MODELLING AND SIMULATION OF A NON-COHERENT IR UWB TRANSCEIVER ARCHITECTURE WITH TOA ESTIMATION

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ABSTRACT
Lately, impulse-radio (IR) based ultra wideband (UWB) has emerged as a leading candidate for short range data communications with positioning capabilities. This paper examines the performance of time of arrival (TOA) position estimation techniques of an IR UWB non-coherent energy collection receiver. We present the performance of two different algorithms, namely, the threshold-crossing (TC) and the maximum selection (MAX) algorithms in terms of time of arrival (TOA) estimation error in IEEE 802.15.3 channel models. The architectures of TOA MAX and TC algorithms, suitable for implementation into IR-UWB based non-coherent receivers are presented and evaluated in a top-down design methodology using a hardware description language. The goal is to evaluate the UWB IR energy collection receiver with TOA capabilities on a complete simulation platform.

I. INTRODUCTION
Impulse-radio (IR) based UWB systems have very good time domain resolution allowing for location and tracking applications and offer the potential for relatively low complexity and low cost. Due to the high time of arrival estimation accuracy, UWB enables UWB devices (tags) to be tracked and located with high precision within a specified area. The non-coherent energy collection receiver is based on recovering the signal energy spread in the UWB channel. One of the benefits of using energy collection architectures for UWB-IR tags is that there is no need of a channel estimation block with the associated drawback of interference and noise enhancement [1]. A non-coherent energy-collection design for IR UWB tags has been presented in [1] and references therein.

Full simulations of radio frequency (RF) components, analogue components and digital stages of a receiver are very time consuming or even infeasible in practice. For UWB systems, the simulation time is even higher than in conventional narrowband systems due to the large signal bandwidth. The designer must rely on Computer Aided Design (CAD) tools which can model the most important properties of the receiver in a reasonable amount of time. One useful tool is verilogA, a hardware description language which has the capabilities to perform time, frequency and noise analysis of a complete (RF+Analog+Digital) receiver path. The fine time resolution associated with the short time duration pulses makes IR-UWB systems a strong candidate technology for indoor positioning systems based on time of arrival (TOA) [2]. Non-coherent energy collection receivers can implement TOA positioning techniques using a bank of overlapping or non-overlapping integrators. A coarse TOA estimate can be produced simply by integrating the received signal in small time windows over a symbol period and then selecting the integrator which gives the maximum value [3] or the integrator which integrates over a threshold value. The integration windows must be sufficiently small to satisfy the desired uncertainty of the TOA estimate.

In this paper, we present the performances of two TOA algorithms and the architecture suitable for implementation as well the behavioral simulation results of the RF components of the receiver. Previous work on high level modelling of energy collection receiver but without modelling of the TOA behavior have been published in [4]. The remainder of the paper is organized as follows: in section II, the receiver component modeling is presented; in section III, the network architecture is presented; in section IV, we present two TOA algorithms, the threshold-crossing (TC) and maximum selection (MAX) algorithm as well the implementation structure of the MAX algorithm into IR-UWB non-coherent receivers. The IR-UWB non-coherent transceiver architecture is presented in section V. In section VI, we present a performance comparison between the TC and MAX algorithms and the simulation results of the RF receiver chain. Concluding remarks are given in section VII.

II. RECEIVER MODELLING
The system level design of the UWB IR receivers must be fast and accurate in order to be useful. In the open literature, there are many published results for evaluation of the front-end performance of a communication receiver. In the case of IR based UWB receivers, the simulation can take more time due to the large bandwidth of the signal of interest. Standard integration tools such as SPICE are very time consuming because of the small time step sizes required to accurately model the wide bandwidth signals. The speedup in the performance evaluation of the receiving system can be achieved by using dedicated algorithms that exploit the receiver properties and by making approximations wherever possible. The UWB IR transceiver architecture with TOA capabilities is presented in Figure 1, where IF and BBA are the filtering and baseband amplifiers, respectively. In our simulation we use a M-PPM modulation while the receiver utilizes N integrators, evenly spaced over the symbol period, to detect the received energy in N time subslots as shown in equation 1. For more details the reader is kindly asked to refer to the review work [1] and
The main advantage of using a behavioral description language is to "hide" the underlying implementation details. In our paper, each receiver component is modeled with Cadence tools, using verilogA language, and takes into account the most important properties of the components as shown in Table 1. The main advantage of using a behavioral description language is that the simulation details of the receiver components may not be known. So, we need to describe the behavior of the receiver components and not just the structure. In our paper we propose a two-stage approach for fast timing acquisition is used in order to obtain the time-of-arrival of the desired signal. First, a coarse synchronization stage is implemented to obtain the estimated position or area of the energy clusters of the received signal without knowing the position of the peak of the particular cluster. The objective of the fine synchronization is to locate the peak energy and collect the energy for that integration window. The fine synchronization is done with the same set of integrators that are used on the coarse synchronization process. This will therefore reduce the hardware complexity of the tag. The main differences between ranging and fine synchronization are as following: the ranging require knowledge of the first energy cluster which is assumed to contain the first path required for delay estimation while synchronization requires knowledge of as many clusters as possible since maximum energy collection is used. The fine synchronization stage is implemented by placing \( N \) integration windows within the coarsely synchronized windows. In this way the searching process of starting point of the cluster will be more refined. If the first stage search is successful, the coarse TOA estimate will satisfy:

\[
\tau_0 - T_{int} \leq \tau \leq \tau_0 + T_{int}/2
\]

where \( \tau \) is the estimated delay, \( \tau_0 \) is the optimal estimated delay and \( T_{int} \) is the integration time interval.

### IV. Energy-Collection Based TOA Estimation

TOA stands out as one of the most suitable signal parameter to be used for positioning with UWB IR based radios. However, due to the ultra short (usually sub-nanosecond) pulses, it poses challenges for synchronization in UWB systems. In order to further reduce the complexity of UWB systems, non-coherent receivers using energy collection and transmitted reference based [5] have recently been proposed. We will first provide a detailed description of the energy collection based approach. A two-stage TOA estimation scheme will then be presented. TOA estimation can also be performed using energy detection structures such as the non-coherent IR UWB receiver architecture published in [1] and references therein. Each one of the integrator’s bank integrates the squared symbol for a fraction \( T_{int} \) of one symbol period \( T_s \) as shown in figure 2.

A search is performed over one symbol duration, then the first integrator starts integration at a chosen time point while each of the other integrators begins integration after a delay of \( T_{int} \) compared to its preceding integrator. The starting time point of the integrator whose output is the maximum among all the integrators provides a coarse TOA estimate. The difference between the starting time point of the integrator whose output
is the maximum among all the integrators and the chosen starting point of the first integrator is denoted as the time error $T_{err}$. After initial synchronization is completed, the TOA estimation is performed by dividing the uncertainty region ($T_u$) around the synchronization point into $N$ integration windows, where $N$ represents the number of integrators available in the receiver. The TOA estimation accuracy is dependent on the uncertainty region size and on the number of integrators. TOA estimation is a fine synchronization process searching for the arrival time of the received signal. Based on the channel energy measurements, a decision is made according to a chosen criterion. For example, a threshold crossing (TC) criterion can be used. With TC, the search is performed serially and is stopped once an integrator value crosses the threshold. The corresponding window is then chosen and its starting point provides the TOA information.

The TC algorithm requires the setting of a threshold. The integrator position which gave a value over the threshold will be saved in a list. A possible implementation of the threshold crossing algorithm is presented in Figure 5. In the mixed criterion between MAX and TC, the maximal measurement is first obtained. Then, the maximum is examined against the threshold. If the threshold is crossed, the related integration window is selected. If the maximum does not cross the threshold, the search resumes. The other approach is the maximum selection (MAX) criterion.

With this criterion, measurements at all windows are first compared. Then, the maximal measurement is produced and the relevant window is selected. In the event that no appropriate thresholds can be readily obtained, the MAX criterion could be desirable. The TOA MAX algorithm implementation structure of the non-coherent receiver is presented in Figure 4. Following, we will describe the basic functionality of the TOA implementation structure: first the capacitor $C$ is reset (R is active), then the output of first integrator (INTEGRATOR1) is fed into the comparator. If the INTEGRATOR1 output is bigger than the voltage across $C$, then the capacitor $C$ will be loaded (LOAD is active) with the output voltage of INTEGRATOR1, otherwise it does not change value (LOAD inactive). The same decision process as described above is applied to the rest of the integrators INTEGRATORSi, i=2,...,N. The integrator position which gives the maximum value among all the N integrators, will be send to baseband as the TOA estimate. The timing signals $T_1, T_2, T_N$ in Figure 4 denotes the integration windows of all N integrators.

V. TRANSCIEVER ARCHITECTURE

The architecture for the IR-UWB tag transceiver as well as details of modulation type is presented in [1] and references therein. The transmitted signal for one user of interest is given by equation (3):

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} (c_p)_j w_{TR} (t - kT_b - jT_c - \delta d_k), \quad (3)$$

where $(c_p)_j$ is the $j$-th chip of the pseudo-random (PR) code, $w_{TR}$ is the transmitted pulse with pulse width $T_p = 750$ps, $T_b$ is the symbol interval, $T_c = NT_p$ with $N \in \mathbb{Z}$ is the chip interval and $\delta = 120$ns is the delay used to distinguish different transmit symbols $d_k \in [0, 1]$. The received signal after the receiver
The signals after the LNA, square mixer and first integrator are presented in Figure 7. The performances of the TC and MAX algorithms are compared in terms of TOA estimation. Simulations are performed utilizing the Saleh Valenzuela channel model 3 (CM3) and channel model 4 (CM4) as defined in the IEEE 802.15.4a standard for indoor office environment. CM3 includes a line-of-sight (LOS) path (corresponding to the shortest time of arrival) in all channel realizations, but this first path is not always the strongest in the whole impulse response. Perfect synchronization between transmitter and receiver clocks is assumed. The simulation parameters are as follows: $T_{acc} = 7.5 \, \text{ns}$, $T_b = 5 \, \text{ns}$, which implies $T_s = 20 \, \text{ns}$. $T_{err}$ is a random number to the interval. The number of integrators is considered to be 5, 10, and 20, respectively defining the integration windows $T_{int}$ of 4, 2, and 1 ns. For the TC algorithm the threshold is set using several integration values obtained in the integration window $T_{int}$ when only noise is present. Both algorithms benefit from an augmented number of integrators reducing the probability of underestimating the delay. On the other hand the increase in number of integrators produce a slight increase of the probability to over estimate the delay.

### Table 1: LNA, Gilbert, Integrator Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LNA</th>
<th>Gilbert</th>
<th>Integrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Gain</td>
<td>15dB</td>
<td>10dB</td>
<td>1mS</td>
</tr>
<tr>
<td>IP3</td>
<td>-10dBm</td>
<td>5dBm</td>
<td>-</td>
</tr>
<tr>
<td>Zin</td>
<td>50ohm</td>
<td>50ohm</td>
<td>1Mohm</td>
</tr>
<tr>
<td>Zout</td>
<td>50ohm</td>
<td>200ohm</td>
<td>0.1Mohm</td>
</tr>
</tbody>
</table>

We noticed from figures 5 and 6 that, passing from 5 to 10 integrators brings to a substantial improvement of the TOA error distribution profile. This improvement is more evident for TC then MAX algorithm. An increase in the number of integrators...
VII. CONCLUSIONS

This paper has examined non-coherent structures for UWB systems. Two different TOA algorithms, TC and MAX, have been considered and compared in CM3 and CM4 channel models. The receiver components have been described in verilogA language with Cadence tools and their simulation parameters have been presented. Behavioral simulations of the receiver decrease dramatically the simulation time when compared with classic schematic simulations while providing useful insights into the system/circuit level tradeoffs. With accurate threshold setting and high SNR, the TC algorithm outperforms the MAX algorithm. The TC algorithm however has relatively high levels of missed detection for low SNR values. The MAX algorithm appears to be more robust to SNR value changes. The implementation structures of MAX and TC algorithms have been presented. In terms of circuit complexity TC algorithm is more difficult to implement since it requires a noise estimation block while MAX algorithm contains more decision logic circuits in its architecture.

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REFERENCES


