Improving the coverage of ultra wideband impulse radio by pulse compression

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***Abstract*—Radio coverage is limited by two parameters: (i) energy per bit radiated by the transmitter and (ii) BER performance of the receiver. In Ultra-Wideband Impulse Radio (UWB IR) the former is limited by the FCC Regulations while the latter depends on the detection algorithm.**

The fact that prevents the use of UWB IR devices in real applications is the unacceptable short radio coverage. The pulse compression technique, that simultaneously increases the maximum attainable energy per bit and introduces a processing gain at the receiver is proposed here to overcome this problem. As a result of pulse compression, the coverage of the new UWB chirp IR devices is 6-times longer than that of the conventional UWB IR devices, i.e., the radio coverage is extended from less than 10 meters up to 40 meters.

I. Introduction

Radio coverage of built UWB impulse radio devices is limited by the energy used to transmit one bit information. Duration of UWB pulses is set to an extremely short time period to get an ultra wideband carrier. Unfortunately, the ultra short UWB pulses carry a very low energy per bit that results in a few meters of coverage [1]– [3]. This short coverage prevents the use of UWB IR technology in real applications.

The energy per bit can be increased in two ways: either the pulse power or the pulse duration has to be increased.

FCC Regulations limit the peak and average power that can be radiated by a UWB device [4] therefore the pulse power cannot be increased. Furthermore UWB devices are typically hand-held devices implemented by CMOS technology having a strong limitation on the voltage swing. Using an AAA-type battery the peak voltage at the output of the transmitter cannot exceed 0.5 V.

One way to increase the radiated energy per bit and so the coverage is the transmission of UWB pulses of long duration. Such a solution has to be found which preserves the ultra-wide bandwidth of the pulse despite its enlarged duration. A great candidate that combines ultra-wide bandwidth with long time duration is the chirp pulse. This paper proposes the application of FM modulated UWB chirp pulses of 100 ns duration.

In real UWB applications the channel is dispersive therefore the UWB chirp pulses of long duration overlap each other. As a consequence, the received pulses propagating along different propagation paths may not be separated at the receiver. The application of chirp transmission and a matched filter at the receiver introduce pulse compression [5] that can handle the problem of the overlapping pulses in the multipath dispersive UWB channel.

The pulse compression approach has got at least two important features: (i) the FM modulated chirp signal generated at the transmitter is a constant-envelope signal that can be amplified by high-efficiency nonlinear power amplifiers and (ii) the pulse compression has a processing gain that improves the noise performance of the receiver.

Considering the effects of increased energy per bit E_b at the transmitter and the enhanced noise performance at the receiver, the coverage of UWB IR devices is improved by a factor of 6, i.e., the radio coverage is extended from less than 10 meters up to 40 meters.

The paper surveys the basic idea of pulse compression, provides the design equations for compression-based UWB chirp impulse radio system proposed here and simulates its behavior in noisy multipath channels that have been derived and published by the IEEE 802.15.4a Channel Modeling Subcommittee.

II. Adaptation of pulse compression approach to UWB IR receivers

The idea of pulse compression is known from radar technology where the goal is to increase the peak power of the transmitted impulse by compression in time. Using pulse compression the high energy of a long pulse can be combined with the ultra-wide bandwidth of a narrow pulse. In this paper the pulse compression approach is adapted for UWB applications.

A. Basic idea of pulse compression

The block diagram of pulse compression approach is shown in Fig. 1. Frequency modulation (FM) is applied to the carrier frequency at the transmitter in order to generate the radiated UWB carrier pulse $x_t(t)$. The received signal $x_r(t)$ is fed into a matched filter characterized by its impulse response $h(t)$. The compressed pulse $x_{comp}(t)$ is measured at the output of a matched filter [5].

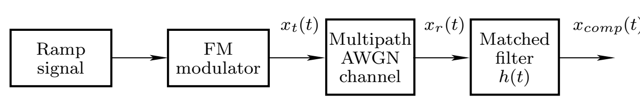

Fig. 1. Signal processing in pulse compression.

In the linear chirp method, considered here, the instantaneous frequency of the carrier is varied linearly over the entire pulse duration

$$f(t) = f_0 + \mu t \tag{1}$$

where f_0 denotes the start frequency and μ is the chirp rate. Note, the generated chirp signal is a constant envelope signal. The relation between the RF bandwidth $2B$ of generated pulse and the duration T_c of UWB chirp pulse is established by the chirp rate

$$\mu = \frac{2B}{T_c} \tag{2}$$

The impulse response of matched filter is derived from the parameters of the radiated chirp signal

$$h(t) = \exp\left\{ j2\pi \left[f_0(T_c - t) + \frac{\mu}{2}(T_c - t)^2 \right] \right\} \tag{3}$$

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B. Waveforms in the UWB chirp IR system

Consider a wideband UWB IR system where $2B = 1333.12$ MHz. Let $T_c = 100$ ns in order to get a reasonable high E_b compared to conventional UWB IR systems where $T_c \approx (2B)^{-1} \approx 0.75\ ns$. As shown in Fig. 2 the power spectrum of radiated UWB chirps, denoted by $x_t(t)$ in Fig. 1, is smooth and free from spikes. This chirp waveform meets the FCC Regulations.

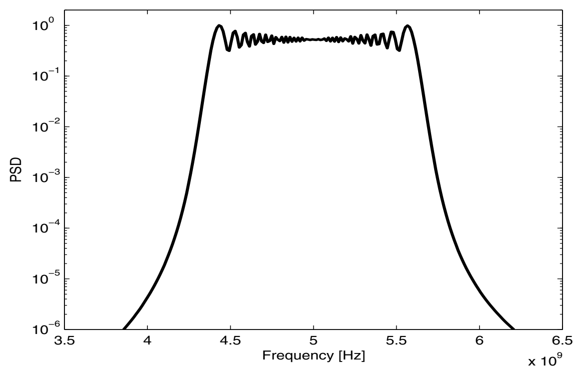

Fig. 2. Spectrum of the UWB chirp pulse.

The output $x_{comp}(t)$ of matched filter performing the pulse compression in Fig. 1 is depicted in Fig. 3.

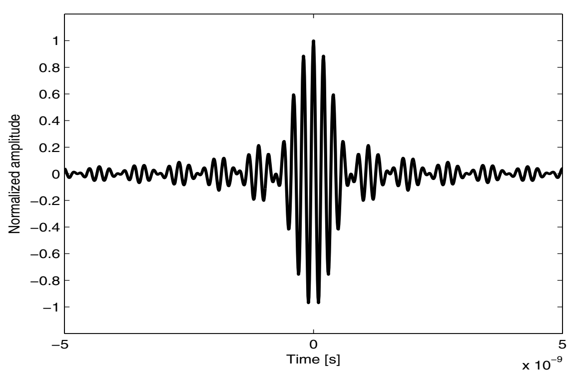

Fig. 3. The compressed UWB chirp pulse at the output of matched filter.

C. Compliance with FCC's Regulations

The FCC Regulations impose a limit on both the peak and average powers of UWB carrier pulses transmitted. The low-data rate UWB systems, considered here, are peak power limited [6]. The *FCC peak power limit* says: "There is a limit on the *peak* level of the emissions contained within a 50-MHz bandwidth centered on the frequency at which the highest radiated emission occurs $\cdots$ That limit is 0 dBm EIRP." EIRP is the product of the power supplied to the antenna and the antenna gain relative to an isotropic antenna.

Observe, the FCC peak power limit is not directly applied to the modulated UWB signals, instead, the output of a bandpass filter is specified.

The output of the 50-MHz FCC bandpass filter, generated by the chirp UWB pulse $x_t(t)$, is shown in Fig. 4. Note, the maximum of instantaneous power generated by the UWB chirp pulse meets the FCC peak power limit.

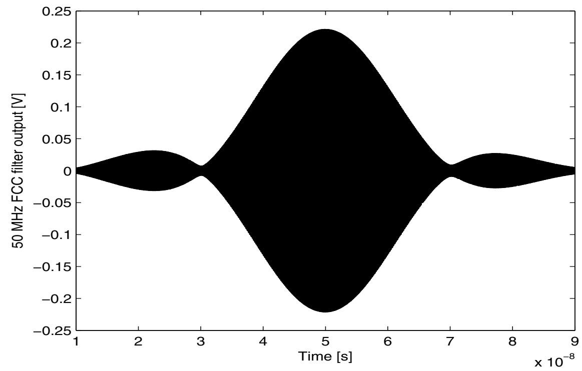

Fig. 4. Output of the 50-MHz FCC bandpass filter. Note, the peak voltage, 0.22 V_{eff}, corresponds to 1 mW peak power over a $Z_0 = 50\ \Omega$ termination.

III. Pulse compression in noisy IEEE 802.15.4a multipath channel

The IEEE 802.15.4a Channel Modeling Subcommittee has developed channel models for various UWB propagation environments in order to evaluate and compare the performance of different UWB IR systems. A Matlab code has been developed for 9 different application areas [7], the use of these channel models (CM) is mandatory.

To demonstrate the effectiveness of pulse compression, the received noisy UWB signals before and after pulse compression are plotted. To get a figure that is easy to evaluate, CM9 developed for snow-covered open air propagation condition has been chosen. The Matlab program has shown that one realization of CM9 has 4 propagation paths. The low number of propagation paths allows us to identify each received pulse in a separated manner and to evaluate the efficiency of pulse compression by observation.

Figure 5 shows the received signal $x_r(t)$ in the time-domain before pulse compression. Addition to the multipath propagation the received signal is corrupted by Gaussian white noise, the signal-to-noise ratio, SNR, is -3 dB. Note, the channel conditions are so bad that the received UWB signal cannot be even recognized in the time-domain.

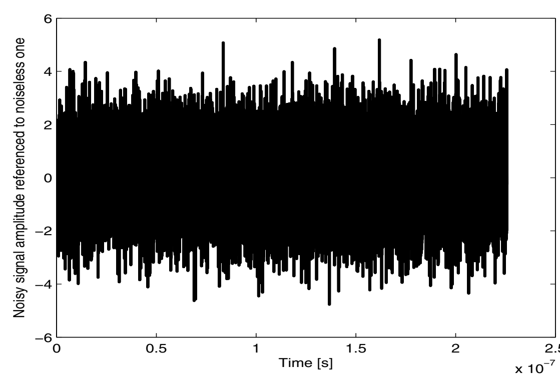

Fig. 5. Received signal $x_r(t)$ in a noisy IEEE 802.15.4a compliant channel. CM9 has 5 propagation paths in the studied case.

An important advantage of pulse compression is that it improves the SNR at the output of the matched filter. The processing gain is proportional to the ratio of pulse duration measured before and after pulse compression

$$R = 2\,\frac{T_c}{T_{comp}} = 2BT_c \tag{4}$$

where T_{comp} gives the duration of compressed chirp pulse.

The output $x_{comp}(t)$ of the matched filter performing the pulse compression is shown in Fig. 6. The matched filter compresses the UWB pulse in time and due to its processing gain it improves the SNR considerably. Note, four received UWB pulses that are hidden in the received signal plotted in Fig. 5 become clearly distinguishable in Fig. 6.

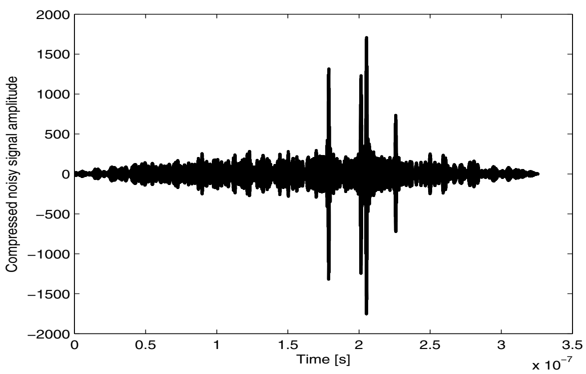

Fig. 6. Compressed UWB chirp signal $x_{comp}(t)$ in a noisy IEEE 802.15.4a compliant channel. CM9 has 5 propagation path in the studied case.

IV. Improvement in UWB radio coverage

The coverage of a radio device depends on two parameters: (i) the transmitted energy per bit E_b and the BER performance of the receiver. The former parameter is limited by the FCC Regulations while the latter one depends on the channel conditions over which the radio device is used and the detection algorithm. These parameters will be evaluated in this section.

The method, proposed in this paper, to extend the low coverage of UWB IR system based on the increase of the radiated E_b and the application of pulse compression technique on the received UWB carrier.

A. Improvement in energy per bit

Most frequently frequency-shifted Gaussian pulses [8] are used as carriers in the conventional UWB IR systems. The duration of one UWB carrier pulse can be as low as 0.75 ns. This extremely short duration has to be compared to the long pulse duration that is used in the UWB chirp IR systems.

A wideband UWB chirp IR system is studied where $2B = 1333.12$ MHz. The parameters of transmitted chirp pulses have been set in such a way that the system meets the FCC Regulations and the limitations implied by the low power voltage. For the reference UWB IR system, transmitting frequency-shifted Gaussian pulses of bandwidth 1333.12 MHz, the maximum attainable voltage swing induces the limitation on E_b, i.e., the peak voltage at the output of the transmitter cannot exceed 0.5 V. For the UWB chirp IR system it is the FCC Regulations that limit the output voltage of the transmitter in 0.22 V [3].

The gain in E_b achieved by the extension of bit duration is 15.3 dB.

B. Improvement in the receiver's BER performance

It is a widely accepted fact today that only noncoherent detectors are feasible in UWB communications [6].

The Transmitted Reference (TR) modulation can be demodulated by an autocorrelation receiver, the most robust noncoherent receiver configuration. In a TR signal each bit b_m to be transmitted is mapped into two UWB IR pulses, where the first pulse serves as a reference while the second one carries the information. If bit 1 is transmitted then the second pulse is a delayed repetition of the reference one, while for bit 0 the second pulse is an inverted and delayed version of the reference pulse. The autocorrelation receiver determines the correlation between the reference and information bearing pulses and the sign of correlation is used to perform the detection. The time delay between the reference and information bearing pulses has to be large enough to prevent the interference caused by the multipath channel.

The block diagram of UWB chirp IR autocorrelation receiver is shown in Fig. 7. The received UWB chirp signal $x_r(t)$, fed to input (1), is processed by the matched filter and the compressed signal $x_{comp}(t)$ is processed by the correlator. The energy capture time is set by the bandwidth of low-pass filter, and the observation signal z_m is fed into the decision circuit. It is a level comparator, its output gives the estimated bit $\hat{b}_m$.

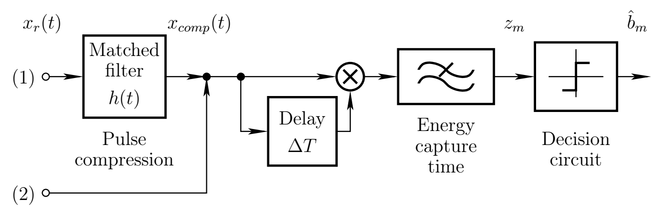

Fig. 7. Block diagram of autocorrelation receiver used in BER performance evaluation and comparison.

A reference UWB IR system has been also constructed to evaluate the effectiveness of UWB pulse compression. The reference system uses a frequency-shifted Gaussian pulse [8] as carrier and the TR modulation. To get a fair comparison, the same autocorrelation receiver is used which means that the received UWB IR signal is fed into point (2) in Fig. 7.

Using the receiver models depicted in Fig. 7 and each Matlab UWB channel models [7] elaborated by IEEE 802.15.4a Channel Modeling Subcommittee, a huge number of simulations have been done to compare the BER performance of the UWB chirp IR system proposed here and the UWB IR system known from the literature.

The results of simulations are shown in Fig. 8. The solid curve depicts the theoretical noise performance [3] of the reference UWB IR system with TR modulation. The '+' marks denote the simulated points that are in a close agreement with the theoretical BER curve when no pulse compression technique has been applied but a traditional autocorrelation receiver has been used. The dotted and dashed curves are plotted based on simulations exploiting the pulse compression technique for CM9 ignoring and including, respectively, the frequency dependent nature of the channel. The effect of frequency dependency will be discussed in Sec. IV-B1.

In a noncoherent radio system $BER = 10^{-3}$ is a good reference for noise performance comparison. The results of simulations have shown that a 7.8-dB improvement can be achieved, on average, due to the pulse compression.

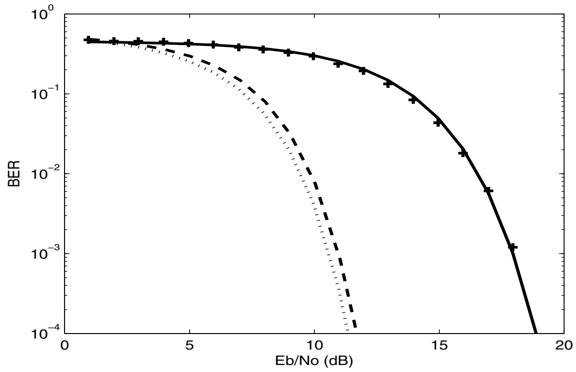

Fig. 8. Noise performance of the reference UWB IR system (solid curve) with the simulated points ('+' marks) and that of the UWB chirp IR system featuring pulse compression technique considering (dashed curve) and ignoring (dotted curve) the frequency dependence of the channel.

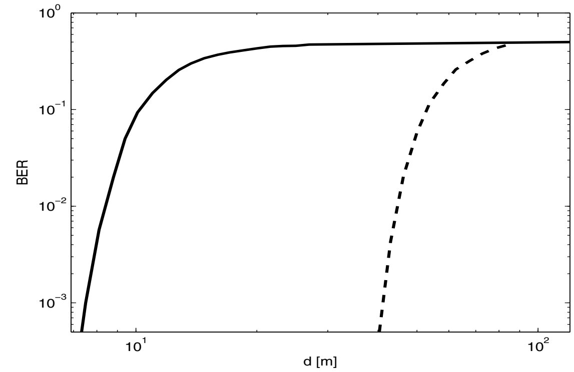

Fig. 9. Noise performance of the reference UWB IR system (solid curve) and that of the UWB chirp IR system (dashed curve) as a function of the distance (d) between the transmitter and the receiver in an indoor office NLOS propagation environment.

1) Frequency dependent nature of the radio channel: The frequency dependent term in path gain can be formulated [7] as

$$10\,(-2\kappa - 2)\,\log_{10}(f/f_0) \tag{5}$$

where the reference frequency f_0 is set 5 GHz, f gives the signal frequency and κ denotes the frequency dependence factor. Depending on the propagation environment the value of κ goes from -1.427 to 1.53. In Figure 8 the dashed curve illustrate the effect of the frequency dependent nature of the channel for $\kappa = 0.53$. A marginal, about 0.5 dB, noise performance degradation can be observed.

C. Improvement in radio coverage

Macro model of UWB radio channel has been also elaborated by the Channel Modeling Subcommittee. The expression for calculating the distance dependent path loss takes the form [7]

$$PL(d) = PL_0 + 10\,n\,\log_{10}(d/d_0) \tag{6}$$

where the reference distance d_0 is set to 1 m, PL_0 is the path loss at the reference distance in decibels, d gives the distance of the transmit and receive antennas in meters and n is the path loss exponent that depends on the environment. Its value varies from 1.2 to 4.58.

Let's consider an indoor office NLOS propagation environment where $PL_0 = 57.9$ dB and $n = 3.07$. Recall, an 15.3-dB gain in E_b and a 7.8-dB improvement in BER performance have been achieved due to the adaptation of chirp pulses and the pulse compression approach, respectively. Substituting these results into (6) one may conclude that the coverage of UWB chirp IR devices is 6-times longer than that of the conventional UWB IR devices, i.e., the radio coverage is extended from less than 10 meters up to 40 meters at $BER = 10^{-3}$ as it is shown in Fig. 9. Recall, the reference UWB IR system and the UWB chirp IR system are limited by the low power voltage and by the FCC Regulations, respectively.

The value of coverage extension depends on the duration of UWB chirp IR pulse, the longer the duration, the larger the coverage extension. However, an increase in pulse duration also increases the probability of pulse collision.

V. Conclusions

A novel UWB IR technology referred to as UWB chirp IR approach and pulse compression technique has been proposed to increase the radio coverage of UWB IR systems. The duration of the radiated UWB chirp pulse can be increased considerably and the enlarged E_b assures a larger radio coverage. The gain in E_b is about 15.3 dB when the UWB pulse duration is set to 100 ns. Recall, in spite of the increased E_b, the UWB chirp pulse still satisfy the FCC Regulations.

The UWB chirp pulse is a constant envelope signal, consequently it can be amplified even by a nonlinear power amplifier at the transmitter.

Pulse compression has a processing gain at the receiver that improves its noise performance. Simulations have shown that the improvement in BER is about 7.8 dB compared to a conventional noncoherent autocorrelation receiver.

In multipath channels the UWB pulses overlap each other. After compression the overlapped UWB chirp pulses become separated.

Due to the increased energy per bit and the improved noise performance of the receiver the radio coverage of the novel UWB chirp IR devices is extended from less than 10 meters up to 40 meters.

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