Algorithms for Synchronization of Coherent UWB Receivers and Their Application

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***Abstract*—In this paper a detailed analysis of an Ultra-Wideband correlation receiver is presented. The synchronization methods are discussed and analyzed in terms of practical realizability. All algorithms are implemented on FPGA and tested with a real UWB transceiver. The measurement results are then evaluated and compared to the ones found in the literature. Finally an application example for the correlation receiver is demonstrated by means of one-way ranging.**

***Index Terms*—correlation receiver, ranging, synchronization.**

I. Introduction

In the past few years several UWB demonstrators for communication and localization purposes were realized [1], [2]. In almost every wireless application it is essential to either minimize the transmit power, increase the maximum distance or reduce the bit-error-rate. In all those cases the SNR in the received signal is the figure of merit. In theory the advantages and disadvantages of different receiver types are known [3]. According to this, the most effective reception method in an AWGN channel is the correlation of the received signal with the template pulse (TP). The correlation can be performed with a *clean* template: one that is locally generated in the receiver, or *dirty* template: TP that is distorted in order to account for the influence of the channel and maximize the correlation result. This technique is also called *transmitted-reference* (TR) [4]. Another reception method, that can be classified as *coherent* is the I/Q demodulation [5]. This method is similar to the carrier recovery in narrowband systems.

In the TR technique two pulses are sent one after another and at the receiver site they are mutually shifted and correlated. This however results in the noise from the channel being correlated as well thus decreasing the SNR. In case of the I/Q demodulation the correlation is performed in the digital domain, after Nyquist-sampling of both channels. This requires an A/D conversion with a speed of several Gsps for sub-nanosecond UWB pulses. The correlation in the analog domain would largely relax those requirements.

Because of those disadvantages, as discussed in the cited literature, the analog correlation transceiver (CR) with a clean template correlation is thoroughly investigated in this paper. The emphasis is put on the receiver in terms of synchronization algorithms and practical realization. The proposed approach is compared with the solutions encountered in the literature. Finally an application example of the CR is given and verified by measurement.

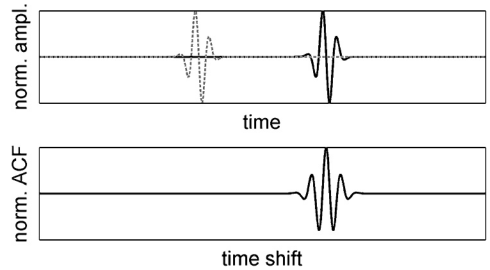

Fig. 1. Two pulses - (top): TP (gray, dashed) and received (black); (bottom): the ACF that occurs as the TP sweeps along the received pulse.

II. Synchronization Schemes

The UWB pulses are extremely short and the duty cycle is typically 1% or less. To perform the correlation the received and locally generated pulse need to overlap. Fig. 1 (top) shows the received pulse (black) and the TP (gray) and Fig. 1 (bottom) is the auto-correlation function (ACF) of the received pulse. Depending on the detection threshold the receiver can synchronize at the side lobes of the ACF. For UWB pulses, with a bandwidth of several GHz a timing precision of several tens of picoseconds is required. As such, the synchronization problem can be generally reduced to precise control of the TP. In following, several methods of synchronizations are described.

- *Linear synchronization (LS)*: During LS the entire search window (SW) (one period of the template signal) is sampled with an increasing delay, that is as shown in Fig. 2(a). The decision of whether the synchronization is obtained or not is done based on several observed pulses at the same position. The parameters that can be adjusted is the delay step and the amount of observed pulses at one delay setting (more in section V-A).

- *Linear-offset synchronization (LOS)*: Here, in contrast to LS, the delay will be increased by one coarse step after the entire SW is sampled. Then another sweep is done. This is shown in Fig. 2(b). This method allows a faster synchronization than the LS in the case when the ACF is broad (signal is strong).When not the case, it will still sample all positions.
- *Tree synchronization (TS)*: In the previous two synchronization schemes the search begins at zero delay and proceeds until

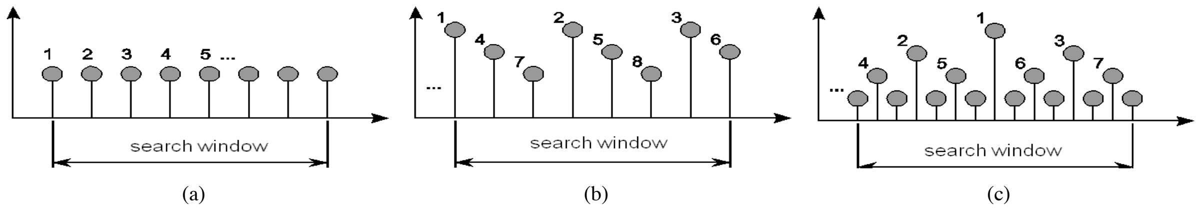

Fig. 2. Synchronization schemes.

the end of SW. With TS the SW will be equally sampled with decreasing step widths. This is as shown in Fig. 2(c). This method represents a width search of a 'tree' (a.k.a. *breadth-first search*). The expected advantage of this approach is the faster synchronization in the cases where the main pulse is surrounded by large amount of side lobes (e.g. originating from close multipaths).

III. Stable Frequency Generation and Phase Shift

In this section a brief overview of methods for generating very precise trigger signals is given. Firstly two important parameters need to be defined:

· *Time jitter, (TJ)*: This is the time domain representation of phase noise in the frequency domain. In the case of digital signals, jitter describes how much the rising/falling slopes of the signal differ from their ideal position. In the coherent UWB transmission the jitter (e.g. of the template signal) has to be much smaller than the width of the auto-correlation function.

· *Frequency accuracy, (FA)*: The FA of an oscillator is the offset from the specified target frequency and is expressed in *parts per million* (ppm). The dependence of synchronization on oscillator FA is because the time offset is the integral of the frequency error. Off the shelf oscillators offer the accuracy at a level of $\pm$5-100ppm. The larger the difference between both pulse repetition rates (PRF) at transmitter and receiver, the more effort is needed to maintain the synchronization.

Methods of generating precise trigger signal:

- *Phase Locked Loop (PLL)*: One possibility to trigger the template pulse is with an oscillator integrated in a PLL. The frequency accuracy of the PLL is determined by dividers and allows only coarse frequency precision. TJ is dependent on the lowpass filter: a steep filter for low TJ does not allow for fast frequency changes without the PLL loosing its lock.
- *Direct Digital Synthesis (DDS)*: The average FA of the DDS depend on the TJ of the reference oscillator divided by the number of bits of the frequency tuning word. The FA in the range of nHz is achievable [6], however the digital counter can cause zero-crossing jitter due to overflow.
- *Serial Shift Register (SSR)*: The precision of the output digital signal depends on the clock frequency of the register. To achieve the precision of 30ps the SSR would need to be triggered at 33GHz. This method can however be still used for coarse synchronization.
- *Programmable Delay (PD)*: PD allows to precisely adjust the phase of the digital signal. The precision of the devices available at the market is downto 10ps. In conjunction with e.g. PLL, PD can be used for very precise frequency or phase adjustments [7].

IV. Hardware and Measurement Setup

The measurement setup is depicted in Fig. 3. The FPGA supplies the clock signal (PLL with adjacent PD), which directly triggers the impulse generator. After an optional attenuation the pulse is radiated through an antenna and propagates towards the receiver. After reception, the signal is bandpass-filtered, amplified and the pulse is multiplied (correlated) with the locally generated template. The correlation result is 1-bit A/D converted. The comparator's output is acquired by the FPGA. Based on that, the decision block (implemented synchronization scheme) manage both the coarse and fine clock control blocks. The coarse control allows for a timing precision of 1ns and the fine one adjusts the programmable delay in 10ps steps.

In the presented system the signal, a 5^{th}-derivative of the Gaussian pulse (as in Fig. 1), with the full width at half maximum of 250ps (10dB bandwidth is approx. 7GHz), is used. The ACF indicates that in order to remain in the region of at least 80% of the maximum, a timing tolerance of only 30ps is allowed. All details on the FCC compliant UWB front-end hardware can be found in [8]. The rate at which the pulses are transmitted is 12.5MHz (period of 80ns). The TS is triggered with 200MHz (5ns period) to accelerate the search. The T-R separation is 2.5m.

With this setup it is possible to evaluate several parameters. If synchronization path (1) is used and clock (2) is off, the synchronization algorithms can be tested without including other effects (e.g. FA). With (2) on and (1) off, the sensitivity of the algorithms against FA of both clocks is tested. Moreover a variable attenuator (3) allows the modification of the SNR in a controlled way. The scenario with the deployed system is depicted in Fig. 4.

V. Measurement Verification

In this section the different synchronization algorithms are evaluated against each other. Within each synchronization scheme the single parameters are investigated. Firstly the evaluation criteria are defined:

1) Time duration until the synchronization is finished - it is the number of transmitted pulses, with a period of 80ns that elapsed until the synchronization is completed.

2) Decision threshold - this is the ratio between the number of pulse periods (transmitter), for which time the system will

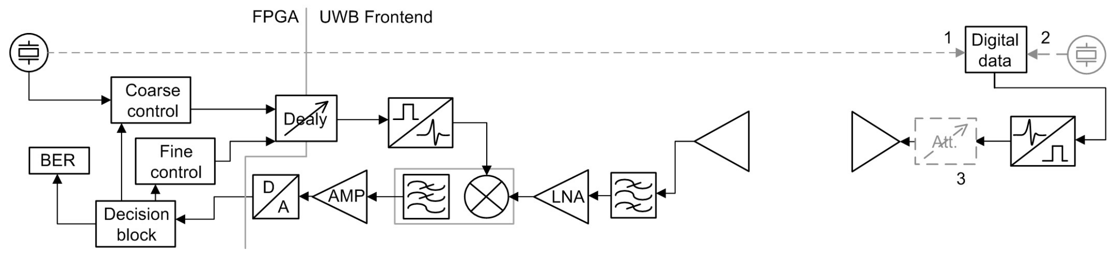

Fig. 3. System configuration used for verification of synch. algorithms. The gray dashed elements 1, 2 and 3, as well as wires are optional.

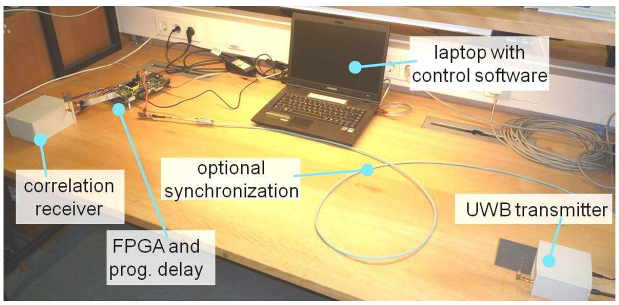

Fig. 4. Photograph of the Measurement scenario.

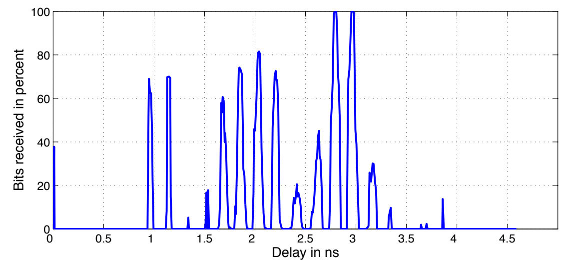

Fig. 5. Correlation result of the TP with the received pulse after propagation through the channel. The time interval is the one width of the search window.

remain by the same delay setting (receiver) and the number of pulses that need to be detected in this time in order to declare synchronization as completed.

For the test purposes a real indoor environment was chosen, where the multipath propagation is very prominent. In addition the transmit signal amplitude was reduced to 950mV U_{pp}. The result of this is a large number of correlation side lobes in received signal (originating from multiple reflections) and low main correlation maximum.

A. LS Accuracy at Different Threshold Settings

Firstly the received signal after propagating through the previously described scenario, is sampled with the CR. The delay element controlling the template impulse is adjusted in the way that at every setting 10000 pulses are observed. This was continued to cover the entire SW (period of the template signal) and is represented in Fig. 5. The delay setting in ns is on the abscissa and the ordinate indicates the number of received bits at this position in percent (probability of detection). In this graph a large number of correlation side lobes is present. This measurement however does not indicate the absolute number of pulses that will be observed during the synchronization process. In order to investigate this more, the LS scheme was chosen and several parameters were varied. In the case when 1000 pulses are to be observed at one delay position and criterion for synchronization completion is 990 received pulses, this results in a relative detection threshold of 99%. If only 100 pulses are to be observed at one delay setting and after 99 received pulses the synchronization is to be completed, theoretically this will result in the same threshold and shorter time required for synchronization.

In Fig. 6 (top) a cut-out of the section with the highest percentage of received bits from Fig. 5 is shown (between 1.8 and 3.1ns). To investigate different thresholds the LS with a 10ps step is used. The results are shown in Fig. 6 (bottom). The lower threshold of only 100 observed pulses (orange) shows a very large variance. The reason for this is that in the correlation side lobes it is possible to detect 99 pulses at a stretch. When the observation period of 1000 pulses is used the synchronization is more reliable and tends to complete the process at the same position. The longer observation time at each position assures better statistical certainty. With the increasing threshold the search result is closer to the main maximum (on the very right), however in most cases the strong side lobe stops the synchronization (except in two cases with 99.9% threshold, where the true position was found: 2950ps).

Regarding the threshold choice and a number of pulses to be observed, a trade-off has to be made. A large amount of pulses will lead to more precise and reliable synchronization. On the other hand, when the T_x and R_x modules are operating with physically separate oscillators((2) in Fig. 3) a certain clock drift will be present. In this case, during the long observation time at one position the searched pulse will migrate, leading to even longer search times. In the worst case the synchronization will not be possible at all. As a consequence, for the tests described in V-B and V-C the threshold was set to 500 received pulses in a row.

B. Influence of the Step Width in the LS Scheme

The results of the LS test for different delay step widths are presented in Fig 7. The search duration (ordinate) is plotted against the determined delay (abscisse). The green circles are the values for the smallest delay step of 10ps. In this case more time is required than if a 20ps is used (blue). The results of

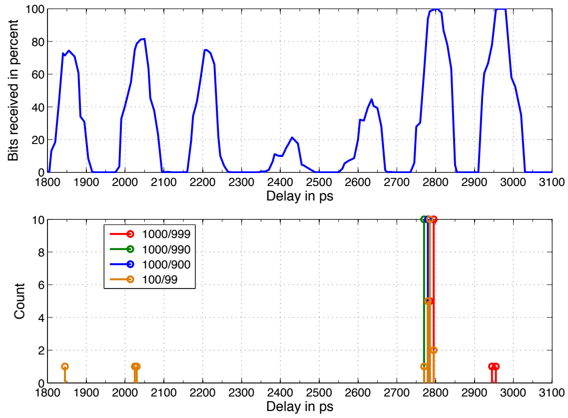

Fig. 6. Comparison of the synchronization thresholds (observed/required): zoom-in of the measured correlation function from Fig. 5 (top) and the delay where the break-up criterion was met (bottom). The main peak is the one on the very right, the others are the correlation side lobes and echoes.

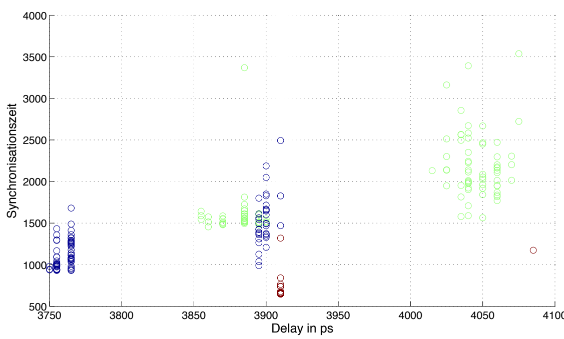

Fig. 7. Duration of the linear synchronization at various step widths.

the synchronization performed with 30ps are marked with red circles. Here only every third delay setting is used, what results in the fastest synchronization. These tests were performed at a 3m distance. The LS synchronizes partly at the side lobes of the ACF that are spaced approx. 150ps from the maximum.

C. Comparison of Synchronization Schemes

In this section the LS, LOS and TS schemes are evaluated under the same conditions and compared with each other. In Fig. 8 the LS, with a step width of 30ps (red, the same as in Fig. 7), is compared with LOS (blue). Apart form one outlier of the LS, the values lie close to one another. The TS scheme (green) delivers similar results as the LS with a 20ps step, but requires more time. This data was obtained at one distance of 3m, where each scheme was run 100 times. In the further test the variable attenuator was used to influence the transmit amplitude ((3) in Fig. 3). The attenuation was changed in 2dB steps between 0 and 10dB. At each setting all the above presented measurements were re-performed and the average values are presented in Table I.

The finest linear synchronization offers the best results at the cost of relatively high search time. Large delay steps often do not allow reliable synchronization (process aborted). With

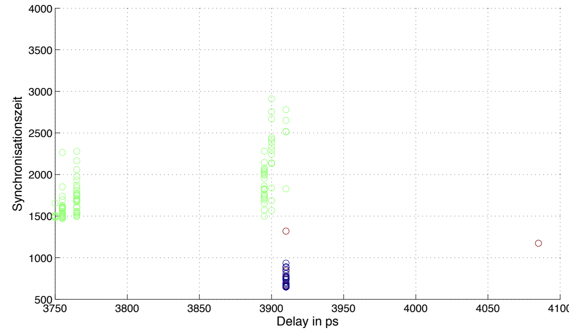

Fig. 8. Behavior of the linear synchronization versus linear-offset and tree synchronization.

TABLE I
AVERAGE SYNCHRONIZATION EFFORT OF LS, LOS AND TS SCHEMES.

scheme	delay [ps]	duration [ps]	aborted
LS 10ps	3920.5	1776	21
LS 20ps	3961.8	1781	132
LS 30ps	3914.3	1683	151
LOS 30ps	3916.2	1354	151
TS	3887.8	1785	100

LOS it is possible to obtain the synchronization after the shortest time. The number of situations where no synchronization was possible is the same as in the case of LS with 30ps step. The TS logs-on after very similar time as LS, however the solution is often wrong.

D. Influence of a Separate Clock Source

For this test the separate clock ((2) in Fig. 3) was used for the transmitter and receiver. Due to the limited frequency accuracy between both sources the obtained synchronization will be lost after short time ($\approx 1\mu$s for 30ppm FA at 12.5MHz) if no countermeasures are taken. Because of this the decision threshold (number of pulses observed) has to investigated. In the previous sections it was shown that longer observation yields better results when the clocks are synchronous. In this case high thresholds will not give the desired result. However setting the lower threshold increases the probability that the receiver will synchronize at the side lobe of the ACF or even at a multipath echo. The results are presented in Fig. 9. It shows that the linear increase of threshold causes an almost logarithmic increase in search time.

E. Application Example: Precise Ranging

One of the possible applications of the CR and presented synchronization algorithms is for precise range measurement. To demonstrate this a test was conducted where the transmitter was placed at three positions separated each time by 1cm. Then the LS scheme with 10ps was used to search for the received pulse. In Fig. 10 different thresholds were used. The higher the number of the pulses to be detected in the row, the higher the probability to synchronize at the absolute maximum of the ACF.

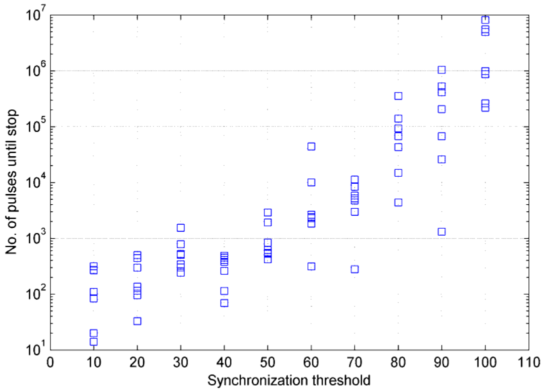

Fig. 9. Unsynchronized clocks: duration of the synchronization process as a function of threshold (pulses required to be detected in a row).

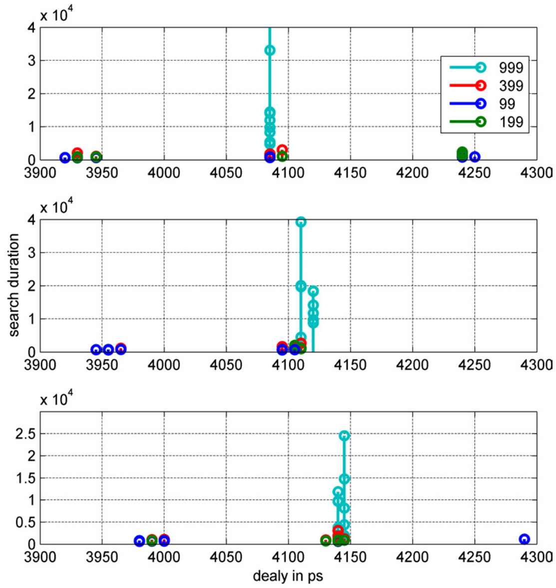

Fig. 10. Time required for synchronization depending on threshold at distance differences of 1cm between measurements.

The measured delays were: 4085, 4110 and 4145. The time change of 35ps corresponds to distance of 10.5mm. The inaccuracy of the system in a one-way ranging is related to the mean delay step width - in this case 3mm (10ps). The maximal step error specified for this PD is ±5ps.

VI. Discussion

There are very few implementations of the CR that can be found in the literature. The presented system is compared with the two of the best ones published to date:

In [9] a PLL-based CR was implemented. The use of the VXCO, controlled through a DAC allowed only minimum step of 60ps. Compared with 10ps presented here, it does not allow for precisely synchronization in the case of such narrow pulses. Moreover the PLL requires certain time to settle and do not allow for erratic phase changes (no TS possible). Our implementation allows in addition to the TP triggering at a 20-times a faster rate, reducing the time required for synchronization.

In [7] the PD approach was chosen. The UWB pulses had only a 500MHz bandwidth (compared to 7GHz in this paper) and the delay step of 160ps was possible. The raw data rate (PRF) was 1Mbps compared with 12.5Mbps in this paper and the maximal ranging precision was ±2.5cm (here presented lower than 1cm; 3mm possible based on hardware specification).

VII. Conclusions

In the presented paper a comprehensive study on UWB correlation receiver is presented. The introduced synchronization schemes were implemented on FPGA and tested on an FCC compliant transceiver. A parametric study was performed to identify the most efficient algorithm. In terms of search time the LOS algorithm is the best one, however the LS with 10ps has the best precision.

Test performed with a separate clock on the transmitter and receiver indicate that the synchronization is very sensitive to frequency accuracy and can only be established for a short time period. In practice this kind of a system has a very large complexity and the advantage of better SNR will not justify the effort (and the loss of throughput). As demonstrated, there are however applications such as mm-precise ranging, where the correlation receiver gets the upper hand as compared to the other reception techniques. The presented system has a larger bandwidth, more efficient synchronization scheme and more precise range finding than other found in literature.

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