

Low Complexity Low Data Rate UWB Devices – Architecture and Performance Comparison

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Abstract—In this work the performance of low data rate Ultra-Wideband (UWB) devices is studied. The most important design constraint is low complexity and low power consumption. Four different architectures of different complexity are built in a modular approach from functional blocks. The trade-offs of these architectures between performance and complexity are shown.

I. INTRODUCTION

In the last years Ultra Wideband (UWB) technology has made its way from an exotic research field to an important approach and is seen as one of the key technologies of the next decade. Introductions to UWB can be found in [1]–[3]. One of the main application areas are low data rate (LDR) devices. The main focus of LDR devices is low complexity, low power consumption and low cost. Those devices work well below the optimum BER but can be built very cheap in large numbers. We propose a modular approach when considering the design of those suboptimal UWB devices. The idea is to investigate a number of physical layer techniques for each kernel component (modules) of the devices, ranging from high to low complexity, corresponding with high to low performance. All considerations are based on pulse based devices because other UWB systems such as multi-band OFDM, Direct Sequence Spread Spectrum or pulsed multi-band UWB require more complexity and are better suited to HDR applications.

The goal of this paper is to study the trade-offs in the physical layer between hardware complexity and power consumption on the one hand and performance on the other hand. The aim of this work is not to find the optimal solution but the best possible solutions for a given hardware complexity.

The LDR UWB devices should cover a wide range of application scenarios and data rates currently applicable and also prepare the pathway for future applications with data rates from 100 bit/s to 11 Mbit/s. The possible scenarios include but are not limited to Sensor Positioning and Identification Networks (SPIN), Wireless Outdoor Sensor Networks (OSN), Wireless Body Area Networks (WBAN), Wireless Indoor Tags Networks (WITN) and Wireless Personal Area Networks (WPAN). Both high-density network topologies (IWAN, SPIN, OSN, WITN) and low-density topologies (WBAN, WPAN) are in the focus.

Section II outlines the different investigated modules for every function of the transceiver. From every functional part one module is chosen for each of the architecture presented in

section III. In section IV these architectures are studied and compared by simulation. It is shown that performance can easily be exchanged against complexity and cost.

II. INVESTIGATED HARDWARE BLOCKS WITH LOW/MEDIUM COMPLEXITY

A. Modulation

The most common impulse radio UWB concepts are based on pulse position modulation with time hopping (TH-PPM). The transmitted information is associated to the instant in time, where the pulse is transmitted and there is no need for phase reference in PPM-based system. Consequently the detection at the receiver-end can be done non-coherently. In TH-PPM systems, a nominal pulse transmission instant is randomly defined by the user dependent pseudorandom code. The result is a higher degree of complexity. As mentioned earlier the phase reference is not required but synchronization is important for time-based systems and therefore the complexity of the synchronizer is expected to be high.

A reduced-complexity alternative will be an M -ary PPM system where the transmission instant is delayed or advanced. The complexity is greatly reduced and the requirements at the receiver-end are expected to be lower than using a time hopping scheme. Two M -ary PPM schemes are selected for low complexity systems with $M=2$ and $M=4$.

BPSK or polarity modulation (BPAM) are more possible alternative modulation schemes for low complexity systems. The complexity level is similar to that of PPM except for the need to alternate the polarity of the pulses. However, a simple non-coherent energy detector will not be able to demodulate BPAM; knowledge of the phase of the signal (pulse polarity) is necessary, and thus a coherent receiver is required in this case. Finally, the simplest alternative will be by using OOK where the complexity at the receiver-end will be of low complexity as well.

Coherent systems provide more information about the received signal, which enables the performance to be better than the performance of non-coherent systems. However, the loss in performance gives rise in the reduced-complexity and cost of the receiver structure.

Table I displays the complexity level of the modulation schemes for non-coherent modulation schemes. The complexity of the modulation will directly affect the complexity of the

TABLE I
MODULATION COMPLEXITY REQUIREMENTS

Type	Modulation	Complexity
non-coherent	4-PPM	high
	2-PPM	medium
	OOK	low

demodulation. The decision on which modulation schemes to use lies in the complexity and the performance required.

B. Detection

In LDR UWB systems, complexity and cost are two important issues that need to be taken into consideration whenever making a decision of the technique to be used. This was exactly the reason why the coherent solutions are ruled out. In non-coherent communication systems, the channel estimation is based only on amplitude estimation. There are several demodulation or detection techniques that could be implemented, such as a simple Energy Detection technique and various variants of RAKE-based receivers [4].

One of the practical rake receiver implementation that can reduce the complexity of detection is using a Selective Rake Receiver (S-RAKE). The S-rake uses only a number of strongest propagation paths (N) and, therefore, knowledge of the channel impulse response is required. Channel estimation algorithms must be used to obtain this information. The SNR is maximized for the given number of paths when the strongest paths are detected. Therefore, the link performance will be improved relative to the single path receiver. The complexity of the S-RAKE receiver is greatly reduced relative to the complete RAKE receiver by selecting only those multipath components which have significant magnitude. The principle is illustrated on Figure 1 for $N = 4$. A simplified version of RAKE receiver is partial (P-) RAKE receiver. The principle behind this approach is that several first multipath components (Figure 1) will typically be the strongest and contain the largest portion of received signal power. This is not necessarily true since it is possible that later paths carry more energy as the first ones and optimal performance can not be achieved for given number of paths with this type of receiver. The very big advantage is that there is no need for channel estimation with the P-RAKE receiver.

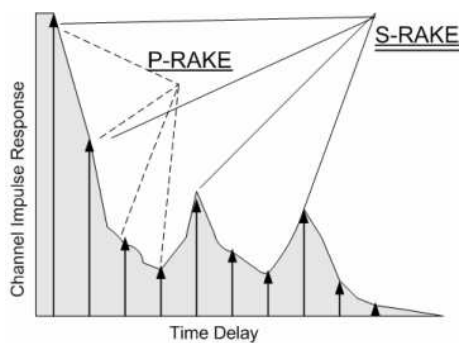


Fig. 1. Channel delay profile and principles of S- and P-RAKE receivers

The figure indicates that there are stronger multipath components at greater delays than those which have been combined by the P-RAKE receiver. The P-RAKE is of reduced complexity compared to the S-RAKE as it does not have selection diversity. P-RAKE does not require full channel estimation. The performance of the P-RAKE is greatly dependent on the delay spread of the channel as well as the number of taps used. The complexity of the detection scheme is dependent on the number of taps used and the type of combining techniques implemented. The lowest complexity solution can simply be implemented using a single tap P-RAKE. This solution has the lowest hardware requirements. The performance of this solution can be improved by varying the size of the integration window. An adaptive system always increases the complexity of the system and, therefore, an optimal window size has to be implemented.

When using diversity receiver techniques an equal gain combining (EGC) can be utilized in non-coherent fashion. In EGC, the energy received from all different taps is equally weighted and non-coherently added to produce a decision variable before the detector.

Maximum ratio combining (MRC) requires the knowledge about the amplitude and phase of the received signal. Non-coherent methods are based only on amplitude information and, therefore, exclude the phase information. MRC can be done non-coherently by adding weights to the different Rake taps based on the amplitude value. The received signal from the RAKE taps having energy above a defined threshold will have more contribution in the detector than the signal coming from the taps adjusted to the weaker propagation path.

C. Channel Coding

The channel coding provides two basic methods to transfer information with a minimum of errors. Redundancy will be added to the information in order to detect and if possible to correct any errors introduced during transmission. One method is the *forward error correction* (FEC). The redundancy is used to detect and possibly correct transmission errors. Table II displays the FEC algorithms chosen for low complexity devices.

TABLE II
CHANNEL CODING COMPLEXITY REQUIREMENTS

Channel Coding	Parameter	Decoder	Complexity
Convolutional ($G = (133, 171)$)	$R = 1/2, L = 7$ $n = 1, k = 2$	Viterbi	high
Reed Solomon ($RS(255, 127)$)	$R = 1/2$ $n = 1016, k = 2040$	Berlekamp-Massey	high-medium
Reed Muller ($RM(3, 7)$)	$R = 1/2$ $n = 64, k = 128$	L-GMC $L = 3$	medium-low
Repetition (Barker-Sequence)	$R = 1/11$ '0':-----+---+ '1':++++-----+	Summation	low

1) *Repetition Codes*: The simplest way of error correction is to repeat a codeword n -times. Instead of the original code $S = \{0; 1\}$ a new code $S = \{\text{sequence}_0; \text{sequence}_1\}$ will be sent, which is called *repetition code*. For device 1 a repetition

code is chosen which consists of a binary Barker sequence [5] of length 11.

2) *Reed Muller Codes*: A more powerful channel code is the Reed Muller Code [6]. Device 2 uses a Reed Muller Code and a L-GMC (*List-Generalized Multiple Concatenated*) decoder [7].

3) *Reed-Solomon Codes*: The Reed-Solomon Code is an algebraic code belonging to the class of BCH (*Bose-Chaudry-Hocquehen*) multiple burst correcting cyclic codes. The Reed Solomon code operates on m -bit symbols of fixed length. Device 3 uses a Reed Solomon encoder. The decoder based on the Berlekamp-Massey decoding algorithm [8] [9].

4) *Convolutional Codes*: Convolutional codes are generally more complicated than linear block codes but have powerful error correcting capabilities. They are encoded using finite state machines that have branching paths for encoding each bit in the data sequence. A well-known process for decoding convolutional codes is the Viterbi Algorithm. Device 4 uses a convolutional encoder and a Viterbi decoder [4].

D. Synchronization

A system based on non-coherent receiver is defined as a system where the signal phase (in the case of impulse UWB, this reduces to the polarity of the signal) is not necessary for demodulation. The modulation types like OOK or PPM are suitable for such demodulation scheme.

For incoherent reception two main receiver structures can be distinguished: the Rake receiver and the energy detection receiver. Both systems require a more or less specific synchronization algorithm.

At the receiving end of the UWB communication system, the receiver synchronization process determines the optimal position in time, where the RF front-end should be placed. In the case of non-coherent systems, the receiver is based on energy detection [10]. The synchronization process will also determine where the fingers of the RAKE shall be placed in order to ensure optimum energy collection.

Synchronization is also important for ranging applications where delay estimation is done. The precision of the synchronization of the first path will enable more accurate delay estimation. This synchronization proposal will address receiver synchronization for both data and ranging scenarios. This process is illustrated on Figure 2.

The receiver synchronization process can be divided into two sub-processes: coarse synchronization 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. This is done by placing series of integration windows within the pulse repetition period (PRP). The energy collected by the window will be compared with a threshold and windows with energy greater than the threshold will be further synchronized with then next sub-process of Fine synchronization. Fine synchronization is implemented to the selected integration windows where the energy collected is above the threshold. These integration windows will be moved with a time step in order to fine-tune the synchronization process. The objective of this sub-process is to locate the

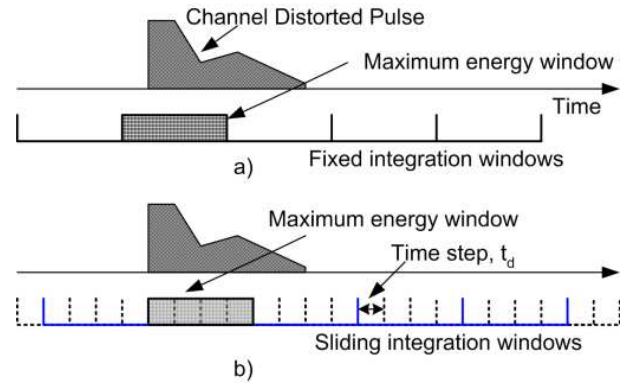


Fig. 2. a) Coarse synchronization b) Fine synchronization process illustration

peak energy and enable maximum energy collection for the particular integration window.

E. Channel Estimation

In the proposed architecture, channel estimation is restricted to a minimum. Advanced techniques like channel tracking and channel equalization are not used. The main reasons for this are:

- The device has to be low complex, low cost, low power consuming which is opposed to advanced channel equalization techniques.
- The channel in our scenarios is assumed to have a large coherence time (slowly moving), thus techniques for fast changing mobile channels are not necessary.
- In non-coherent detection an exact knowledge of the channel is not required, only a rough knowledge to capture most of the signal energy is needed.

1) *High Complexity Solution*: The suggested high complexity solution estimates the whole channel impulse response and selects the strongest paths which are then used as RAKE fingers. For non-coherent demodulation the channel estimation is less complex than for coherent demodulation. Instead of a correlation only an energy integration is needed. In addition, only the amplitude and delay of the strongest paths is passed to the S-RAKE. The receiver does not need the exact delay of every path, instead the delays for which large amounts of energy of the received pulses can be detected are needed. One finger can deal with several paths as long as their delays are close together, because only the collected energy and not the pulse shape is used in the receiver.

If different finger results are combined without different weighting of the taps (EGC), the performance can become worse for a higher number of tabs because the noise energy becomes larger. Using channel estimation the S-RAKE can weight different integration windows with the estimated channel amplitudes (MRC). Therefore, paths with a low amplitude (which causes a low SNR in this path) are weighted with a low amplitude and do not degrade the performance. Instead of an optimal number of tabs the performance with an increasing number of fingers converges against the performance of an A-RAKE. The highest possible time resolution of the channel

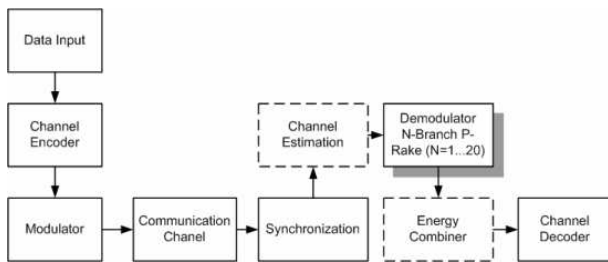


Fig. 3. Common system block diagram for proposed architectures

estimation is one pulse length. If the resolution of the channel estimation is decreased, the complexity of the receiver is lowered, but the performance also decreases.

2) *Medium Complexity Solution:* For the medium complexity solution, channel estimation is done for the P-RAKE. Instead of the whole channel impulse response only the first part of the channel impulse response is estimated which contains typically most of the signal energy. Since the complexity of the channel estimation increases linearly with length of the estimated channel impulse response this decreases the complexity compared to the high complexity solution. Instead of selecting the strongest paths all values are passed to the RAKE receiver. The performance loss compared to the high complexity solution with the same number of passed RAKE fingers depends on the channel characteristics. Especially in the case where the density of arriving multipath compared to resolution of the estimated channel is low, there exist many fingers with nearly zero energy which degrades the performance of a P-RAKE.

3) *Low Complexity Solution:* The simplest solution for channel estimation is the estimation of the delay and the amplitude of the strongest path. Since the estimation of amplitude and delay can be interpreted as synchronization, a low complexity solution would work without any channel estimation. The performance loss compared to the high and medium complexity solution increases with the amount of energy in the delayed paths.

III. ARCHITECTURES

The proposal of system architectures requires the understanding and the evaluation of different components and their individual complexity. Four initial architectures are made and their common system block diagram is given on Figure 3. Since the entire process of down-selecting the architectures requires to satisfy different scenario demands regarding system performance, several architectures are needed to be analyzed for complete investigation.

Table III gives a summary of the main components used in configuring these devices.

Device 1 is considered as suitable for low cost LDR applications for low power sensor applications. The device 2 supports a class of LDR applications supporting localization and tracking, while the Device 3 is intended for higher data rate applications with LT capability. The Device 4 is intended to provide the highest data rate of up to 11 Mb/s.

TABLE III
SIMULATED DEVICE MAIN FEATURES

Device Type	1	2	3	4
Modulation	OOK	OOK	2-PPM	4-PPM
Energy Combining	-	-	EGC	MRC
Number of Taps	1	1	8	20
Synchronization	Coarse	Coarse/ Fine	Coarse/ Fine	Coarse/ Fine
Channel code	Repetition	Reed- Muller	Reed- Solomon	Convolutional

IV. RESULTS AND ANALYSIS

Figure 4 shows the simulated performance of the devices from section III. The four different channel model parameter set recommendations from the IEEE 802.15 3a Task Group [11] were used. Device 1 has an extremely low complexity resulting in a poor performance. This device is recommended for extremely cheap battery powered tags with a very low data rate. With device 1 it is easy possible to exchange data rate against performance and range by changing the length of the Barker code. The increase in the number of used integrators worsens the performance of the system, especially in channel model 2 to 4. The reason is that for 8 integrators the integration time becomes longer which enlarges the collected signal energy in a single tap RAKE. Device 1 can be used for scenarios where there are high cost and complexity constraints, for example in Sensor Positioning and Identification Networks and Wireless Indoor Tag Networks. These scenarios are implemented in a centralized network structure where all signal processing should be done in the master device.

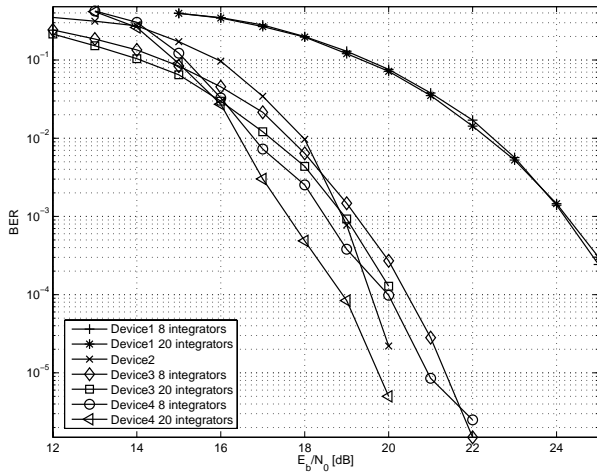
Device 2 performs relatively poor for low E_b/N_0 , but relatively good for high E_b/N_0 . Especially in a bad channel it does not have to deal with error floors.

Device 3 performs generally better in most cases especially in better channel conditions compared to device 1 and 2 but the performance deteriorates when the channel worsens (CM3 and CM4). In contrast to device 1 and 2, the increase in the number of taps improves the performance of the system. The reason is that the RAKE selects the optimum number of active taps, which can be done more efficient by 20 taps than with 8 taps. These two devices are proposed for scenarios where a higher data rate is required and where a lower cost restriction is given.

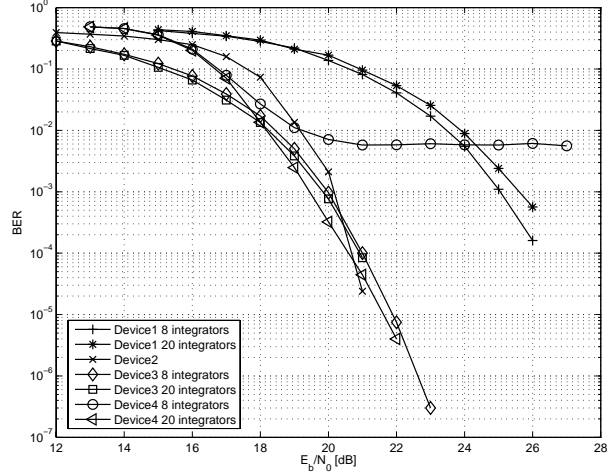
Device 4 provides the highest possible data rate under the given boundary conditions (low cost, low complexity devices). However, this data rate mode only works in good channels (either LOS or a distance of less than 4 m). Thus, this device always needs a fall back mode with a lower data rate (e.g., 2PPM instead of 4PPM or channel codes with a lower code rate). Device 4 can be used for scenarios where a moderate data rate is needed and the price per unit is not too restrictive (e.g., Wireless Body Area Networks).

V. CONCLUSION

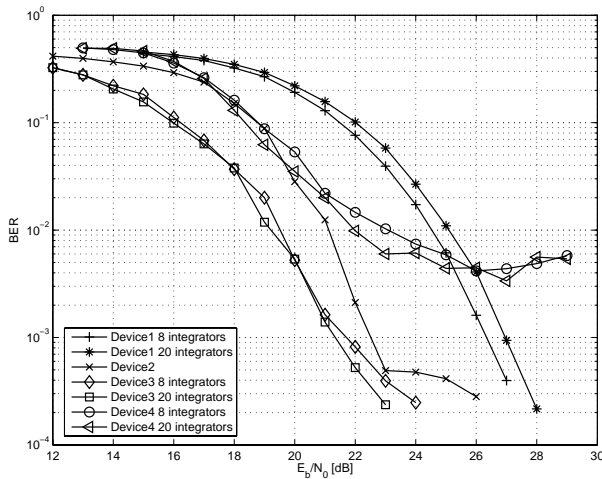
This work showed the performance of low data rate devices of different complexity. For every functional part of



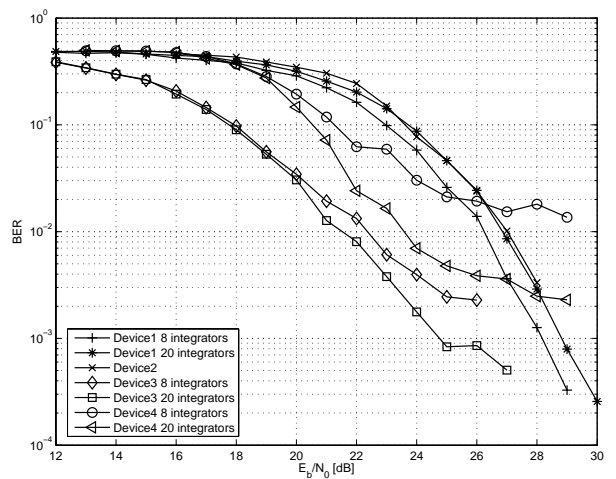
(a) channel model 1



(b) channel model 2



(c) channel model 3



(d) channel model 4

Fig. 4. Comparison between the devices in table III in different channel scenarios

a transceiver structure several candidate blocks of different complexity were considered. The four final architectures were chosen as a combination of block sets. The trade-off between complexity, cost and power consumption on one hand and performance, data rate and range on the other hand was shown.

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