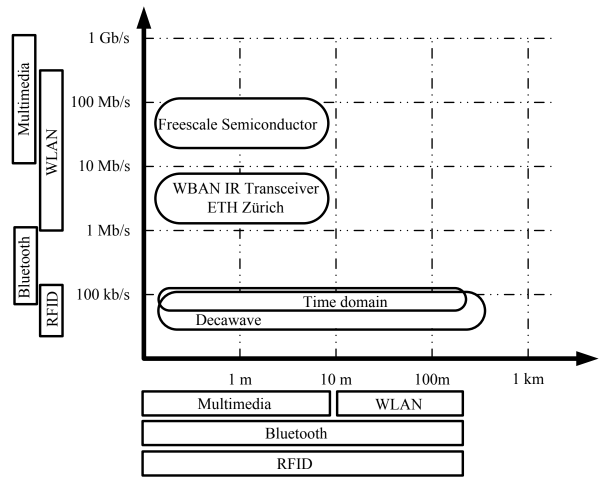


Fig. 1. Overview of different impulse radio transceivers.

Within this application note our recent research activities are presented including the employment of the LeCroy Wave-Master 808Zi–A oscilloscope.

## III. Transmitter Concept

The design goal of the transmitter is to achieve a very flexible solution which enables to test novel or classical IR modulation schemes like on off keying (OOK), pulse position modulation (PPM), binary pulse amplitude modulation (BPAM) and pulse code modulation (PCM). In addition flexible pulse repetition rates within a range from 5 MHz–62.5 MHz as well as transmitted reference (TR) modulation technique is supported by the transmitter.

A photo of the transmitter is depicted in Fig. 2 and the corresponding block diagram is illustrated in Fig. 3. To achieve the afore mentioned flexibility an Avnet development board [8] is used for digital generation of pulse trains. The main part of the board is a Virtex 5 FPGA which can be flexible programmed, so that different waveforms can be stored in the random–access memory (RAM). An universal serial bus (USB) 2.0 controller enables to connect the FPGA with a host personal computer (PC). Thereby the USB controller can be either used in a configuration or in a streaming mode. A home–made device driver enables to use MATLAB for configuration and streaming of data. Consequently arbitrary waveforms and modulation schemes can be designed and visualized in MATLAB. A specifically developed interface board is applied

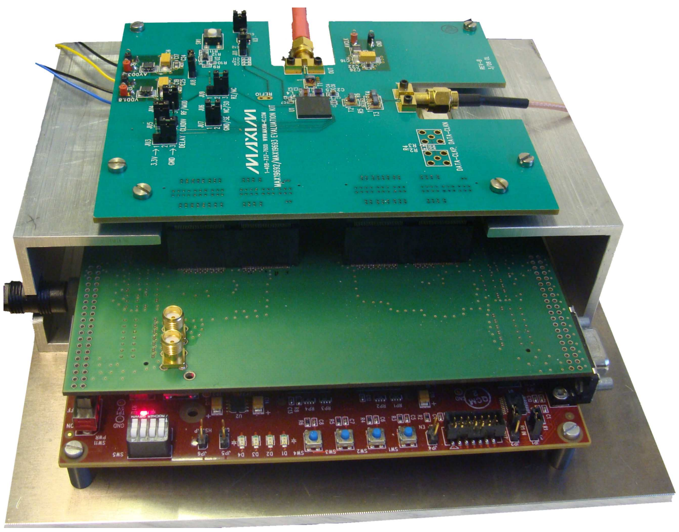


Fig. 2. Developed IR SDR UWB transmitter including FPGA and DAC development boards.

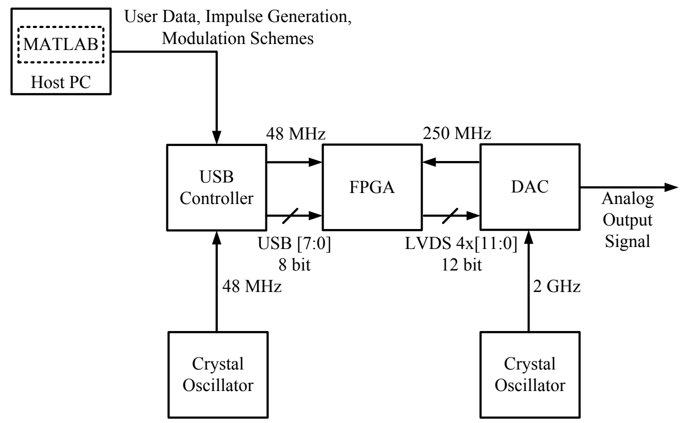


Fig. 3. Block diagram of the digital signal synthesis in the transmitter.

to connect the Avnet evaluation board with the Maxim DAC board [9] (see Fig. 2). The DAC board includes a high speed multi-Nyquist DAC which has an update rate of 2 GHz. To achieve a synchronous design the clock signal of the DAC is divided by 8 to guarantee an accurate data processing on the FPGA. Hence enormous parallelization on the FPGA is required to transmit the waveforms over four low voltage differential signaling (LVDS) buses with 12 bit resolution to the DAC.

Different DAC impulse responses enable to generate UWB signals with 1 GHz bandwidth in higher Nyquist zones [9]. In Fig. 4 two possible designs for UWB transceiver architectures are depicted. In common concepts the signal is synthesized at an intermediate frequency (IF) whereas up- and down conversion to the radio frequency (RF) band afford analog mixer stages (see Fig. 4).

This approach has the disadvantage that additional analog mixer stages cause signal distortions because of their non ideal transfer characteristic and thus degrade the performance of the transmitter. To overcome this problem a bandpass sampling approach [10] can be applied. As each time discrete signal has a periodic spectrum a signal which is digitized on an IF in the first Nyquist zone has multiple attenuated replicas in higher Nyquist zones. Different impulse responses of the DAC enable to generate UWB signals with 1 GHz bandwidth, a high signal to noise ratio (SNR) and gain flatness in higher Nyquist zones. Thus a subsampling direct conversion transmitter can be implemented without any mixer stages. Hence the RF frontend only consists of passive bandpass filters, antennas and optional amplifiers (see Fig. 4). Compared to recently published UWB–IR SDR systems, which are focusing on the receiver implementation [11], [12], a UWB SDR transceiver including the novel transmitter concept enables a much higher flexibility to investigate different IR concepts.

In Fig. 5 the impulse generation in higher Nyquist zones is illustrated in the frequency domain. According to a rectangular impulse response of each sample in the time domain the resulting spectrum has the familiar sinc shape. The current transmitter includes the MAX19692 DAC [9] which has a high SNR and exceptional gain flatness in the first, second and third Nyquist zone. As the regulations of the FCC are not fulfilled the concept is only suitable for laboratory use at the moment. Due to the hardware limitations additional mixer stages will be used in the final implementation of the transmitter prototype. However the upconversion stages needed in the transmitter can be reduced by a direct generation of the signals in the third Nyquist zone.

In 2011 the MAX5879 DAC [13] has been presented, which enables impulse generation with 14 bit resolution up to the 6th Nyquist zone. Based on the RF mode of the MAX19692 DAC the gain flatness and dynamic range has been significantly improved by applying an additional radio–frequency–return–to–zero (RFZ) mode in the MAX5879 DAC. However the maximum update rate is restricted to 1.15 GHz and hence the concept is not suitable for IR applications yet.

## IV. Time Domain Measurements

For designing and dimensioning of transceiver components high quality time domain measurements are indispensable. In the following sections different measurement purposes are presented.

### A. Hardware Development

For developing and implementing novel board designs an efficient test of transmitted signals is essential to debug and improve designs. Critical measurement applications on the transmitter board are the LVDS busses or the differential high speed clock signals. They can be scanned with high bandwidth differential probes.

### B. Effective Isotropic Radiated Power Measurements

As UWB signals are usually transmitted over a frequency spectrum which is already in use by other applications the emission limit is restricted [1]. Hence emission level measurements are necessary. To fulfill the regulations spectrum analyzer measurements with a resolution bandwidth of 1 MHz, a root mean square (RMS) detector and 1 millisecond or less averaging time are suggested. However, the spectrum of almost

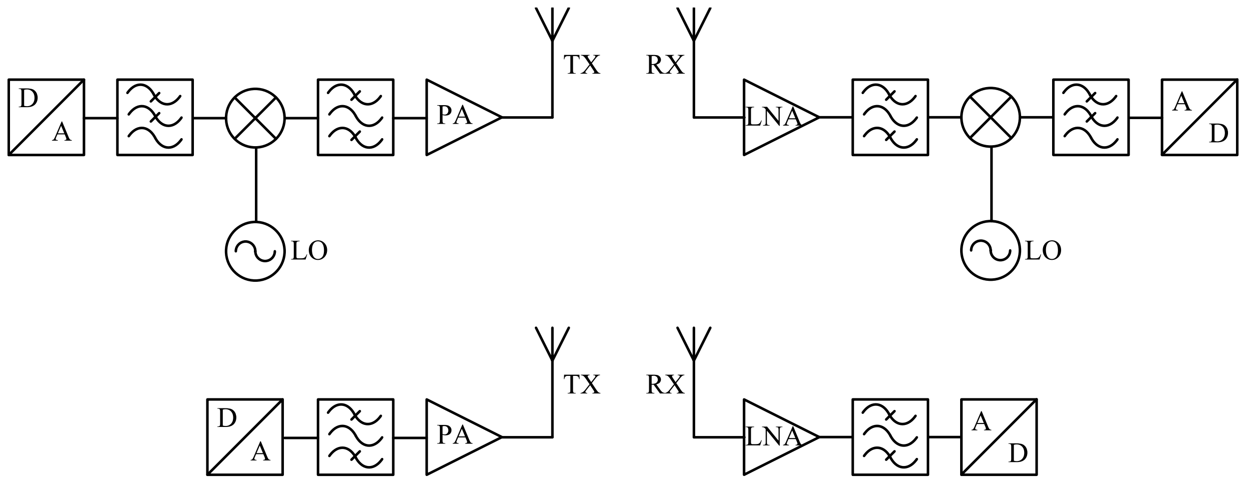


Fig. 4. Block diagram of a conventional transceiver (top) and a SDR architecture (bottom).

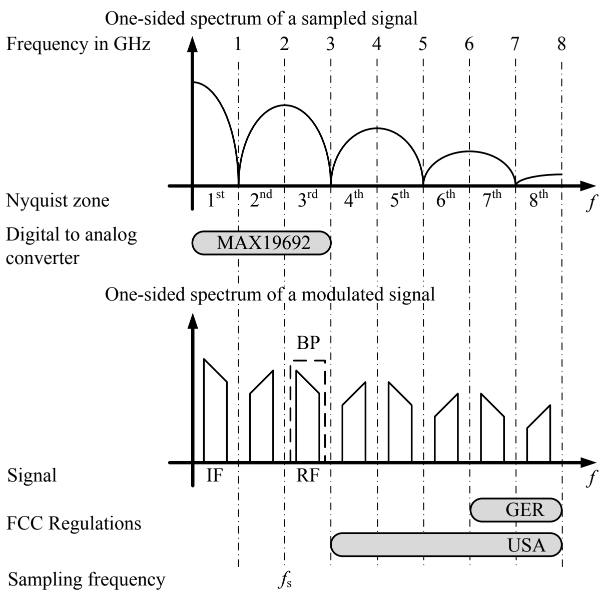


Fig. 5. Spectrum of a time discrete signal and a band–limited modulated signal.

all transmission and modulation schemes contain peaks with a frequency separation rate equivalent to the pulse repetition rate. Based on the regulations peak measurements are required with a resolution bandwidth (RBW) of 50 MHz which is comparable to the widest victim receiver. As common spectrum analyzers provide only RBW smaller than 3 MHz a method of measuring the effective isotropic radiated power (EIRP) with oscilloscopes is presented in [14]. For achieving accurate results this approach is extended by using a setup combining frequency and time domain measurements (see Fig. 6). The output signal of the transmitter is directly measured with the oscilloscope whereas the radiated field is determined in an anechoic chamber by applying a vector network analyzer (VNA). In a post processing step the EIRP is computed offline by using Gaussian digital filters with 1 MHz or 50 MHz RBW, respectively.

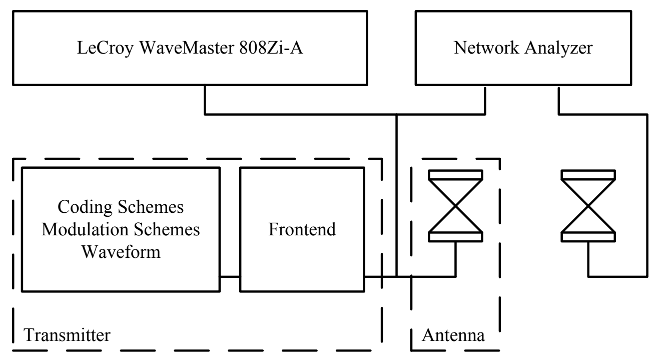


Fig. 6. Block diagram of the measurement setup for EIRP measurements.

### C. Receiver Planning

To investigate the performance of different modulation schemes various receiver designs are possible. The challenge is to find the optimum solution for the receiver design including clock recovery and equalization of the channel before a FPGA based receiver is implemented. To evaluate the performance of the receiver an offline simulation is used for planning purposes. Due to its wide input bandwidth the real-time oscilloscope LeCroy WaveMaster 808Zi–A (see Fig. 7) is perfectly suited to acquire the receiving signal. With the XDEV Advanced Customization Package it is possible to test the receiver algorithms directly on the oscilloscope. In Fig. 8 an exemplary measurement and post processing of an impulse train is depicted. From the recorded pulse train the spectrum is computed by using the math functions of the LeCroy WaveMaster 808Zi–A oscilloscope. Employing digital filters in MATLAB the received signal in different Nyquist zones can be diagrammed on the oscilloscope, which enables a detailed appraisal of the signal quality.

## V. Outlook

Our aim is to test different IR radio links in the near future. For signal analysis we will use the LeCroy oscilloscope. Therefore our focus is now on the frontend development of the

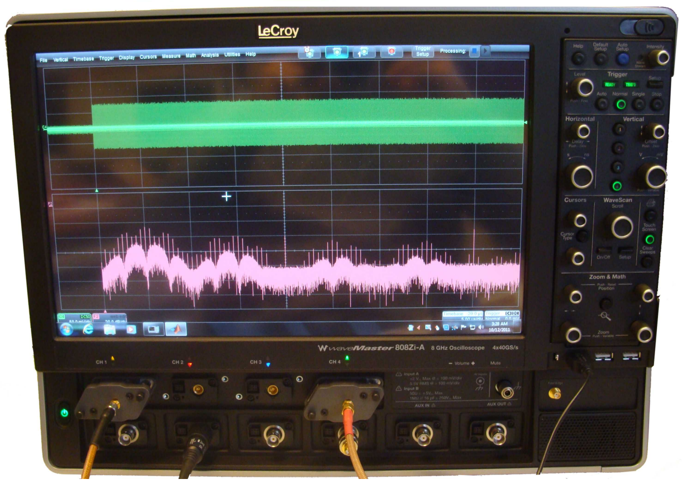


Fig. 7. Measured pulse train and output spectrum with a LeCroy WaveMaster 808Zi–A oscilloscope.

transmitter and the receiver. Whereas on the transmitter side power amplifiers (PAs) are used, a low noise amplifier (LNA) as well as an automatic gain control (AGC) loop will be applied on the receiver side. Hence the entire setup allows to test the link quality at distances ranging from several centimeters within body area networks up to 10 m for indoor applications.

## REFERENCES


[1] FCC. (2002, Apr.) Revision of Part 15 of the Commission's Rules Regarding Ultra–Wideband Transmission Systems. [Online]. Available: http://www.fcc.gov

[2] A. Batra et. al., "Ieee multi–band ofdm physical layer proposal for ieee 802.15 task group 3a," *IEEE P802.15 Wireless Personal Area Networks*, 2004.

[3] R. Fisher et. al., "Ds-uwb physical layer submission to 802.15 task group 3a," *IEEE P802.15 Wireless Personal Area Networks*, 2004.

[4] Time Domain Corporation. (2011) PulsOn 400 RCM. [Online]. Available: http://www.timedomain.com

[5] DecaWave. (2011) ScenSor. [Online]. Available: http://www.decawave.com

[6] O. Lauer, D. Barras, M. Zahner, and J. Frohlich, "An impulse radio UWB hardware demonstrator for body area network communication," in *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*. IEEE, Apr. 2011, pp. 2377–2381.

[7] Z. Zou, D. S. Mendoza, P. Wang, Q. Zhou, J. Mao, F. Jonsson, H. Tenhunen, and L. R. Zheng, "A Low-Power and flexible energy detection IR-UWB receiver for RFID and wireless sensor networks," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, no. 7, pp. 1470–1482, Jul. 2011.

[8] Avnet. (2006) Xilinx Virtex-5 LX50 Development Kit. [Online]. Available: http://www.avnet.com

[9] Maxim Integrated Products, Inc. (2006) 12-Bit, 2.3Gsps, Multi-Nyquist DAC with Selectable Frequency Response. [Online]. Available: http://www.maxim-ic.com

[10] R. G. Vaughan, N. L. Scott, and D. R. White, "The theory of bandpass sampling," *IEEE Transactions on Signal Processing*, vol. 39, no. 9, pp. 1973–1984, Sep. 1991.

[11] C. M. Keller, J. M. Burkhart, and T. T. Phuong, "Ultra-Wideband direct sampling receiver," in *IEEE International Conference on Ultra-Wideband, 2007. ICUWB 2007*. IEEE, Sep. 2007, pp. 387–392.

[12] S. W. Chen and R. W. Brodersen, "A subsampling radio architecture for ultrawideband communications," *IEEE Transactions on Signal Processing*, vol. 55, no. 10, pp. 5018–5031, Oct. 2007.

[13] Maxim Integrated Products, Inc. (2011) 14-Bit, 2.3Gsps, Multi-Nyquist DAC with Selectable Frequency Response. [Online]. Available: http://www.maxim-ic.com

[14] J. Takada, "Measurement techniques of emissions from ultra wideband devices," *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. E88-A, pp. 2252–2263, Sep. 2005.


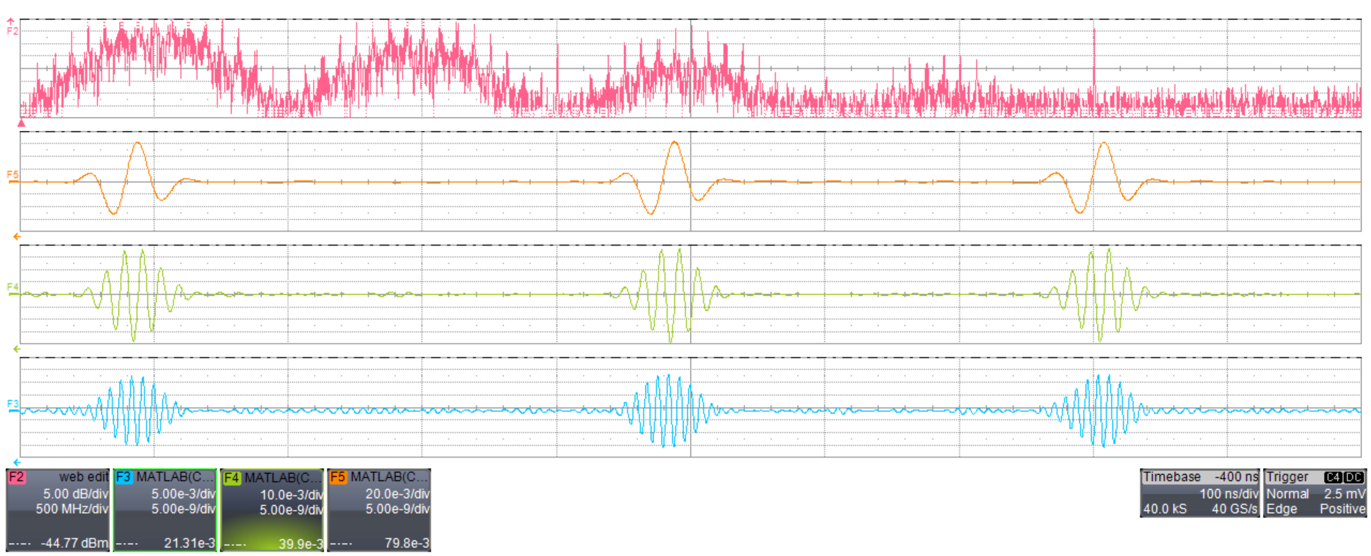


Fig. 8. Measurement of the output spectrum (top) and modulated Gaussian pulses in different Nyquist zones at the output port of the DAC.