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An Efficient Low-Cost Time-Hopping Impulse Radio for High Data Rate Transmission

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Abstract

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An efficient low-cost time-hopping impulse radio for high data rate transmission

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Abstract: We present an efficient, low-cost implementation of time-hopping impulse radio that fulfills the spectral mask mandated by the FCC and is suitable for high-data-rate, short-range communications. The system was proposed to the IEEE 802.15.3a group for standardization as high-data-rate personal-area network (PAN). Key features are: (i) all-baseband implementation obviates the need for local oscillators and other passband components, (ii) all sampling and digital signal processing is done at 200MHz, (iii) fast acquisition is accomplished by novel search algorithms, (iv) the spectral can be shaped adaptively to accommodate different spectrum regulations and interference environments. We show that this system can provide 110Mbit/s at 7-10m distance, as well as higher data rates at shorter distances. Due to the spreading concept of time-hopping impulse radio, the system can sustain multiple piconets, and can suppress narrowband interference effectively.

1. Introduction

In recent years, ultrawideband (UWB) communications have attracted great attention from commercial, academic, and military research. The report and order of the FCC (Federal Communications Commission) in the USA that allowed UWB communications systems in the 3.1-10.6 GHz range has intensified the interest especially from possible chip and equipment manufacturers. One possible application lies in Personal Area Networks (PAN), where high data rates are sent over a short distance. The mandate of the standardization committee IEEE 802.15.3a is to develop a system that can provide multiple piconets with 110Mbit/s at 10m distance, as well as higher data rates at smaller distances.

Time-hopping impulse radio (TH-IR) has been considered as the "classical" UWB scheme since the pioneering work of Win and Scholtz [Scholtz 1993], [Win and Scholtz 2000]. However, some aspects of their generic system are not immediately suitable for implementation with the restrictions of the FCC and IEEE requirements. We have thus developed a TH-IR system that overcomes these restrictions, and gives high performance under those restrictions.

Several key ingredients of our proposal are discussed in separate documents

- block-synchronization [Gezici et al. 2003] allows fast synchronization.
- a new analogue Rake receiver based on a pulse generator enables sampling and digital processing at the symbol rate instead of the chip rate.
- a channel estimator similar to the swept-time-delay-cross correlator [Cox 1972] allows to obtain full channel information with sampling at the *symbol* rate [Li et al. 2003].
- polarity scrambling allows a better spectral shaping of any UWB system, both for pulse-position modulation and BPSK [Nakache and Molisch 2003].
- a novel pulse-combination scheme allows the shaping of the transmit spectrum as well as the matched-filter receiver, leading to better compliance with spectral regulations, coexistence with victim receivers, and immunity to interference [Wu et al. 2003].

In this paper, we discuss the total system design, the interplay between the components, and the total system performance.

The remainder of the paper is organized the following way: in Section II, we present the system overview, and show the interplay of the components mentioned above. Next, the spectral properties, and the influence of interferers as well as regulatory requirements are discussed. The outage probability in AWGN, multipath channels, and interference is the subject of Section IV. A summary and conclusions wrap up the paper.

2. System overview

A block diagram of the system is shown in Figures 1 and 2. The transmit data stream is split into several streams of approximately 100Mbit/s each. If the required data rate is 110Mbit/s, then only a single substream (and one transmitter branch) is used. Each of the streams is divided into blocks of 8096 bits each. Each block encoded with a convolutional coder with rate ½, and tail bits are added. Then, a preamble is added that contains sequences for both acquisition and channel estimation. The structure of the preamble allows fast acquisition (with the algorithm described in [Gezici et al. 2003]) and channel estimation with a low-sampling-rate channel estimators [Li et al. 2003].

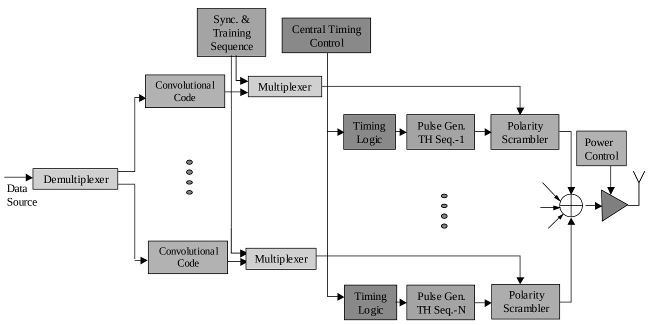

Figure 1 Block diagram of the transmitter

The modulation and multiple access format is BPSK-modulated TH-IR. Each data bit is represented by a sequence of N time-delayed pulses, where the delays, amplitudes, and polarity of the pulses is unique to each user. The whole sequence is multiplied by ±1, depending on the bit to be transmitted. Finally, the different data sequences are added up, amplified (with power control, in order to minimize interference to other systems), and transmitted.

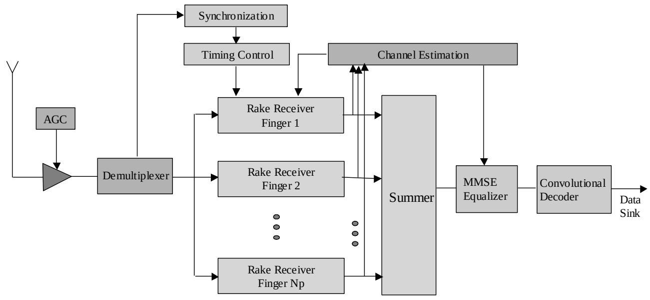

Figure 2 Block diagram of the receiver

At the receiver, the acquisition part of the preamble is taken and used to determine the timing of the timing control part. Once this has been established, the "channel estimation part" of the preamble is used to determine the coefficients for the Rake receiver and the equalizer. The signals in the main body of the data block are first match-filtered by the time-hopped sequence. This matches the received signal both to the pulseshape (group of pulses, which influences the spectrum) and the time-hopping sequence. Note that if there are several parallel data streams, then several matched filter (and other parts of the receiver) are used.

The matched-filtered signal is then sent through a Rake receiver. We use here an innovative structure that requires only pulse generators and no delays to do both the matched filtering and the Rake reception, which makes an implementation in analogue possible – this allows us to perform the sampling and A/D conversion only at the symbol rate, instead of the chiprate. The outputs of the Rake fingers are weighted (according to the principles of optimum combining) and summed up. The optimum location and weight of the fingers can be determined from the channel sounding sequence, which is processed before the reception of the actual data. The output of the summer is then sent through an MMSE equalizer and a decoder for the convolutional code.

One important point of the system is that all the pulses are *baseband* pulses, more specifically, derivatives of Gaussian pulses. This allows for a simple pulse generation, and obviates any need for passband components and local oscillators. This is a typical property of time-hopping impulse radio; however, it is not a trivial task within the restrictions of the FCC that the main power is emitted in the 3-10GHz range. We will show in Sec. 3 how we achieve that goal.

The goal of our design is to obtain a low-cost implementation. IEEE has stipulated that the cost per transceiver should be comparable to a Bluetooth (802.15.1) transceiver, even though the datarate of

802.15.3a is two orders of magnitude larger. Thus, the design is not theoretically optimum, but rather contains a number of simplifications that simplify the implementation and thus reduce costs.

3. Implementation details

3.1 The Rake receiver structure

Conventional Rake receivers sample the received signal, and correlate with a template of the transmit signal. A key aspect of our system is that it uses a novel Rake receiver structure in the analog domain, so that all sampling and digital processing can be done at the (coded) symbol rate of 220Mbit/s. We propose the use of a new Rake finger structure that is especially suitable for TH-IR. Accordingly, each finger includes a programmable pulse generator, controlled by a pulse sequence controller. The signal from the pulse generator is multiplied with the received signal. The output of the multiplier is then sent through a low-pass filter, which generates an output proportional to a time integral of an input to the filter. The difference to standard Rake fingers is an implementation in analogue, while the adjustable delay blocks have been eliminated.

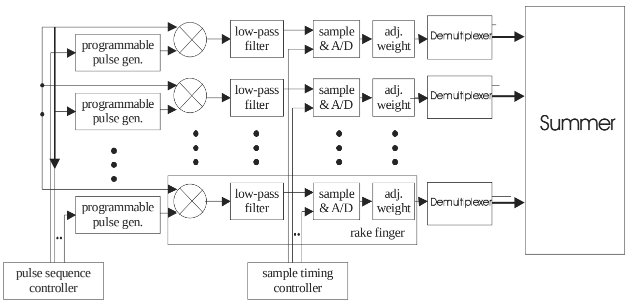

Figure 3 Rake receiver structure

The hardware requirements for each Rake finger are: one pulse generator (which can be controlled by the same timing controller), one multiplier, and one sampler / AD converter. In the following, we assume the use of 10 Rake fingers; this is a very conservative number. Obviously, a larger number of Rake fingers would give better performance; this is one of the complexity/performance tradeoffs in our design.

3.2 Channel estimation and equalization

A training sequence is used for the determination of the parameters. It is desirable to use the correlators and A/D converters of the Rake receivers, since these components have to be available anyway. The problem lies in the fact that we need to estimate the channel coefficients every Δ=1/BW=133ps, while the sampling occurs with a rate of 4.8ns. In order to solve this seeming paradox, we use an approach that shows some similarity to the “swept time delay cross correlator” channel sounder [Cox 1972], where the training sequence is transmitter repeatedly, and during each repetition sampled at an instant that is offset by Δ compared to the previous repetition.

The combination of the channel and the Rake receiver constitutes an equivalent channel; however, since the symbol duration is shorter than the delay spread of the channel, intersymbol interference (ISI) does occur. We combat that by means of a MMSE (minimum mean square error) equalizer with

3.3 Spectral shaping

One of the key requirements for a UWB system is the fulfillment of the emission mask mandated by the national spectrum regulators. In the USA, this mask has been prescribed by the FCC and essentially allows emissions in the 3.1-10.6 GHz range with a power spectral density of –41.3 dBm/MHz; in Europe and Japan, it is still under discussion. In addition, emissions in certain parts of the band (especially the 5.2-5.8 GHz ranged used by wireless LANs) should be kept low in order to fulfill the coexistence requirements of the IEEE [IEEE SC 2003]. We are using two techniques in order to fulfill those requirements. The first one is a linear combination of a set of basis pulses to be used for shaping of the spectrum a transmitted impulse radio signal. The delayed pulses are obtained from several appropriately timed programmable pulse generators.

The computation of the delays and weights of those pulses is obtained in a two-step optimization procedure. In a first step, an approximate quadratic approximation problem is solved in closed form. These solutions serve as initialization for an iterative optimization based, e.g., on a neural network approach. The details of this procedure can be found in [Wu et al. 2003].

A further improvement of the spectral properties can be obtained by allowing different polarities of the pulses that constitute the pulse sequence that represents one symbol. Using different pulse polarities does not change anything for the signal detection, as it is known at the receiver, and can thus be easily reversed. However, it does change the spectrum of the emitted signal, and thus allows a better matching to the desired frequency mask [Nakache and Molisch 2003].

The first technique (combination of pulses) leads to a shaping of the spectrum, allowing the placement of broad minima and an efficient "filling out" of the FCC mask. The second technique is used to reduce or eliminate the peak-to-average ratio of the spectrum, and allow the design of more efficient multiple-access codes. However, note that those two aspects are interrelated, and the optimization of pulse combination and polarity reversals must be done jointly.

3.4 Acquisition

Before any data demodulation can be done on the received UWB signal, the template signal and the received signal must be aligned. The aim of acquisition is to determine the relative delay of the received signal with respect to the template signal. The conventional technique to achieve this is the serial search algorithm. In this scheme, the received signal is correlated with a template signal and the output is compared to a threshold. If the output is lower than the threshold, the template signal is shifted by some amount, which usually corresponds to the resolvable path interval and the correlation with the received signal is obtained again. By this way, the search continues until an output exceeds the threshold.

4. Performance results

In this section, we analyze the performance of our system in multipath and interference. The performance of the system was simulated in "typical" UWB channels, which were defined by the UWB channel modeling subgroup, and are presented in [IEEE CM 2003] and [Foerster et al. 2003]. We distinguish between four different types of channels (called CM1, CM2, CM3, and CM4). CM1 describes line-of-sight (LOS) scenarios with distances between TX and RX of less than 4m; CM2 and CM3 describe non-LOS scenarios at distances 0-4, and 4-10m, respectively. CM4 is valid for heavy multipath environments.

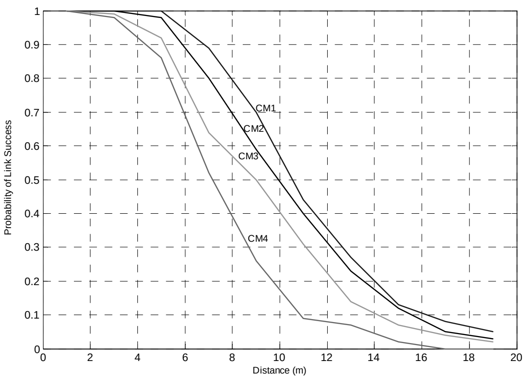

Figure 4 Probability of link success as function of distance for 110Mbit/s mode

Figure 4 shows the probability for obtaining a successful link. A "successful" link means that acquisition is obtained successfully, and the packet error probability (over the ensemble of different channels) is less than 8%. For CM1, the mean coverage distance is about 10m. The 10% outage distance (meaning that 8% packet error rate or less is guaranteed in 90% of all channels) is 7. For heavy multipath (CM4) these values decrease to 7 and 4m, respectively.

Figure 5 shows the analogous curves for a data rate of 200Mbit/s. Due to the higher rate, two parallel data streams are used. The time hopping codes for the two data streams are identical, but offset in delay by one chip. In an AWGN channel, those codes would remain orthogonal, and the performance should be worsened only by 3dB (since the E_b/N_0 is decreased). However, in a multipath channel, the temporally offset codes lose their orthogonality, which worsens the performance. One way to remedy this situation is to use different (not just offset) hopping codes. However, this decreases the number of possible simultaneous piconets. Another approach would be the use of the scheme of [Giannakis 2002], which retains the orthogonality of codes even in delay-dispersive channels.

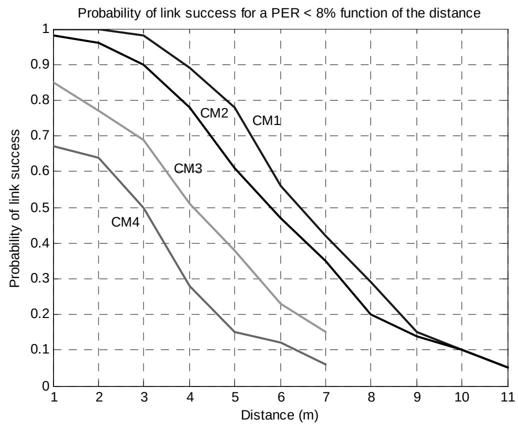

Figure 5 Probability of link success as a function of distance for the 200Mbit/s mode.

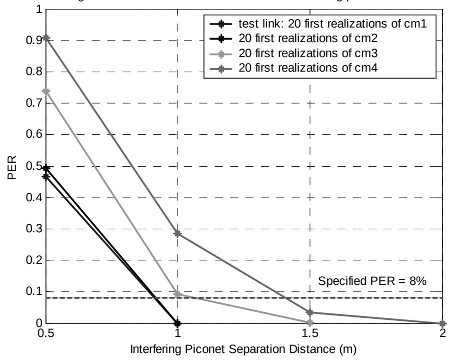

Figure 6 Packet error rate as a function of the distance of interfering piconet in CM 1.

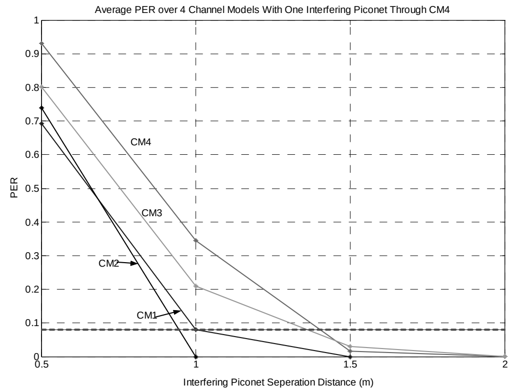

Figure 7 Packet error rate as a function of the distance of interfering piconet in CM 4.

Figures 6 and 7 show the performance when two users (independent piconets) are operating simultaneously. The desired users are located at half the distance that gives the 90% outage probability (i.e., there is a 6dB margin with respect to the single-user case); shadowing is not considered in that graph. We find that an "interfering piconet" can be at a distance from the victim receiver of about 1m (if the desired piconet is operating in CM1 or CM2), or 1.5m (if the desired piconet is operating in CM3 or CM4). The performance does not depend on which channel model is used for the interfering piconet.

Table 1 shows the coexistence of our system with other communications devices, obeying various narrowband standards. We find that if the UWB transmitter emits with the full power allowed by the FCC, it can significantly interfere with other communications devices. A suppression of about 15dB is necessary to allow coexistence within a 1m range. We achieve this suppression with the spectral shaping as described in Sec. 3.3.

System	Desired	Achieved	FCC Mask
802.11a	-88dBm	-90dBm	-75dBm
802.11b	-82dBm	-85dBm	-70dBm
802.15.1	-76dBm	-95dBm	-80dBm
802.15.3	-81dBm	-85dBm	-70dBm
802.15.4	-91dBm	-95dBm	-80dBm

Table 1: Coexistence for other systems

Finally, we also analyzed the resistance of the UWB system to interference *from* other communications devices. We found that again, a minimum distance of 1m is sufficient to allow operation with less than 8% PER.

5. Summary and conclusions

We have presented a UWB communications system based on time-hopping impulse radio. This system uses only baseband components, while still being compatible with FCC requirements, and providing a flexible shaping of the transmit spectrum in order to accommodate future requirements by other spectrum governing agencies, as well as not interfere with 802.11a wireless LANs and other communications receivers in the microwave range. Our system has been submitted to the IEEE 802.15.3a for standardization. It can sustain data rates of 110Mbit/s at 15m in AWGN channels, and 4-7m in multipath channels specified by the IEEE. It is also resistant to interference from other UWB users, as well as interference from wireless LANs, microwave ovens, and other interferers.

References

[Cox 1972] D. C. Cox, Delay-Doppler characteristics of multipath propagation at 910 MHz in a suburban mobile radio environment, IEEE Transactions on Antennas and Propagation, AP-20, issue 9, pp. 625-635, 1972

[Gezici et al. 2003] S. Gezici, E. Fishler, H. Kobayashi, H. V. Poor, A. F. Molisch, "A Rapid Acquisition Technique for Impulse Radio", PACRIM 2003, in press.

[IEEE SC 2003] IEEE 802.15.3a, "Selection Criteria", document at http://grouper.ieee.org/ groups/802 /15/pub/ 2002 /Nov02/.

[IEEE CM 2003] IEEE 802.15.3a channel modeling subgroup, J. Foerster (ed.), "UWB channel model", document at. http://grouper.ieee.org/ groups/802 /15/pub/ 2003 /May03/.

[Li et al. 2003] Y. G. Li, A. F. Molisch, and J. Zhang, "Channel estimation and signal detection for UWB", WPMC 2003, submitted.

[Molisch et al. 2003] A. F. Molisch, J. R. Foerster, and M. Pendergrass, „Channel models for ultrawideband Personal Area Networks", *IEEE Personal Communications Magazine*, submitted.

[Nakache and Molisch 2003] Y. P. Nakache and A. F. Molisch, "Spectral Shape of UWB Signals –Influence of Modulation Format, Multiple Access Scheme and Pulse Shape", *Proc. VTC 2003* spring, in press.

[Scholtz 1993] R. A. Scholtz, "Time Hopping Impulse Radio", Milcom 1993.

[Win and Scholtz 2000] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications", IEEE Trans. Communications, 48, Issue: 4 , pp. 679 –689, 2000.

[Wu et al. 2003] Y. Wu, A. F. Molisch, S. Y. Kung, and J. Zhang, "Impulse Radio Pulse Shaping for Ultra-Wide Bandwidth UWB Systems", submitted to PIRMC 2003.