A UWB Radio Testbed-System Design and Implementation

Nan Guo, John Qiang Zhang and Robert C. Qiu.

Abstract—This paper outlines an ongoing ultra-wideband (UWB) testbed project and discusses design and implementation issues. The project is motivated by the need for low-complexity UWB transceivers for a wide range of applications, and by the intention to study and validate new concepts/ideas on a practical platform. The testbed is built using off-the-shelf components and is designed to be flexible enough to accommodate a number of features/functions. For the baseline testbed, energy detection is chosen as a low-complexity reception technique which eliminates the need for channel estimation and precise synchronization. Key items associated with system design and prototyping, such as pulse generator and initial timing acquisition, etc., are discussed. Board level design and implementation issues, including several challenging ones such as automatic gain control (AGC), high-speed analog-to-digital (A/D) converter, and adaptive thresholding, are reported. In addition, further work to advance the testbed is highlighted in the paper.

Index Terms: Ultra-wideband (UWB), testbed, system design, radio frequency (RF).

I. INTRODUCTION

Ultra-wideband (UWB) radio is a rapidly evolving technology for short to medium range communications and positioning applications. A UWB communication system can be viewed as any communication system whose instantaneous bandwidth is many times greater than the minimum required to convey a specific data rate. The very first UWB system might be the Marconi Spark Gap Emitter built in 1876. In the past 40 years, advances of electronics and UWB signal theory have enabled practical UWB system designs. IEEE 802.15.4a applications include medium rate (up to 1Mbps) communications at 100 meters distance, and positioning feature with one foot level accuracy. UWB radio does have a few advantages over other conventional systems: large bandwidth, or equivalently fine time resolution, precise imaging and positioning; short pulses prevent from strong signal fading; low transmitter power and very wide bandwidths allow coexistence with other systems, and provide covert communication feature and low probability of intercept (LPI). UWB radio has found a new range of applications, including medical applications (monitoring of patients), family communications/supervision of children, search-and-rescue (communications with fire fighters, or avalanche/earthquake victims), control of home multimedia applications, logistics (package tracking), security applications (localizing authorized persons in high-security areas), and military applications.

In 2002 the Federal Communication Commission (FCC) allocated limited use of a huge chunk of spectrum between 3.1 GHz and 10.6 GHz to allow UWB systems overlaying over existing narrow-band systems. Since then the tremendous potential has triggered great interest in both academia and industry [1]-[16]. Industrial standards such as IEEE 802.15.3a (for high data rate) and IEEE 802.15.4a (for low data rate with ranging) using UWB band have been introduced. Among many proposed UWB systems for IEEE 8092.15.3a are two major proposals: the Multi-Band OFDM Alliance (MBOA) proposal and the direct-sequence UWB (DS-UWB) proposal. The MBOA system employs orthogonal frequency-division multiplexing (OFDM) modulation to solve the severe multipath problem. On the other hand, the DS-UWB system uses direct-sequence spread-spectrum technology and relies on the RAKE receiver to capture signal energy dispersed over a large number of paths. The both systems may give high performance, but they are not low-cost solutions at present.

In contrast, suboptimal alternatives targeting at low-cost wireless applications, such as sensor networks, have received great attention [1]-[7]. The price point will be in the sub-$1 range for asset tracking and tagging, up to $3 to $4 per node for industrial-control applications. These suboptimal solutions include transmitted reference (TR) [1]-[4] and energy detection using a square law detector [5]-[7].

To research these new concepts unique to UWB, theoretical and simulation approaches are not sufficient. It is desired to use experimental ways to test schemes and algorithms, verify theoretical and simulation results, and remove some uncertainties caused by channels, hardware and software. A testbed would be very convenient to evaluate the pros and cons of some specific system aspects, such as modulation schemes, receiver structures, and the analog-to-digital (A/D) converter, etc. In particular, the experimental approach is usually the only effective means to find the actual impacts of radio frequency (RF) circuits, including antennas.

As part of the research effort in UWB communications and ranging, a UWB testbed project supported in part by the DoD DURIP grant was conducted recently in Tennessee Technological University. In this paper our baseline testbed work is briefly reported. Essential tasks of the testbed project include: (1) theoretical investigation of the receiver performance; (2) system design; (3) board level design; (4) implementation; and (5) test and validation. Major contributions of this paper are two-fold:

1) Key issues associated with system design and prototyping are discussed;

2) Board level design and implementation work is reported.
The paper is organized as follows. In Section II a list of major system design considerations are presented. Section III reports baseline testbed prototyping. Advanced features to add to the testbed are discussed in Section IV, followed by some remarks in Section V.

II. MAJOR SYSTEM DESIGN CONSIDERATIONS

Implementing UWB transmitters and receivers poses a number of challenges. The difficulties mainly come from generating, transmitting and processing the very high-bandwidth signal. Major design considerations are discussed in this section.

A. Pulse Generator

Because of the minimum bandwidth requirement (-10 dB bandwidth greater than 500 MHz or -10 dB fractional bandwidth greater than 20%) and the Part 15 power limit (maximum equivalent isotropic radiated power spectrum density of -41.25 dBm/MHz), efficient use of a piece of UWB spectrum is a big challenge. The MBOA system relies on multiple subcarriers to achieve desired overall signal spectrum. On the other hand, pulse based UWB schemes are attractive for low-cost low-data-rate communication and ranging applications. The spectral content of pulse waveforms is highly dependent on the shape of the pulse generated, which makes pulse design more challenging. There have been a number of proposals of pulse generators. A simple way is to upconvert a baseband pulse to an RF center frequency. It has been proposed to use root raised cosine baseband (RRC) pulse shape for the DS-UWB system.

B. Modulation Schemes and Receiver Strategies

A direct consequence of a high-bandwidth UWB signal is ultra fine multipath delay resolution in multipath propagation environments. Theoretically, to efficiently capture the signal energy dispersed over a large number of individual paths, either a RAKE receiver scheme or an OFDM scheme can provide high performance, given perfect synchronization and channel estimation. Realistically, a RAKE receiver with tens of fingers is infeasible, and both schemes mentioned above are financially improper for low-cost low-data-rate applications. There is a huge potential market for these lower-end applications, such as sensor networks. In response to this need, several suboptimal receiver schemes, including TR and energy detection using a square law detector, have regained popularity in the UWB community [1]-[7]. Although both TR and energy detection suffer from performance penalty, they have no need for sophisticated channel estimation and precise synchronization, which significantly reduces receiver complexity and cost. On-off keying (OOK) modulation and energy detection is indeed a reasonable combination. Received signal energy can be captured easily using a diode (square law) detector followed by an integrator, and OOK works fine if the data symbol boundary is roughly known and inter-symbol-interference (ISI) is negligible. Pulse position modulation (PPM) is another popular modulation for pulse based UWB systems, and high order PPM or called M-ary PPM is promising to work with channel coding to achieve wide range of scalability.

C. Synchronization

Synchronization is a common issue for all types of communication systems and there have been many proposed strategies for initial timing acquisition and tracking during communication. For pulse based UWB radio, signal acquisition is extremely difficult since the pulses are often very narrow (say, 1 ns) and run at very low duty cycles. Timing is relaxed for demodulating signal of OOK format, but at least symbol boundary has to be roughly known. Energy detection employed in our testbed is one of non-coherent demodulation schemes which are not able to identify signal polarity. One challenge for any non-coherent receiver is that initial acquisition has to rely on a uni-polar sequence (e.g., the Baker code) whose autocorrelation is typically less sharp than that of a bi-polar sequence (e.g., the m-sequence). It has been found that in multipath case the uni-polar sequence works poorly, especially when ISI occurs. In addition, non-zero-mean noise at the output of the detector, an inherited disadvantage of a non-coherent receiver, makes decision more difficult. To ensure acceptable probability of detection given certain probability of false alarm, the search needs longer time compared to the approaches for conventional systems. Some commonly used search strategies, such as multi-stage search [11], can be adopted to improve acquisition performance.

D. Other Issues

1) Co-existence and anti-interference: The UWB spectrum is shared with other systems and one major problem is the mutual interference between the UWB and WiFi systems. From a point of view of physical layer design, traditional countermeasures to achieve capability of co-existence and anti-interference include spread spectrum and interference cancellation. For non-coherent receivers, frequency hopping (FH, one of spread spectrum techniques) can be considered, where the mutual interference is reduced by a factor of the processing gain. Notch filter is another effective means which is simpler but less flexible than FH.

2) Spectral Spikes: This is a problem unique for OOK and PPM modulation schemes. Owing to unbalanced modulation, lines would appear over the spectrum of the RF signal. Without proper means to reduce the spectral spikes, signal power has to be backed up to prevent from violating the FCC power limit. Pseudonoise (PN) code scrambling is a normal way to balance the signal in time domain statistically and smooth the spectrum. The scrambling method can be in the manner of direct-sequence spread-spectrum (DS/SS) or time hopping (TH).

3) Multiple User Access: Carrier sense multiple access/collision detection (CSMA/CD) is a popular random multiple access protocol that is suitable for a network with relatively low traffic load. Other candidates include pulling, code division multiple access (CDMA), and hybrid protocols. Recently a rate division multiple access (RDMA) scheme
that takes advantage of low duty cycle of pulse based UWB signaling was proposed [12]. Because of the low duty cycle manner, users with different transmit rates can be supported at low probability of collision.

4) Adaptive threshold: the decision threshold has a great impact on the performance of the energy detection receiver. A good threshold can be determined by using some channel quality indicator and feedback information provided by the digital processor (back-end) at the receiver.

5) Data Format and Scalability: Research has showed that the UWB channels are relatively stable compared to narrow band channels, which implies that a large packet with limited control bits in the head followed by pure information bits can be used. Scalability is highly desired since application and propagation environment change dynamically. A wide range of data rates need to be supported through using different combinations of modulation, channel coding and spread spectrum.

III. PROTOTYPING

The main goal is to build a pair of concept-proof transmitter and receiver to test and verify various schemes. The testbed is expected to be flexible enough to accommodate several major transmission and reception techniques. The strategy is to develop the testbed based on our latest research work and use commercially available off-the-shelf components to expedite the project.

A. Baseline System Design

The baseline testbed is expected to accommodate the following functions/capabilities: (1) efficient pulse generation methods; (2) enabling investigation of A/D technologies such as mono-bit; (3) experimental evaluation of radio RF circuitry impact; (4) different modulation schemes, OOK, PPM and PAM; (5) test of various signal processing algorithms; (6) interface with multimedia (video, audio, etc). Several specific parameters of the baseline testbed are as follows:

- Center frequency: 3.5 - 4.0 GHz
- Bandwidth: ≥ 500 MHz
- Distance: up to 30 m
- Pulse repetition frequency: up to 20 MHz

Proposed transmitter and receiver architectures are illustrated in Fig. 1. The transmitter uses an upconverter based pulse generator. The receiver relies on one or two diodes to realize square law operation. Following the diode detector is a low-pass filter which enables use of relatively lower sampling frequency. Amplifier gain and required dynamic range are key parameters that affect RF front-end design, and they can be determined with consideration of the Part 15 limit, distance range and raw data range, etc. The FPGAs serve as digital back-end playing signal processing functions. Advanced AGC and adaptive thresholding are accommodated based on digital signal processing. Several key parameters of the transmitter and receiver, such as center frequency, amplifier gain, A/D converter’s sampling rate and resolutions (from 1 to 8 bits), pulse repetition frequency (PRF) and data rate, are programmable.

Depending on the propagation environments, either the Barker code or the optical orthogonal codes (OOC) [18] are used for initial timing acquisition purpose. The OOC codes can be much longer than the Barker code (11 chips) and exhibit better autocorrelation property, which is desired for severe propagation cases.

Finally, a link budget example is shown in Table I, where 500 kbps raw bit rate, 4 GHz center frequency and 30 meters distance are assumed.

B. Board Level Design and Implementation

Board level design and implementation is guided by the system design. Some RF circuit simulations were done using PSpice before actually selecting components. Shown in Fig. 2 is the transmitted signal with central frequency of 3.5 GHz and bandwidth of 500 MHz. Illustrated in Fig. 3 is the printed circuit board (PCB) layout for the top layer of the transmitter RF board. Major issues with respect to implementation are discussed in the following.

1) Selection of Antennas: Generally, a small-size omni-directional antenna with voltage standing wave ratio (VSWR) ≤ 2 is a reasonable choice. The antennas selected are a pair of omni-directional print antennas. The antenna gain is about

![Transmitter and receiver architectures.](image-url)

**Table I. A link budget example.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw bit rate $R_b$</td>
<td>500 kbps</td>
</tr>
<tr>
<td>Average Tx power</td>
<td>-20 dBm</td>
</tr>
<tr>
<td>Tx antenna gain</td>
<td>2 dB</td>
</tr>
<tr>
<td>Center frequency</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Path loss at 1 m</td>
<td>44.48 dB</td>
</tr>
<tr>
<td>Path loss at 30 m</td>
<td>74.03 dB</td>
</tr>
<tr>
<td>Rx antenna gain</td>
<td>2 dB</td>
</tr>
<tr>
<td>Average Rx power</td>
<td>-90.03 dBm</td>
</tr>
<tr>
<td>Thermal noise power per bit</td>
<td>-117.01 dBm</td>
</tr>
<tr>
<td>Noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>Total noise power per bit</td>
<td>-110.01 dBm</td>
</tr>
<tr>
<td>Minimal required $E_b/N_0$</td>
<td>1.2 dB</td>
</tr>
<tr>
<td>Implementation loss</td>
<td>4 dB</td>
</tr>
<tr>
<td>Link margin</td>
<td>3.98 dB</td>
</tr>
<tr>
<td>Proposed minimal Rx sensitivity</td>
<td>-94.01 dBm</td>
</tr>
</tbody>
</table>
2 dBi at 4 GHz, and it exhibits a voltage standing wave ratio (VSWR) ≤ 2 for a frequency range of 3.1 - 10.0 GHz.

2) Pulse Generator: Upconverter based pulse generator is used. The baseband pulse is generated using digital logic circuitry. The width of the baseband pulse, or equivalently, the signal bandwidth, is controlled by the FPGA, and the pulse strength is adjusted to meet the mixer’s requirement. To flexibly generate a wide range of frequencies, a phase lock loop (PLL) based frequency synthesizer with an external loop filter and voltage controlled oscillator (VCO) serves as the local oscillator (LO). The frequency synthesizer can support frequency up to 6 GHz, the bandwidth of the loop filter is 50 kHz, and the averaged tuning sensitivity of the used VCO is 62 MHz/V. A double balanced mixer followed by a bandpass filter is used to shift the baseband signal to an RF signal. The designed local oscillator generates output frequencies with 10 MHz channel separation from 3.5 GHz to 4.0 GHz. Several filters are placed at the transmitter front-end to improve the overall transmitted signal spectrum.

3) Variable Gain Power Amplifier: A power amplifier in conjunction with a variable attenuator serves as the variable gain power amplifier. The overall gain is from -11 dB to +12 dB controlled by an analog signal. The control signal comes from the digital back-end through a digital-to-analog (D/A) converter with 10 bits resolution and 1.2 V reference voltage.

4) Variable Gain Low Noise Amplifier (LNA): A variable gain LNA is combined using several LNAs and a variable attenuator. The gain range is from 55 dB to 70 dB considering the desired received power range and the input voltage range required by the diode detector. The overall gain in the receiver RF chain is controlled by the digital back-end through an AGC feedback loop.

5) Programmable A/D Converter: An 8-bit monolithic bipolar A/D converter with sampling rate up to 1.5 Gbps is selected. A high-frequency clock synthesizer is used to generate the sampling clock for the A/D converter. The variable sampling rate is achieved by controlling the output frequency of the clock synthesizer. The A/D converter features an on-chip, selectable 8:16 output demultiplexer. A double-data-rate (DDR) interface implemented in FPGA connects the A/D converter to the FPGA. Although the maximal resolution is 8 bits, lower resolution can be chosen in signal processing.

6) Diode Based Square Law Detector: A surface mount schottky diode with sharp I-V slope and small capacitance is used as the square law device. Following the diode is a low-pass filter which enables use of relatively lower sampling frequency, and a baseband amplifier to interface with the A/D converter.

7) FPGA: The Xinlix Virtex-II FPGA family is considered for the digital back-ends for both of the transmitter and receiver. The Virtex-II family is a popular platform of FPGA based on IP cores and customized modules, and is suitable for wireless applications. The model selected is XC2V1000 corresponding to one million system gates which is sufficient for the testbed needs.

8) Signal Processing Algorithms: A large number of digital signal processing and controlling functions need to be implemented in the digital back-ends. Listed below are most basic functions at the transmitter and receiver.

Transmitter:
- Controller and interface
- Modulation
- Coding

Receiver:
- Controller and interface
- Synchronization
- Demodulation
- Decoding
- AGC
- Automatic thresholding

IV. ADVANCED UWB TESTBED TO DEVELOP

With experience and confidence gained from the current development of the preliminary testbed, we are moving forward to add more features to leverage the testbed. Items to consider include channel coding, spread spectrum coding, ranging algorithms, and time reversal [13]-[17].
One unique characteristic that differentiates a UWB system from a “narrow” band system is the UWB propagation channel. The UWB channel impulse response (CIR) contains a large number of resolvable components coming through different paths, especially in indoor environments. Time reversal is a signal focusing technique that can turn multipath spreading (and even ISI) into benefit. It takes advantage of rich scattering environments to achieve signal focusing both temporally and spatially. The principle follows. Consider downlink data transmission from a base station to a node. Assume the uplink and downlink channels are reciprocal [16] and both have the same CIR denoted by $h(t)$. The node first sends a pilot pulse $p_{\text{tx}}(t)$ to the base station via the uplink. If we ignore the background noise, then the base station obtains a received pilot waveform $h(t) \otimes p_{\text{tx}}(t)$, where “$\otimes$” denotes convolution operation. A prefilter whose impulse response is a time-reversed version of the estimated pilot waveform is placed at the base station transmitter. Finally the base station transmitter sends the data via an equivalent downlink channel consisting of the prefilter and the actual propagation channel.

An equivalent channel would have an impulse response $h_e(t) = p_{\text{tx}}(-t) \otimes [h(-t) \otimes h(t)]$. Due to the random-like $h(t)$, the equivalent CIR $h_e(t)$ has a sharp profile. Since this equivalent CIR is location-dependent, the transmitted signal is concentrated in time at an intended location, but is widely dispersed in time at other locations. This location-dependent profile sharpness is also called spatial focusing. Time reversal is promising for low-cost applications since it shifts part of receiver complexity burden to the transmitter side. In addition, a sharpened signal would enable narrow-window integration that reduces noise accumulation without remarkably affecting signal energy collection, which is greatly in favor of some low-complexity suboptimal receivers, such as the energy detection receiver.

Implementing UWB time reversal is very challenging. The difficult parts include a prefilter and a waveform estimator. According to our research [16], the complexity of the prefilter can be greatly reduced, so that implementing the prefilter using FPGA becomes possible. Waveform estimation is the key to UWB radio with time reversal enhancement. Further investigation is necessary to design a feasible and effective waveform estimator.

V. SUMMARY

Ongoing work on a UWB testbed project has been outlined. The project is motivated by the need for low-complexity UWB transceivers. A pair of transmitter and receiver is building using commercially available off-the-shelf components. The RF front-ends can be digitally controlled by setting a few key parameters. Digital signal processing relies on FPGA chips. The testbed is flexible to accommodate various functions and verify results of analysis or simulation. Major design issues and implementation challenges have been discussed. The current testbed is a baseline version and an advanced testbed with enhanced features, such as time reversal and ranging, is under development. UWB time reversal is an emerging technique that takes advantage of the unique properties of UWB channels. Currently there are no proper channel models for exploring UWB time reversal and majority of research in this area is based on experiments. Building a time reversal enabled testbed would be a very meaningful extension.

ACKNOWLEDGMENT

The authors like to thank Drs. Brian Sadler, Ananthan Swami, Robert Ulman, Santanu K. Das and T. C. Yang for useful discussions.

REFERENCES


