A New Symmetric Transceiver Architecture for Pulsed Short-Range Communication

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Abstract—**This paper proposes a novel symmetric super-regenerative transceiver architecture for pulsed short-range communication. The proposed architecture is targeted for wireless applications where ultra low power consumption and data-rate in tens of megabits per second are needed over distances in the range of tens of centimeters. The transmitter and receiver are both based on super-regenerative principle and both functions in the transceiver utilize one mutual super-regenerative oscillator. Additionally, the transceiver architecture allows fast synchronization of transceivers thanks to the delayed reflection phenomenon which makes it possible to detect correct timing simultaneously at both ends of the system. Measurement results demonstrate the feasibility of the proposed principle.**

Keywords-super-regeneration; low-power transceivers; short-range communication; smart space; ultra-wideband

I. INTRODUCTION

We take a content and data centric perspective to Ambient Intelligence (AmI) by envisioning a future where today's familiar objects are embedded with concurrently updated digital content. The envisioned content can range from relevant sensor information updates during life span of the object to the entertainment content embedded in posters and concert passes during the manufacturing. Further information on some initial use cases are elaborated in [1]. The vision is founded on decreasing price and power consumption of nonvolatile memory [2], advances in low power sensor technologies and development of energy scavenging technologies. Regarding wireless communication, the vision requires that objects must be capable of communicating increasing amount of embedded content wirelessly with other devices within their immediate proximity (tens of centimeters) and energy budget achievable for energy scavenging methods. Flexible and convenient interactions necessitate data-rates in range of 10-50 Mb/s and beyond, which are out of reach for today's RFID techniques. The transceiver must be also capable of acting with equal performance as receiver and transmitter to enable both downloading and uploading of content. Thus, symmetric transceiver architecture is preferred. It also addresses a desire to avoid higher bill-of-material cost when implementing reading functionality to a device compared to simple content download functionality; familiar in RFID standards. Such cost and complexity differences may significantly hinder integrability of the reading functionality in multi-purpose devices.

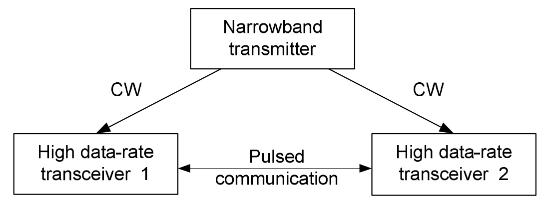

Figure 1. Communication system.

A. Communication system

A communication system is presented in Fig 1. Clock reference for the communication is provided by a narrowband transmitter as a continuous wave (CW) signal. The transceivers at the bottom are similar to each other and they are capable of extracting mutual clock reference from the narrowband CW signal, which can also be used for wireless power transmission. Depending on the application, both transceivers and the transmitter may exist in individual devices. Alternatively, a narrowband transmitter and one high data-rate transceiver form one functional unit which communicates with another high data-rate transceiver.

As mentioned, communication distance is low i.e. tens of centimeters at the maximum. As a result the channel impulse response is short and energy is gathered in a short period of time. The amount of devices communicating simultaneously and sharing the communication channel is expected to be low. The power consumption of the high data-rate transceivers must be in the range feasible for energy scavenging the narrowband transmitter operating as source of energy. The main target is to achieve data-rate of 10-50 Mbit/s and beyond when keeping these limitations in mind.

B. Solution positioning

In addition to orthogonal frequency division multiplex (OFDM) based ultra-wideband (UWB) systems [3], recent UWB research and standardization have also focused on low-power communication over longer distances [4]. The research has concluded that impulse UWB transmitters provide good performance measured as energy/bit supporting high data-rates due to inherently low duty cycle of transmitted signal. However, the power consumption and complexity in receiving end of systems have been significantly higher and out of the range feasible for energy scavenging. The main reasons have been the challenges related to synchronization and low energy

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multipath recovery due to low transmission power [5]. Moreover, very few receivers take advantages of the inherently low duty cycle of UWB pulse waveform as transmitters do. This has steered UWB based RFID and sensor networks research to develop systems that utilize impulse UWB as transmitter technology from sensor node to a sink node and a narrowband technology in the opposite direction [6]. Narrowband signal is more efficient for wireless power transmission whereas UWB provides higher uplink data-rate than what is achievable with conventional RFID techniques. This research however, does not address the symmetric transceiver architecture requirement.

We propose a new concept mixing efficiently impulse UWB and narrowband communication. UWB technology is used to overcome data rate limitation of classical RFID standards. The UWB transceiver uses parametric oscillator theory to act alternatively in receiver/transmitter mode of operation. The principle shows promising and simple solution to get a pure symmetric transceiver which takes efficiently benefit from duty cycle of impulse UWB signal. This could lead to significant breakthrough in term of mean power consumption. The narrowband signal is used for wireless power transmission and frequency synchronization which is a major issue in UWB communication. The phase synchronization is acquired with a new feedback approach which is strongly related to the novel hardware implementation.

The paper is organized as follows: Section II presents symmetric low-power high bit rate transceiver architecture. Section B introduces a phenomenon called delayed reflection which enables a novel phase synchronization method of transceivers. The feasibility of the architecture and reflection phenomenon is validated with measurements in Section IV.

II. TRANSCEIVER ARCHITECTURE

Parametric oscillators are defined as oscillators whose one intrinsic parameter is varied over time. This general theory has been applied in many fields of application such as mechanics, optics and electronics. In this section we explain how it may be efficiently used in the framework of near field communication to act as an UWB emitter and pulse detector.

A. From parametric oscillator theory to symmetric super-regenerative transceiver

A sub-class of parametric oscillators relies on the control of its damping factor. The principle was widely used in vacuum tube circuits since invented in 1922 by E.H. Armstrong who named super-regenerative circuits [7]. These circuits were mainly used as RF receivers. Less attention was paid to the principle after the use of super-heterodyne architecture providing better selectivity in narrowband communication became common. Due to simple structure and low power consumption of super-regenerative receivers the principle has been used in low-cost applications and recently also in wireless sensor networks where available power for communication is limited [8]. A simplified block diagram of a super-regenerative receiver is presented in Fig. 2(a). It consists of a low-noise amplifier, an oscillator and envelope detector followed by a low-pass filter and demodulator. The core of the receiver is an unstable circuit, super-regenerative oscillator (SRO). This parametric oscillator is made unstable by controlling its damping factor ζ with a specific command called quench signal, which controls the growth and the cut off of the oscillations.

Recently, super-regenerative architecture has also been proposed for impulse UWB receivers [9], [10]. The principle is reminded in Fig. 2(b) with a trapezoidal quench signal. If the damping factor ζ goes negative at $t = 0$ without any input signal $v_i(t)$ at the input of SRO, the self-oscillation starts from noise. Therefore, in the first quench period the amplitude of resulting self-oscillation $v_o(t)$ does not exceed the detection level v_d before the oscillation is already damped at $t = t_a$ by the inactivation of quench signal. However, if the amplitude of incoming signal $v_i(t)$ is large enough within the sensitivity period of the receiver, the oscillation increases much faster and the resulting amplitude exceeds the detection level of the detector at t_b as presented in latter quench period. This enables extraction of information from input signal modulated with On-Off Keying or Pulse-Position Modulation.

In [9] an RF front-end for UWB receiver has been implemented and the feasibility of concept achieving high RF gain and sensitivity with a SRO core has been demonstrated. The peak power consumption remains below 2.3 mW while the intrinsic duty cycle of the system enables adjustment of the mean power consumption according to data rate. Indeed, super-regenerative receiver architecture takes benefit from the duty cycle of impulse UWB communication since it is fully active only when damping factor ζ of the unstable circuit is negative. Thus, the mean power consumption of the receiver can be decreased according to targeted data rate as in impulse UWB transmitters. However, the sensitivity of such a receiver is high only for a limited period of time around the negative zero-crossing of the damping factor [11]. This is well in line with the application since energy of impulses is concentrated in time. Nevertheless, good synchronization between incoming pulses and sensitivity period is needed to achieve maximum sensitivity [10], [12]. An original method for phase synchronization is explained in Section III.

In Fig. 2(a) the regenerative principle is used as a pulse receiver. If the LNA stage is removed the generated and re-generated pulses highlighted in Fig. 2(b) are directly radiated in the air due to the direct connection between the oscillator and the antenna. In this sense, the super-regenerative principle acts as an emitter. This principle is close to what is most commonly known in the UWB emitter literature as pulse-injected locked oscillator principle [13] which can be used to generate short UWB wavelets [14]. Next subsection explains how to use this principle to get a symmetric architecture.

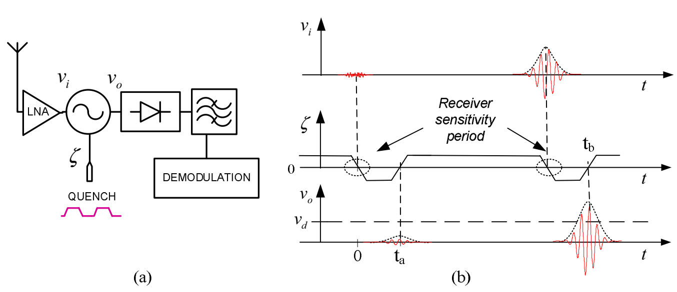

Figure 2. (a) Block diagram of conventional super-regenerative receiver and (b) principle of operation in pulsed communication.

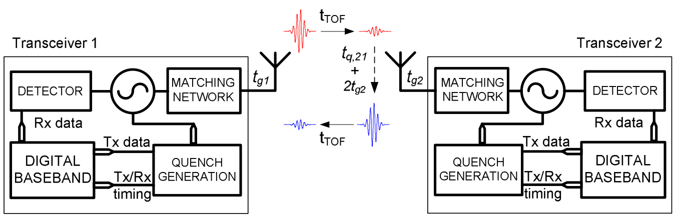

Figure 3. Symmetric impulse UWB transceiver architecture based on super-regenerative structure.

B. Symmetric architecture

A transceiver architecture utilizing super-regenerative oscillator in both generation and detection of UWB impulses is presented in Fig. 3. The timing of quench periods for the transmission of pulses and detection of received pulses is triggered by the digital *Tx/Rx timing* signal. In transmission state the quench signal of oscillator is modulated with the *Tx data* signal. The actual shape of quench waveform in transmission and reception states is defined by the quench generation block. The minimization of the overall power consumption of the transceiver is made feasible by removing amplifier stages. Indeed, since the target communication range is only tens of centimeters, no linear amplifiers, such as power amplifier in transmission or low-noise amplifier in reception, are necessary to compensate the path loss between the transceivers. All the needed gain is achieved from super-regeneration [10]. Basically, the SRO is connected directly to the antenna. An example of link budget for 50 MHz pulse repetition rate on 4 GHz center frequency is presented in Table 1. According to [9] the super-regenerative gain may compensate the 30 dB pathloss shown in Table 1.

As mentioned, the damping periods are triggered digitally and the resulting output waveform from the quench generation block can be optimized separately for reception periods and transmission periods. According to [10] the waveform of the damping function in reception can be adjusted so that the bandwidth of receiver is adapted to the incoming pulse. Thus, the receiver operates like a pulse-matched filter. In reception the resulting amplitude of oscillation is detected by a peak-detector stage. The peak value of the oscillation is directly dependent on the amplitude of the incoming pulse. The resulting *Rx data* stream is received by the digital baseband.

This extremely simple transceiver architecture contains only one super-regenerative oscillator which is used in half-duplex communication to alternately generate transmitted pulses and amplify received pulses.

TABLE 1. EXAMPLE OF LINK BUDGET

Center frequency	f_c	GHz	4
Signal Bandwidth	B	MHz	500
Pulse Repetition Frequency	PRF	Mp/s	50
Tx Power Spectral Density limit	$p_{TX\text{-}mean}$	dBm/MHz	-41.3
Tx (ideal) signal power	$P_{TX\text{-}ideal}$	dBmW	-14.3
Tx maximum output voltage (100 Ω)	$V_{p\text{-}TX}$	mV	225
Usage distance	d	cm	20
Far-field approximation (4 GHz)	$\lambda/2\pi$	cm	1.2
Time of flight	TOF	ns	0.67
Overall Path loss	Pl	dB	30.5
Rx Signal to Noise Ratio	Ep_{RX}/n_0	dB	49.9
Rx maximum input voltage (100 Ω)	$V_{p\text{-}RX}$	mV	6.7

III. DELAYED REFLECTION METHOD FOR PHASE SYNCHRONIZATION OF UWB COMMUNICATION

In addition to the gain needed to overcome path loss, in traditional super-regenerative receivers, LNA and buffer amplifiers are also used to minimize unintentional leakage of the regenerated signal from the oscillator to the antenna and signal re-radiation. In narrowband systems this is necessary to avoid interference of other systems. However, in the proposed transceiver architecture the amplifiers are excluded. One of the reasons not to use buffering amplifiers is the idea to re-use the leaked regenerated pulse and emit it on purpose within the regulatory limits set for UWB communication. The leaked pulse is delayed in comparison with the incoming one and it is therefore seen as a delayed and amplified reflection by the other end of the system. A detailed description of the phenomenon is presented below.

A. Delayed reflection in super-regenerative transceiver

A time-diagram of a successful reflected pulse between the transceivers is presented in Fig. 4. The three uppermost time-lines present the waveforms relevant for the transceiver 1 (TRx1). The input and output pulses at the SRO of TRx1 are presented with $v_{i,1}(t)$ and $v_{o,1}(t)$. The damping factor for the super-regenerative oscillator of TRx1, controlled by the quench signal, is presented with $\zeta_1(t)$. The three lowermost time-lines describe the functionality of TRx2, respectively.

Transmission of the first pulse $v_{o,1}(t)$ occurs in TRx1 when the quench signal allows the oscillator to go unstable. The peak of transmitted pulse occurs after $t_{q,11}$ from the falling edge zero-crossing of $\zeta_1(t)$ when it goes back to positive.

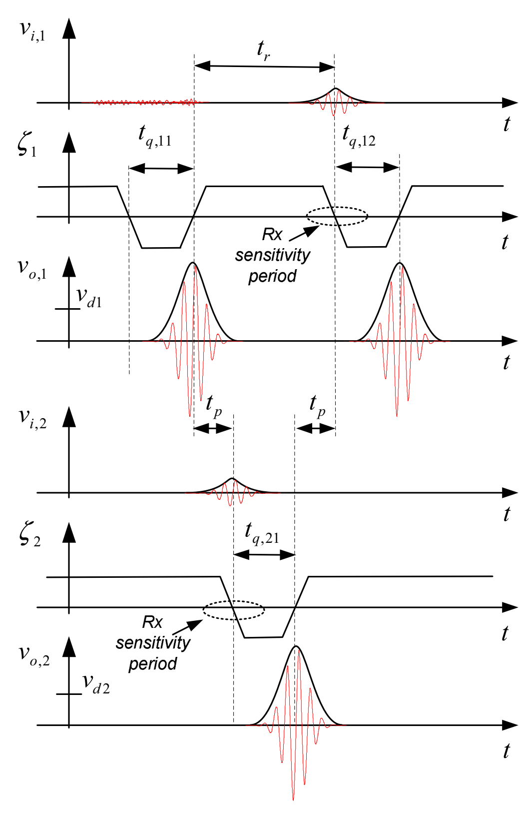

Figure 4. Delayed reflection of pulse in time-domain.

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After propagation delay t_p the transmitted pulse is received by TRx2. The overall propagation delay is $t_p = t_{g1} + t_{TOF} + t_{g2}$, where t_{TOF} is the time-of-flight proportional to the distance between the antennas, and t_{g1} and t_{g2} are the group delays in TRx1 and TRx2 due to antennas and transmission lines. Propagation loss attenuates the input signal $v_{i,2}(t)$ from $v_{o,1}(t)$ but because of the line-of-sight channel due to short distance, energy of the received pulse is concentrated in time.

If the input signal $v_{i,2}(t)$ is well aligned with the sensitivity period of TRx2, the oscillation amplifies during super-regenerative period $t_{q,21}$ to the level which exceeds the detection level v_{d2}, whereas oscillation starting from noise stays below v_{d2}. Since the proposed transceiver architecture has no buffering amplifier between the oscillator and antenna, the pulse generated by the oscillator in TRx2 is also radiated in the air. The delay between incoming $v_{i,2}(t)$ and radiated $v_{o,2}(t)$ RF pulses is defined by the quench signal duration $t_{q,21}$.

After the propagation delay t_p the regenerated pulse from TRx2 arrives to the input of TRx1 as shown on $v_{i,1}(t)$. If the timing of input signal $v_{i,1}(t)$ is aligned well with the sensitivity period, the oscillation in TRx1 also exceeds the detection threshold v_{d1} during the regenerative period $t_{q,12}$. Thus, when the timing conditions are fulfilled it is possible to detect the delayed reflection correctly in both TRx1 and TRx2.

The usability of the delayed reflection for communication is based on two main elements. First, the delay in the reflection from the perspective of TRx1 must be long enough. This is needed to avoid unintentional overlap of oscillations related to the transmission and reception of pulses which is called "hangover" in classical super-regenerative circuits [11]. Overlap may occur, for example, due to antenna ringing. Therefore, the delay defined by the duration of quench signal $t_{q,21}$ is essential for the detection of reflection in TRx1. Secondly, the amplitude of the reflected and delayed pulse must be significantly larger than what is the amplitude of a reflection from a physical object. The needed amplitude difference is achieved from super-regenerative gain in TRx2 when the timing of the pulses is correctly aligned.

B. *Synchronization based on reflected pulses*

As in any communication system, a prerequisite for the communication is synchronization between the transceivers. Synchronization is often problematic in impulse UWB systems because of the low duty cycle of impulse signal. In a conventional impulse UWB system the acquisition of phase synchronization with the incoming transmission requires correct reception of a preamble sequence and usually receiver has to search through a large number of possible phases. If duty cycle of receiver is also low, preamble must be repeated multiple times to ensure high probability of correct reception.

In the proposed system frequency synchronization is achieved thanks to the mutual narrowband CW signal which can be also used as reference clock for quench signal. Additionally, the phenomenon of delayed reflection is proposed for a fast acknowledgment method to find correct phase synchronization for communication even if the duty cycle of receivers is low. The principle is based on the usage of successfully detected delayed reflection as a time-stamp at both ends of the system for the start of the phase synchronization validation. In the starting point the transceivers are not aware of the correct timing of communication. TRx1 scrolls the position of its first emitted pulse $v_{o,1}(t)$ over the pulse repetition period (PRP) until it reaches the sensitivity period of TRx2. Scrolling may also follow a pseudo-random timing sequence. As a correctly aligned reflection (Fig. 4) occurs, it means that TRx1 and TRx2 are phase synchronized which triggers a verification phase. The verification phase may include multiple reflections and without the occurrence of sufficient amount of consecutive reflections the transceivers return back to starting phase where the first time-stamp reflection is searched.

The main difference to the conventional methods is that both ends of the system may participate to the searching of synchronization by using the time-stamp reflection as an excitation for the search. To interleave communications of multiple users a back-off protocol can be used, since the expected number of devices sharing the communication channel is low.

IV. VALIDATION OF PRINCIPLE

The measurement set-up which we used to validate the feasibility of the proposed principle is presented in Fig. 5 and its block-diagram in Fig. 6. We used an existing super-regenerative receiver RF front-end circuitry operating with UWB pulse signal on 3-4.5 GHz frequency band to emulate the functionality of the proposed transceiver architecture. The main difference between the used circuitry in comparison with the architecture in Section II is amplifiers between antenna and the super-regenerative oscillator core. In order to radiate the (re)-generated signal and provide the reflected pulse, an additional antenna is connected after the output buffer.

The set-up included two similar integrated circuits, TRx1 and TRx2. The quench waveforms generated with pattern generators controlled the damping function of oscillators as presented in Section III and the timing of quench signals was controlled by a Matlab algorithm. The output signals of the SROs were divided by using directional couplers to Tx antennas and to an oscilloscope. Digital processing emulated by Matlab code achieved the signal envelope recovery and peak detection.

During the measurements the timing of quench signal in TRx2 was repeated regularly with 10 MHz pulse repetition rate. Both transceivers had the same clock frequency but TRx1 drove the synchronization protocol. The transmitted pulse position was stepped with 0.2-1 ns steps according to the fine or coarse synchronization algorithm to find the correct alignment with TRx2 quench signal. One measurement round included the following phases. In TRx1 the first quench pulse generated oscillation which resulted as the first Tx pulse. This pulse was transmitted from antenna 1 to antenna 2 at the input of TRx2. If the sensitivity period of TRx2 was correctly aligned with the incoming pulse, the oscillation regenerated in TRx2 resulted as a pulse with amplitude comparable to the Tx pulse. Otherwise, the regenerated oscillation started from noise and resulted as significantly smaller amplitude. The resulting pulse was directly transmitted from antenna 3 to antenna 4 and in case where the input pulse was correctly aligned with the sensitivity period of TRx1 it resulted as a successfully detected reflection.

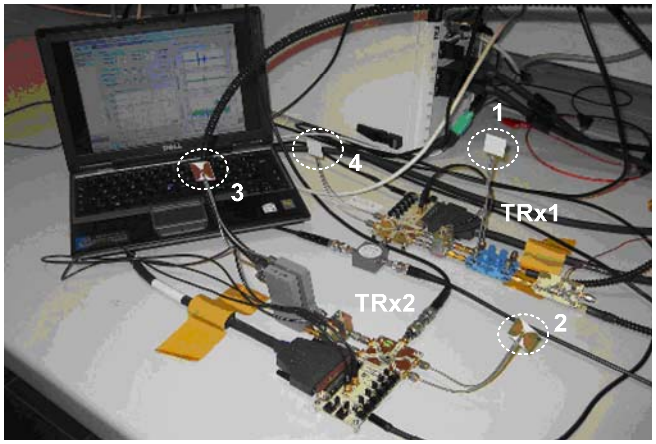


Figure 5. Validation platform highlighting TRx1, TRx2 and PC with Matlab.

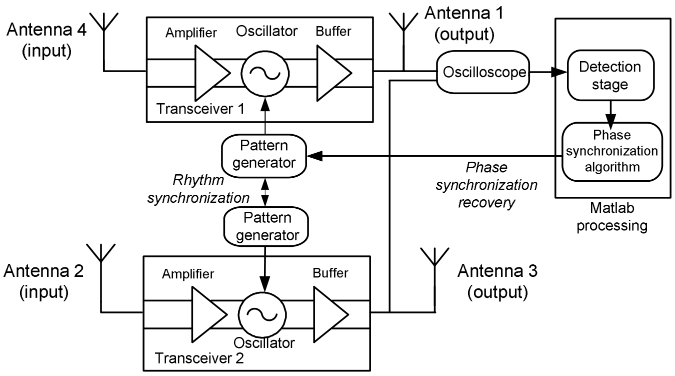
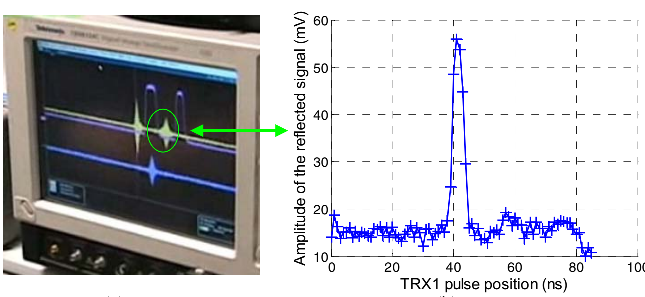


Figure 6. Block diagram of validation platform.



(a) (b)

Figure 7. (a) Output waveforms of transceivers in optimal synchronization point. (b) Amplitude of reflected pulse at TRx1 during synchronization.

Fig. 7 illustrates the measurement results in successful phase synchronization. The oscilloscope snapshot in Fig. 7 (a) shows the chronogram at TRx1 (uppermost curve) and TRx2 (lowermost curve) outputs. As it has been explained from theoretical point of view in Fig. 4, measurement shows the transmitted pulse from TRx1, the regenerated pulse at TRx2 and the feedback detection at TRx1 that provides to TRx1 the information of correct phase synchronization.

Fig. 7(b) shows the amplitude of the detected reflected pulse at TRx1 side as a function of the time position within a PRP of its transmitted pulse. We can clearly distinguish a peak value in the vicinity of 42 ns which corresponds to the presence of reflected signal demonstrating the optimal synchronization. The width of this peak is an indicator of the synchronization accuracy requirement which is on the order of 5 ns with a pulse bandwidth of 500 MHz.

CONCLUSIONS

In this paper we have introduced a novel symmetric transceiver architecture for ultra low power short-range communication. It takes efficiently benefit from duty cycle of impulse UWB signal. The feasibility to use one mutual SRO in generation and reception of impulses at 10 MHz pulse repetition rate has been demonstrated. Also the feasibility of the original feature called delayed reflection and its utilization in phase synchronization has been demonstrated. The simple transceiver architecture is a promising approach for wireless short-range communication in the context of content and data centric ambient intelligence.

The future work will focus on development and analysis of the proposed synchronization method and validation of delayed reflection in varying conditions typical for short-range communications.

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