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An Impulse Ultra-wideband System Capable of Concurrent Transmission and Reception, Part I: Requirements and Innovations

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An Impulse Ultra-wideband System Capable of Concurrent Transmission and Reception, Part I: Requirements and Innovations

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Abstract—This paper presents a novel ultra-wideband (UWB) system for low power, long range, mid to high data rate mesh networking applications. Combined with the complementary code division multiplexing modulation and the multicode interleaved direct sequence spread spectrum techniques, the system aims to achieve interference resistance, coexistence with legacy systems, and robust performance in hostile multipath environments. The unique feature of the system is the support for concurrent transmission and reception, which will enable a medium access control mechanism with cut-through routing to be developed for high-throughput UWB mesh networks. It is concluded that this new UWB system represents a fundamental advance in UWB technology.

I. INTRODUCTION

Ultra-wideband (UWB) technology has been used for a large range of applications in many different ways due to the UWB signal's unique characteristics, such as resistance to interference and interception, deep ground and through wall penetration, and high time resolution [1]. In response to the growing practicality of the UWB based communications, the Institute of Electrical and Electronic Engineers (IEEE) is currently in the process of selecting two UWB based alternative physical layer (PHY) standards, IEEE 802.15.3a and IEEE 802.15.4a, for wireless personal area network (WPAN) applications [2].

The IEEE 802.15.3a standard targets high data rate (hundreds Mega to over 1 Giga bits per second (bps)), low power, low cost, and short range (<10m) applications in the consumer electronics market, whereas the IEEE 802.15.4a aims for low data rate (several Kilo to Mega bps) communications and high precision ranging and location at ultra low power, low cost and longer range (tens of meters indoors to potentially several kilometers outdoors). The mid to high data rate (several Mega to hundred Mega bps) and long range communication protocols for wireless local area network (WLAN) applications have been defined under the IEEE WLAN standards such as IEEE 802.11/a/b/g [3]. However, these WLAN systems usually have a relatively narrow bandwidth (such as 20 MHz) and operate at higher power.

For military and increasingly important public safety applications, it is required that the communication systems operate at low power (for handheld devices) and over long

distances (on battlefields and at the scenes of fires or other disasters). The data rates must be highly scalable to suit a variety of applications, such as voice and data communications and video streaming, and also adaptive to different channel conditions. To provide high mobility and extended range, the communication systems must be tolerant of topology change and capable of multiple hopping. In addition, the systems must resist interference and coexist with legacy systems. All these requirements suggest that a high throughput UWB mesh network is desirable. However, since neither the available WLAN standards nor the UWB WPAN standards currently under development are satisfactory, a new UWB system for mid to high data rate, low power and long range operation is necessary.

This first part of the paper describes the fundamental requirements and proposes novel solutions for developing an UWB PHY suitable for a ground-based scalable data rate UWB mesh network capable of supporting voice, video and data communications in hostile environments. Such a network will be particularly useful for military and public safety applications. To enable a high-throughput UWB mesh network, the new UWB PHY will support concurrent transmission and reception (Tx/Rx) operation, which represents a fundamental technical advance in UWB technology. A cut-through routing medium access control (MAC) algorithm, taking advantage of this concurrent Tx/Rx, is also under development.

The rest of this first part paper is organized as follows. In Section II, the requirements of this new UWB system are summarized, and the innovations are proposed and justified. In Section III, novel modulation and spreading techniques used in this UWB system are described briefly. Section IV introduces the concurrent Tx/Rx concept and outlines its benefits. Section V provides the solutions for interference mitigation when the UWB system operates at the concurrent Tx/Rx mode. Finally, conclusions are drawn in Section VI.

II. NEW UWB SYSTEM REQUIREMENTS AND INNOVATIONS

As the new PHY aims to support an UWB mesh network for military and public safety applications, there are several fundamental problems that need to be solved. These problems include: (1) how to make the network resistant to interference, (2) how to prevent the network from interfering with other systems, (3) how to achieve low power and long range, (4) how

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to mitigate adverse multipath effects, and (5) how to improve network throughput over multiple hops.

Conventional spread spectrum approaches, such as time-hopping and direct sequence spreading, can not completely solve these problems. Time-hopping UWB systems usually use very low duty cycle impulses to provide the necessary processing gain and multipath mitigation, but the signals have large peak-to-average power ratios and demonstrate spectral lines. Conventional direct sequence UWB systems suffer from intersymbol interference (ISI) due to multipath propagation when the data rate or range increases. Other solutions include multi-band UWB systems, but they cause compliance and complexity concerns. The continuous-wave signalling nature also prohibits the use of pulse-interleaving for possible concurrent Tx/Rx operation.

Our solution to the above mentioned problems is a new UWB PHY that combines complementary code division multiplexing (CCDM) modulation [4] and multicode interleaved direct sequence (MCIDS) spreading [5] techniques to generate a Gaussian-noise like UWB signal and provide the necessary processing gain. The transmitted UWB signal is chosen as a series of carrier-modulated impulses (i.e., the signal spectrum is shifted to a frequency band with a center frequency). The impulse train has a moderate duty cycle to facilitate concurrent Tx/Rx operation for the UWB transceiver. The CCDM is used to provide an asymptotic Gaussian distributed data sequence with a variable spreading ratio. The MCIDS is then used to further spread the Gaussian data sequence with a fixed spreading ratio, determined according to the channel delay spread, and generate a final transmitted signal sequence that is suitable for transmission over a multipath channel. The overall spreading ratio for the signal sequence before it is modulated by an UWB impulse is the product of the spreading ratios provided by the CCDM modulation and MCIDS spreading respectively.

These innovative techniques solve the above mentioned fundamental problems satisfactorily. The white Gaussian-noise like transmitted UWB signal represents a natural perturbing noise and thus causes less harmful interference to narrowband systems [6]. The adaptive processing gain will maximize the system's immunity to both legacy narrowband systems and intentional jammers. The MCIDS's ISI-free ability to resolve multipath will enable high-speed data transmissions over severe multipath channels. The concurrent Tx/Rx capability will enable a pipelined multi-hop mechanism to improve network throughput substantially.

III. UWB SIGNAL GENERATED USING CCDM AND MCIDS

The CCDM modulation makes use of a complementary code spreading technique to generate a spread spectrum signal with asymptotic Gaussian distributed amplitude, and provides a wide range of variable spreading ratios. The complementary code spreading technique works in two steps. First, a complementary code spreading sequence is constructed using a set of complementary codes [7]. Then, this spreading sequence is used to modulate the input data symbols. Figure 1 shows an example of this complementary code spreading technique,

where the input data sequence is assumed to be $\{+1, +1, -1, +1, -1\}$ (Figure 1(a)) with symbol interval equal to 2 chip times (i.e., the spreading ratio is 2), and the complementary code spreading sequence is $\{+1, +1, +1, +1, +1, -1, -1, +1\}$ which is formed by interleaving the complementary code pair $\{+1, +1, +1, -1\}$ and $\{+1, +1, -1, +1\}$. This spreading sequence is modulated by each symbol (Figure 1(b) to (f)) and all the modulated sequences are summed up to produce the output spread sequence. This spreading process can be described as a linear convolution of the input data sequence with the complementary code spreading sequence. The output spread sequence is indicated by the dashed cycles in Figure 1(g). To limit the spread sequence to a fixed length, which is the number of data symbols multiplied by the spreading ratio, the linear convolution can be replaced by a circular convolution. This is equivalent to overlapping the tail (the part that exceeds the fixed length) of the linearly convolved sequence with its beginning. The final result is indicated by the solid dots in Figure 1(g), which is a block of discrete samples $\{+2, -2, 0, +4, +2, -2, 0, 0, -2, +2\}$ of length 10.

Figure 1. Example of complementary code spreading.

The MCIDS spreading is a combination of multicode direct sequence spreading with block interleaving. It works as follows. Firstly, the input data symbols are divided into data blocks. Each symbol in a block is spread by a specific spreading sequence. After all symbols in the block are spread by a set of orthogonal spreading sequences respectively, the spread signal is then passed through a block interleaver to produce the final MCIDS spread signal. A cyclic prefix may also be added at the beginning of the interleaved spread signal. The length of the cyclic prefix is required to be longer than the maximum channel delay. The MCIDS spreading offers ISI-free data transmission over severe multipath channels that can have a delay spread much longer than the symbol interval.

Assume that a block of data symbols, $\{+2, -2, 0, \dots, +2\}$, are generated by the example of Figure 1, and that the respective spreading codes for these symbols are $\{+1, +1, -1, \dots, +1\}$, $\{+1,$

$-1, -1, \dots, +1\}$, $\{+1, -1, +1, \dots, -1\}$, ..., and $\{+1, +1, +1, \dots, -1\}$. The MCIDS spreading process is shown in Figure 2, where (a) shows the spread signal $\{+2, +2, -2, \dots, +2\}$ obtained by spreading the symbol $+2$ with its corresponding spreading code $\{+1, +1, -1, \dots, +1\}$, (b) shows the spread signal $\{-2, +2, +2, \dots, -2\}$ obtained by spreading the symbol -2 with its spreading code $\{+1, -1, -1, \dots, +1\}$, (c) shows the spread signal $\{0, 0, 0, \dots, 0\}$ obtained by spreading the symbol 0 with its spreading code $\{+1, -1, +1, \dots, -1\}$, (d) shows the spread signal $\{+2, +2, +2, \dots, -2\}$ obtained by spreading the symbol $+2$ with its spreading code $\{+1, +1, +1, \dots, -1\}$. We can then imagine that these spread signals are stored in rows. A block interleaver will read out the signal column-wise, resulting in the final MCIDS spread signal shown in (e). A segment of cyclic prefix is also added in this example, which is the same as the last segment of the block interleaved signal.

Figure 2. Example of MCIDS spreading.

IV. CONCURRENT TX/RX OPERATION AND BENEFITS

The new UWB system enables concurrent Tx/Rx operation to greatly improve the throughput over multiple hops. Consider a three-hop system as shown in Figure 3 wherein Node A desires to forward packets to Node D. For the conventional store-and-forward packet transmission over multiple hops, a packet is firstly sent by Node A. After receiving the packet, Node B retransmits it to Node C. Similarly, Node C retransmits the packet to Node D after the entire packet is received. In this operation mode, a node in the system can only transmit or receive a single packet at a time. If the nodes in the system are capable of concurrent Tx/Rx, a packet can be sent to the next hop before the packet has been completely received by the forwarding node. The only time delay between the beginning of the packet reception and the start of the subsequent transmission to the next node is caused due to the need to receive and parse the packet header, but it is only a fraction of the duration of the entire packet. When operating in this mode, a node may therefore be seen as transmitting and receiving at the same time and will enable pipelined packet transmission

over multiple hops. This will substantially improve the overall end-to-end system throughput.

Figure 3. A three hop system.

Figure 4 shows the propagation of the pipelined approach over a network supporting concurrent Tx/Rx. The packets represented with a solid border are those in a pipelined approach while those with a dashed border are those in a traditional store-and-forward approach.

Figure 4. Packet propagation by pipelined approach.

Denoting the time taken to transmit a packet over one hop as T_{PACKET} and the time for transmitting the packet header as T_{HEADER} , the throughput for the store-and-forward packet transmission scheme over N hops is $T_1 = \frac{1}{T_{\text{PACKET}}} \times \frac{1}{N}$, and the corresponding throughput for the pipelined scheme is $T_2 = \frac{1}{T_{\text{PACKET}}} \times \frac{1}{1 + \frac{T_{\text{HEADER}}}{T_{\text{PACKET}}} \times (N - 1)}$. In a network where

the packet header is 5% of the total packet length, Figure 5 shows the normalized throughput of the two schemes versus the number of hops. It can be seen that the pipelined packet transmission has superior performance. By the 10th hop, the throughput is almost 7 times greater.

V. RECEIVED UWB SIGNAL MODEL AND INTERFERENCE MITIGATION

During the pipelined packet transmission, a node receives signal from multiple sources. Figure 6 shows the signals that are present at the RF front-end of the first packet destination,

Figure 5. Throughput comparison of store-and-forward (T_1) and pipelined (T_2) packet transmission schemes.

Node B, under concurrent Tx/Rx operation. There are four different types of signals at the receive path of Node B. One is the signal leakage from Node B's transmit path due to the non-ideal isolation of the hybrid. The other three are received from its antenna and can be classified as the signal transmitted from Node A (including multipath reflections), reflections from the Node B's own transmitted signal, and the signal transmitted from Node C (including multipath reflections). Since the only desired signal is the one from Node A, Node B must be able to reject the other signals as they are only sources of interference. We refer to the signal leakage and the reflections coming from Node B's transmission as self-interference caused by the local transmitter, and the signal and reflections coming from Node C's transmission as interference caused by a remote transmitter. Thus, from the signal processing point of view, the received signal model for concurrent transmission and reception can be depicted as in Figure 7.

Figure 6. Signals present at RF front-end of Node B.

In order for the transceiver to work properly, the receiver must be capable of eliminating the interference generated by both local and remote transmitters.

A. Local transmitter interference cancellation

The isolation between transmission and reception paths in a transceiver is commonly provided by a hybrid, as shown in Figure 6. The ideal hybrid would offer infinite isolation, i.e., no energy would leak from the transmit input to the receive output.

Unfortunately, the ideal hybrid is impossible to realize, given that no physical material can completely stop electromagnetic propagation. As a result, the isolation offered by a practical hybrid, such as those based on circulators or quarter-wavelength-sections, is approximately 20dB. Therefore, given that a radio with an effective range of, for example, one-hundred meters, can have more than 80dB difference between the locally transmitted signal and the received one, such hybrids are clearly insufficient. Hence, most practical radios use a time-division duplex scheme wherein the radio's receiver is simply turned off when it transmits. The impact of near-field reflectors can also cause problems since a reflection of the locally transmitted signal will be delayed and overlapped with the desired incoming signal.

Figure 7. Received signal model for concurrent transmission and reception.

Although there are many ways of eliminating self-interference from the local transmitter, the preferred means is to use block data transmission with code-division outer codes. In this embodiment, the data to be transmitted at a transceiver is grouped block by block. The block size is chosen so that the length of transmitted signal waveform for one data block is significantly longer than the maximum channel delay spread. An outer code is then applied to the transmitted data block. These outer codes are managed so that the signal that a given transceiver transmits is orthogonal from the one that it is attempting to receive. For example, the simplest orthogonal outer code set is composed of the codes $\{+1, +1\}$ and $\{+1, -1\}$. Figure 8 illustrates (a) how the code $\{+1, +1\}$ is applied to the transmitted signal block 1 and 2 from a remote transmitter and (b) how the code $\{+1, -1\}$ is applied to the transmitted signal block X and Y from the local transmitter. We see in (c) the combination of both signals at the local receiver before despreading. Then in (d) we see how only the original remote signal remains after the transceiver removes the locally generated interference through despreading. For the proposed new UWB PHY, the outer codes are applied to the MCIDS blocks.

Note that the outer code effectively halves the data rate in return for an additional 3 dB of processing gain. So as to ensure that the effective data rate is unchanged, the CCDDM symbol rate needs to be doubled when concurrent transmit and receive mode is operating.

With the addition of an automatic gain control (AGC) enable and disable function, the use of an outer code will also eliminate the need for transmit/receive switching. That is, the

Figure 8. Applying orthogonal outer codes to transmitted signals for local and remote transmitters.

receiver will always be operating, even when the transmitter is active. The key to realizing this “always on” receiving is to disable the AGC when the transmitter starts transmitting a packet. As shown in Figure 9, since the transmitted signal (solid line) is much stronger than the received signal from a remote transmitter (dashed line), it will get clipped and then eliminated during the signal processing (i.e. the correlation of the outer code) performed by the receiver.

Figure 9. Locally transmitted signal pulses get clipped when AGC is disabled at the receiver.

B. Remote transmitter interference mitigation

When outer codes are used to eliminate the local transmitter interference as described above, two different outer codes will be alternated at each hop of the pipelined transmission path. For example, in the context of Figure 3, if the outer code for Node A is $\{+1, +1\}$, the outer code for Node B must be $\{+1, -1\}$. Accordingly, the outer code for Node C must be $\{+1, +1\}$. We see that the signal to be received (transmitted by Node A) and the remote interference (transmitted by Node C) have the same outer code, meaning that they would interfere with each other if nothing more was done to discriminate between them.

By exploiting the capability of the MCIDS spread spectrum technique to distinguish between signals arriving at different time delays, the remote transmitter interference can be easily removed. In this embodiment, the data to be transmitted is grouped block by block and then spread by MCIDS spreading technique. As shown in Figure 10, the signal transmitted from Node C only needs to be delayed a certain amount of time relative to the signal transmitted from Node A to allow Node B to receive the signal from Node A only, and discard the signal from node C. The reason why this can be done is because rather than attempting to resolve the delayed signal, as is the case when resolving multipath, the delayed signals in this case are simply discarded. The time delay introduced by Node C is one half of the maximum channel delay which the MCIDS scheme is designed to cope with, i.e., $L/2$, where L stands for this maximum channel delay (in chip time). The only cost to using this technique is that the maximum channel delay that

MCIDS can cope with will be halved. Fortunately, this cost is not significant since the MCIDS spreading can be designed to ensure that it is still appropriate for the given application's expected channels.

To ensure that the time delay of the transmitted signals between every two transmitters with one local transmitter in-between along the transmission path is $L/2$, we can simply always delay the transmitted signal by $L/4$ relative to the adjacent transmitter. Note that these delays are in terms of synchronization between transceivers and not in terms of a particular block (i.e. the delay is used to exploit the orthogonality of the underlying codes used in MCIDS).

Figure 10. Received signal at Node B is a combination of signal from Node A and a delayed signal from Node C.

VI. CONCLUSIONS

Aimed at providing robust communications with mid to high data rate over long range in hostile environments, the proposed new UWB system will be very suitable for mesh networking applications. The research and development of this new UWB system not only augments current UWB standard activities but also advances our knowledge base in UWB technology. The unique combination of the CCDDM modulation and the MCIDS spreading techniques enables an UWB transceiver to transmit and receive concurrently, so that a pipelined packet transmission can be realized to greatly improve the system throughput over multiple hops in a UWB mesh network. Since there is a huge market potential for military and public safety applications using UWB technology, the development of this new UWB system is of great practical significance.

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