Published in proceedings of 2011 7th Conference on Ph.D. Research in Microelectronics and Electronics, 3-7 July 2011, Trento, Italy, which should be cited to refer to this work.
DOI: 10.1109/PRIME.2011.5966279

A Discrete-Component Impulse-Radio Ultra-Wide Band (IR-UWB) Receiver with I/Q Demodulation

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***Abstract*—We describe an Impulse-Radio Ultra-Wide Band (IR-UWB) receiver with I/Q demodulation made of commercial off-the-shelf discrete components. It is designed to be used in a UWB testbed for measurement and algorithm validation purposes. The central frequency of the UWB signals is 4.25 GHz with a bandwidth of 500 MHz. We have achieved a data-rate of 10 Mb/s. We experimentally validate the use of the I/Q demodulation in UWB localization. This paper can also be used as a starting point for implementing a custom IR-UWB I/Q receiver.**

I. INTRODUCTION

In this paper, we propose a novel UWB receiver design that uses In-phase/Quadrature (I/Q) demodulation to improve the Signal-to-Noise Ratio (SNR) of the wave form by removing undesired envelope. This receiver is built entirely of Commercial Off-The-Shelf (COTS) components. The novelty of this paper compared to existing UWB receiver designs is the use of I/Q demodulation (on a non-modulated signal) to decrease the "beat" which is an artifact of transmitter/receiver differences in the oscillation frequency.

The contributions in this paper are as follows. (1) We propose a novel UWB receiver design that uses I/Q demodulation to improve the SNR. (2) We use numerical simulation to show the distortion of the received signal due to minor frequency drift in the transmitter and receiver oscillators. The same model can be used to show how I/Q demodulation improves the received waveform. (3) We implement the proposed design with COTS components. (4) We show experimental results in the context of a UWB ranging testbed. The initial experimental results indicate that the proposed receiver delivers improved performance for ranging compared to a traditional receiver that does not use I/Q demodulation.

II. IR-UWB TEST-BED

The I/Q receiver described in this paper (Figure 1) is an improved version of the one used in the UWB testbed described in [1]. It was, however, built by using experimental modules and there were several optimisations required, especially about the size of the device and the quality of the obtained signals (due to PCB routing and RF shielding). The UWB receiver is built with a cascade of LNAs [2] and the I/Q demodulator as shown in Figure 1. The LNAs are designed to have variable gain from 0 to 30 dB and they can be safely cascaded due to their adjustable input impedance matching network and high maximum input power.

The impulse generator, shown in Fig. 1, generates a square impulse of about 3 ns. This signal drives a mixer that switches on and off the sine wave oscillator and produces the IR-UWB signal [3]. The received signal is amplified and filtered (see [2]) and then down-converted by the I/Q-mixer. The local oscillator of the mixer is of the same type as of the one in the transmitter. The I and Q components of the signal are amplified, squared, and then added together in order to obtain a base-band signal with a constant average power. This signal is amplified and sent to the acquisition board for processing.

For robustness and flexibility, the UWB transmitter [3] is based on a conventional architecture as shown in the left part of Figure 1. A PLL based oscillator produces a 4.25 GHz sine wave that is switched on during about 3 ns. The mixer, when driven by a digital impulse, behaves like a switch. The square impulse generator is driven by an FPGA and converts each incoming digital impulse into an impulse for the mixer. The obtained signal is sent to an omnidirectionnal UWB antenna [4].

III. IR-UWB RECEIVER WITH I/Q DEMDULATION

In what follows we describe the design and implementation of the IR-UWB receiver.

A. Design Rationale

As Impulse-Radio UWB transmissions are asynchronous and carrierless, there is a small frequency drift between the transmitter and the receiver local oscillators because it is impossible to perfectly synchronise two remote oscillators. When using a conventional mixer for down-conversion, this frequency drift produces a beat in the down-converted base-band signal that has a negative effect on data integrity and synchronisation algorithm (they do not work at all, see [1]).

During frequency downconversion, there are three scenarios that can occur. The first one (Figure 2, left) is the ideal case where both oscillators are perfectly synchronised. In this scenario, a conventional mixer works perfectly because the

The work presented in this paper was supported (in part) by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322

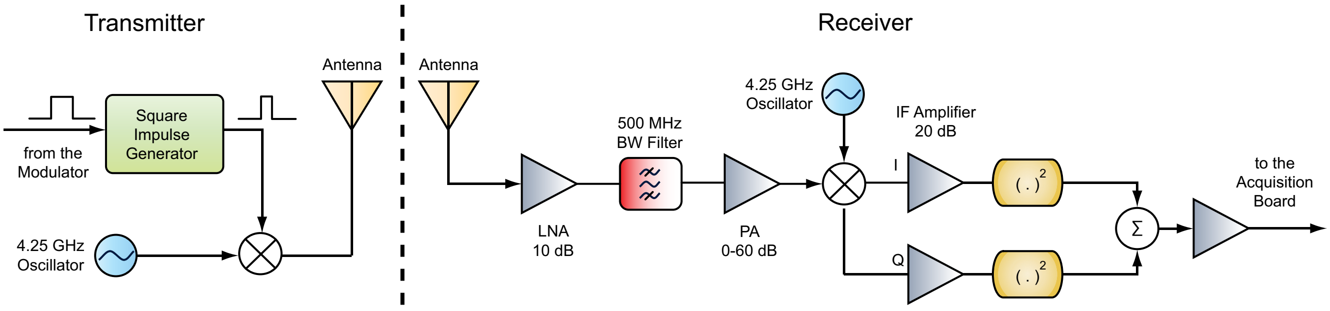

Fig. 1. Overview of the analog RF parts of the IR-UWB testbed

phasor of the obtained baseband signal is colinear with the I axis and remains steady. This case happens in practice very rarely and never remains stable long enough to be useful. The second scenario (Figure 2, center) is the case where the oscillators are synchronised in frequency but not in phase. In this scenario, a conventional mixer would work correctly provided that both oscillators are not too much out of phase. The third scenario (Figure 2, right) is the case there is a frequency drift between the oscillators; this is the scenario seen in practice. In this scenario, the frequency drift produces a beat that makes the downconverted UWB impulses have an envelope that distort the signal when a conventional mixer is used.

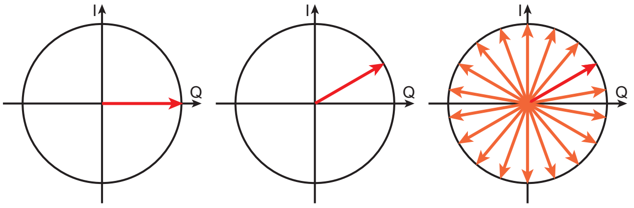

Fig. 2. The three scenarios that occur when transmitter and receiver local oscillators are used for UWB generation and down-conversion

Figure 3 shows by simulation the effect of the beat on the baseband signal. The I/Q demodulator is required to extract the quadrature component in addition to the in-phase one in order to preserve the power of the signal and remove the beat. Taking the I and Q components, squaring both of them and adding them together in order to have the magnitude ensures that the average power is constant, without any beat (see Figure 4). It is visible from the two plots that the SNR of the I/Q-demodulated signal is better.

Our design, due to the fact that it is experimental, does not need to optimize the power consumption. In this particular case, we have chosen a PLL-based oscillator in order to meet more easily the FCC compliance rules.

B. Schematic of the I/Q Receiver

The complete schematic of the UWB I/Q receiver is shown in Figure 6. The main part of the circuit is the I/Q mixer. The I and Q components obtained from the mixer are amplified with two Monolithic Microwave Integrated Circuit (MMIC)

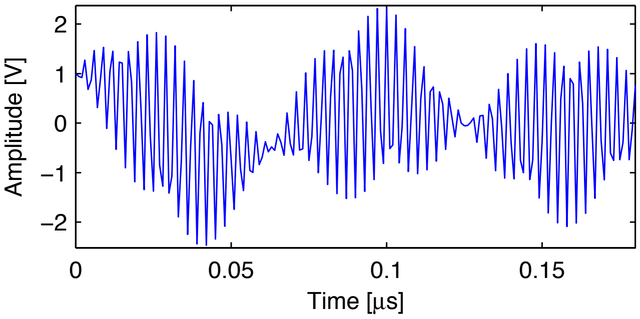

Fig. 3. Down-conversion of UWB impulses without I/Q demodulation (signal obtained by simulation that is similar to signals obtained in practice)

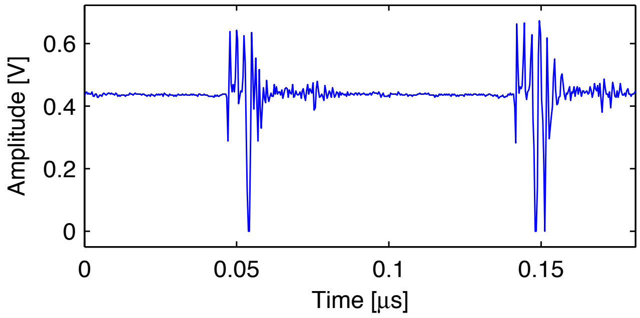

Fig. 4. Down-conversion of UWB impulses with I/Q demodulation (signal obtained by acquisition of real UWB data)

amplifiers by about 30 dB. Decoupling capacitors are required because of the high frequency and high power of the RF signals. The inductor is used to feed the amplifier without RF leakage; the resistor is used to decrease the quality factor of the inductor because of the wide bandwidth of the signals. The I and Q signals are then squared by using a conventional mixer that is fed with the same signal on its RF and LO inputs. An RF power splitter (resistor network in blue) is used in order to have the signal available for both inputs of the mixer with impedance matching. The value of the power splitter resistors is calculated as follows:

$$R = \frac{N-2}{N} \cdot Z_0$$

where N is the number of ports of the power splitter (here 3) and Z_0 is the characteristic impedance (here 50 Ω). The attenuation of the signal due to the power splitter is given by:

$$A_{dB} = 10 \cdot log(N-1)^2$$

These formulas give $R = 16\ \Omega$ and $A = 6.021$ dB. As the power supported by the RF input of the mixer is much smaller than the power required on the LO input, the RF signal is attenuated by inserting an attenuating cross pad (resistor network in red) that is calculated by using the following formulas (see Figure 5):

$$R_2 = \frac{Z_0^2 - R_1^2}{R_1}$$

$$A_{dB} = 10 \cdot log \left(1 + \frac{2R_1}{Z_0 \cdot R_2} \cdot (Z_0 + R_1 + R_2)\right)^{-2}$$

The attenuating cross pad shown in Figure 5 is used to decrease the power of a signal by maintaining the impedance matching. The pad is designed by choosing a value for R_1 and calculating the corresponding R_2; then the attenuation is calculated for these R_1 and R_2 values. The desired attenuation is obtained by iterating the calculation. In the circuit, $R_1 = 20\ \Omega$ and thus $R_2 = 105\ \Omega$ which is rounded to $R_1 = 110\ \Omega$; the attenuation is 7.27 dB. Finally, the I and Q components are added together by using a power combiner (exactly the same network as the power splitter) in order to have the magnitude (or more precisely the square of the magnitude, corrected in the DSP algorithm) of the baseband signal; this signal is amplified once again by the same kind of amplifier used previously and is sent to the acquisition board.

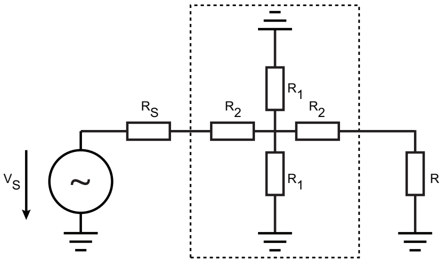

Fig. 5. Attenuating cross pad

The left part of Figure 6 shows the I/Q mixer with its incoming RF and LO signals. The I and Q components given by the mixer are amplified by about 20 dB and then are squared by using a simple mixer fed with the same signal on its own RF and LO inputs. An RF power splitter is used in order to have the signal available for both inputs of the mixer with impedance matching; in order to respect the power supported by the RF input of the mixer, this part of the signal is attenuated by using an attenuating pad. Finally, the two components are added by using a power combiner (the same network as the power splitter) in order to have the magnitude of the baseband signal; this signal is amplified once again and sent to the acquisition board.

C. Construction of the IR-UWB I/Q Receiver

The Printed Circuit Board (PCB) of the UWB I/Q receiver is made of Duroid RO4003C, which is better suited than FR4 for high frequency designs. The construction process of the I/Q demodulator is exactly the same as for the LNA, as explained in detail in [2]. The resulting circuit is shown in Figure 7. The RF shielding case (not shown here) is made of aluminum.

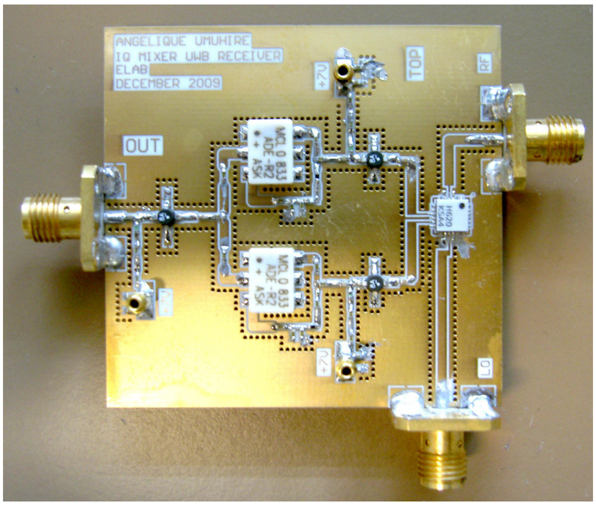

Fig. 7. Close view of the I/Q receiver

IV. EXPERIMENTAL RESULTS

The performance characteristics of the proposed receiver are discussed in the same context as in [1], except that the datarate in our experiments is set 10 Mb/s. The acquisition board uses a dual 1.5 GS/s analog to digital converter and an FPGA, and is similar to the one described in [5]. The sampling frequency can be configured in the range from 2.816 GHz to 2.904 GHz, in 8 MHz increments. The sampled signal is then sent to the FPGA where it is processed. A threshold detection is applied for identifying a pulse and the time differences between two successive pulses is calculated.

Figure 4 shows the acquired UWB impulses with I/Q demodulation (measurements results). The impulses can easily be distinguished when compared with the signal (obtained by simulation as the original setup is no more available) shown in Figure 3 where the UWB impulses are entirely overwhelmed by the beat.

Figure 8 shows the average arrival time of the UWB impulses, with I/Q receiver, for different sampling frequencies. As the datarate is 10 Mb/s, the time difference between two consecutive UWB pulses is ideally 100 ns. In practice, the results are closer to the nominal 100 ns for the lowest rate of 2.816 GHz and the error increases for higher frequencies. Part of the error is introduced by the ADC which under-performs at higher sampling rates. In all the cases, however, the error is of a few nanoseconds, which, given the small sample size, indicates a good receiver performance for localization and ranging applications.

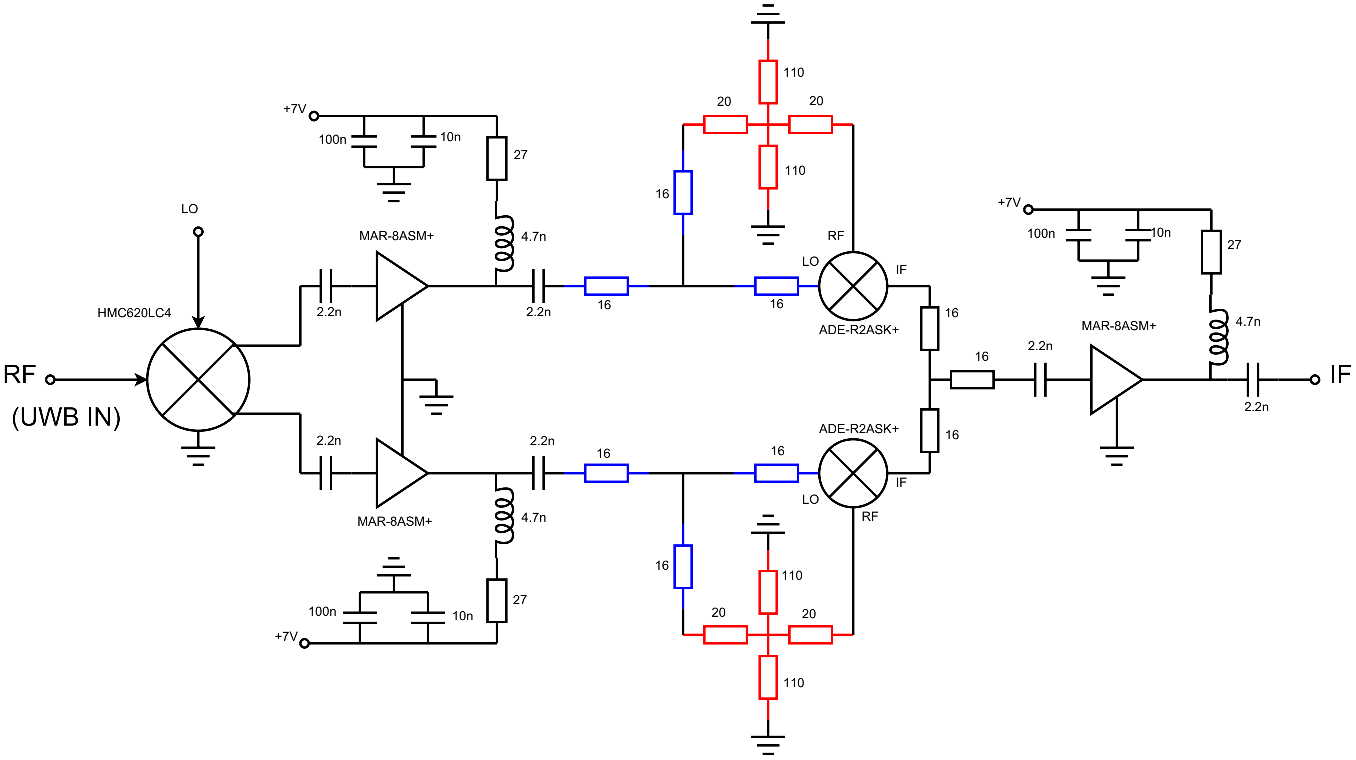

Fig. 6. The complete schematic of the UWB I/Q receiver

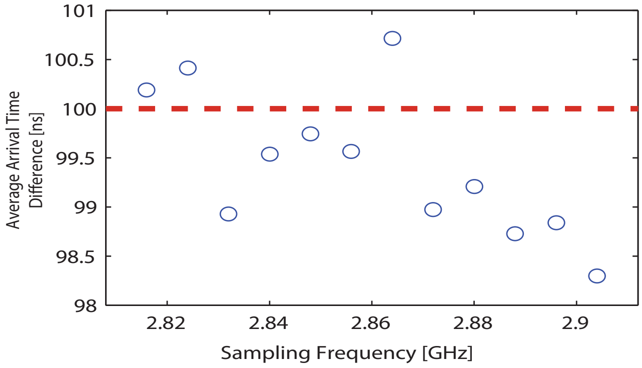

Fig. 8. Measured average difference of pulse arrival time for different sampling frequencies

V. CONCLUSION

We have developed a generic UWB I/Q demodulator that is easy to use and to build and that allows an accurate Impulse-Radio UWB reception by ensuring a constant average power of the obtained baseband signal. Its architecture is easy to modify for different central frequencies or bandwidths (provided that the LNA is modified in the same way). The results of the experimental demonstration and validation of the IR-UWB I/Q receiver completely fulfills the expectations.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge Ms. Angélique Umuhire for her good work during her master thesis, Mr. Jean-François Zürcher (EPFL) who gave a lot of valuable information about RF design and shielding techniques, Prof. Jean-Yves Le Boudec (EPFL) for his scientific advice, as well as the ACI and ACORT team from EPFL-STI for their technical support and the quality of their work.

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APPENDIX
LIST OF COMPONENTS

Component	Catalogue Number & Producer
3-7 GHZ I/Q mixer	HMC620LC4, Hittite Corporation
DC-1 GHz amplifier	MAR-8ASM+, Mini Circuits Corporation
2-1000 MHz Mixer	ADE-R2ASK+, Mini Circuits Corporation
Duroid substrate	RO4003C, Rogers Corporation
Aluminium case	ZG4-2, Telemeter