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Abstract

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This paper describe such a system that takes advantage of the high data rate offered by UWB. We first implemented the complete MB-OFDM PHY layer using multi-FPGA hardware and discrete RF design. Out implementation is fully compliant to the WiMedia/MBOA PHY specifications and the FCC power regulations. The system achieved 110Mbps maximum data rate with a BER better than 10-6 over a range of 4 meters.

Subsequently, we developed a testbed that demonstrates simultaneous transmission of multiple High Definition video streams over the MB-OFDM link. The use-case scenario is a Multimedia Client-Server application where we have one Media Server (transmitter) and several Media Players (receivers).

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Ultra Wide Band technology has attracted a lot of attention recently as a viable solution for high data rate, low power, short-range wireless link. The growing multi-media home networking is demanding more bandwidth and wireless throughput has become a bottleneck for high quality multi-media services. With the maximum data rate above 100 Mbps, UWB is a perfect solution for such applications.

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Keywords: UWB, HDTV, wireless network

1. Introduction

In early 2002, the Federal Communications Commission (FCC) approved the use of ultra-wideband (UWB) technology for commercial applications. The ruling granted the unlicensed use of 3.1 to 10.6 GHz spectrum for UWB transmission for indoor (and certain outdoor) situations. The power spectral density level is limited to -41dBm/MHz to minimize its interference to other (narrowband) systems.

This ruling accelerated the already fast growing research and development effort in UWB technology as an enabling technology for high date rate, low power and short-range personal area networks.

Compared to narrowband wireless links, UWB has several very distinctive characteristics:

a) *Large RF bandwidth*. MB-OFDM signal has the bandwidth of 528MHz in non-hopping mode and >1.5GHz in a 3-band hopping mode.
b) *Low power density in the transmission band.* The total power transmitted in the passband of a narrow band system is very low and hence has very little interference to the existing narrow band systems.
c) *Resistance to fading.* Due to the large number of resolvable multipath components, UWB systems show performance advantage in multi-path environment.
d) *Short range.* This is due to the restriction on the emission power. This is especially true for high data rate systems that have little spreading gain.

As UWB is reaching maturity, there is a lot of interest in developing applications that can take full advantage of this technology. Some of the examples are wireless USB and home multimedia wireless networks.

The home multimedia network market is growing rapidly. For some content such as video streams, the demand for bandwidth is very high. Most of the existing narrowband networks are not suitable for such applications because of the bandwidth bottleneck. UWB can remove some of the constraints in building applications in such a wireless network. The WiMedia alliance has created a UWB physical-layer standard based on multiband-OFDM (MB-OFDM) that supports a data rate of up to 480Mbps.

In this paper, we describe a system that transmits multiple high definition video streams simultaneously in a wireless network with high data rate UWB links.

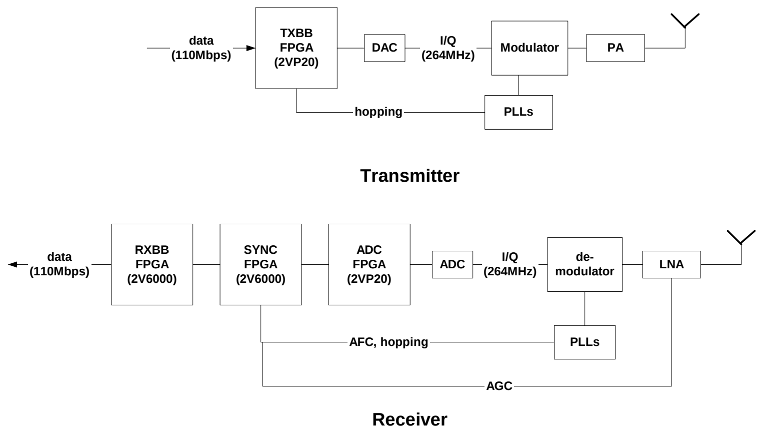

Figure 1. System Hardware Block Diagram

We created both the hardware that implements the MB-OFDM standard, and the software that allows the simultaneous transmission of multiple high definition video streams from a multimedia server.

2. System Design and Implementation

There are two essential parts required for building a system that utilizes UWB technology. First of all, a robust UWB physical link must be available as a foundation. The other part is the application that takes full advantage of the physical layer.

2a. UWB PHY Link Realization

Formed in 2003, the MultiBand OFDM Alliance (MBOA) develops and promotes UWB transmission schemes based on OFDM in different frequency bands; the alliance was merged with WiMedia in March 2005.

In January 2005, the MBOA released its version 1.0 PHY layer specification. The specification supports data rates up to 480 Mbps.

a) Each OFDM subcarrier is modulated with quadrature phase shift keying.
b) Techniques such as convolutional codes, bit interleaving, time domain spreading and tone spreading etc. are used for coding gain.
c) The transmission is packet based. Each packet consists of symbols separated by guard intervals. Each symbol occupies 528MHz bandwidth and is 312 ns long.
d) For each symbol, the 528MHz spectrum is divided into 128 tones, of which 100 tones are data tones. There are 12 pilot tones inserted for phase tracking; guard tones are used on the edge of the band.
e) The operation frequency is from 3.1 to 4.8 GHz. The transmission power is subject to FCC limits. Frequency hopping is allowed among sub-bands to minimize interference and overcome fading at certain frequencies.

The physical link is built using FPGA and discrete RF components and is compliant with the MBOA specifications [1]. Figure 1 shows the block diagram of the system. The entire baseband signal processing functionalities are implemented using a generic FPGA platform for its flexibility and expandability. Such a platform also allows us to stay compliant to the specification that was being modified during the development.

The transmitter baseband section uses a single Xilinx® 2VP20 FPGA. The outputs (I and Q) drive a dual-channel D/A converter at 528Msps. Even though the DAC takes 14 bits, only 8 bits are significant. Internally, all the samples are 8 or 9 bits as well. Our calculation indicates that using more bits yields very little gain for the overall system performance while costing a lot of resources.

Each of the OFDM symbols is transmitted at a different carrier frequency, depending on a time-frequency code. This is achieved by switching the frequency of the LO input of the IQ modulator. The MBOA standard specifies the guard interval to be 9.47ns. This is the switching time from one LO frequency to another. We use RF switches to switch between the LO outputs.

The original OFDM signal has a large peak-to-average ratio (~15dB). To ease our transmitter RF circuit design and improve the transmitter efficiency, we clip the signals in the digital domain to reduce the peak-to-average ratio. Even though this raises the noise floor, we noticed no degradation in the overall system performance. The clipping is implemented in a digital power control block in the FPGA.

The receiver baseband logic is more complicated than the transmitter and requires more resources. The entire receiver design is partitioned and fits into 3 FPGAs. One FPGA is dedicated to synchronization, another is to baseband processing, and the third one to ADC interfacing.

The synchronization FPGA searches for preamble symbols. Once the packet is synchronized, it generates a signal that triggers the baseband signal processing blocks. It also computes RSSI and controls the AGC loop. Frequency offset is calculated using channel estimation symbols and used for AFC. In addition, this FPGA generates frequency hopping control signals.

Major functional blocks of the receiver baseband FPGA include FFT engine, de-spreading, de-interleaver, Viterbi decoder, CRC check and etc.

The interfaces from the FPGAs to the host are not compatible to the released MBOA PHY-MAC interface spec. In our design, there are two separate channels between the host and the transceiver. One is a slow, bi-directional 8-bit bus for slow control command and status check. The max throughput is 10Mbps. The second channel is a dedicated high-speed link for data transfer. This link is 32bit wide and has the maximum data rate of 528Mbyte/s. The high-speed link uses the DMA channel on the Host side.

Both transmitter and receiver have built-in buffers that can buffer up to 8 packets. Data for each packet include 10 bytes of MAC header and up to 4 Kbytes of payload. The receiver can be configured to receive all packets or only the broadcast packets and the packets with correct destination receiver ID to minimize the probability of overflow in the receiving buffer.

In parallel to the baseband hardware design, we also designed the entire RF circuit and antenna. The transmitter RF subsystem includes the IQ modulator, PLL and gain stages. The receiver RF circuit has LNA, I/Q demodulator, PLLs and filters. The baseband FPGA controls gain(AGC) and frequency(AFC) control. The hopping switches are controlled by the FPGAs for both the transmitter and the receiver.

The system operates on three frequencies: 3.432, 3.960 and 4.488 GHz respectively. The transmitter power is lower than the FCC indoor communication power density limit of -41dBm/MHz.

The receiver RF circuit offers a dynamic range of 64dB and LO PLL pull range of +/-100ppm.

A compact antenna was designed for the system. The dimension of the antenna is $40\text{x}20\text{mm}^2$. The max gain is 4.7dBi at 4GHz. In the operating frequency range from 3.1 to 4.7GHz, the gain variation is 1.2dB and VSWR is <2.

2b. Application Software Design

We built an application to achieve simultaneous transmission of multiple High Definition video streams utilizing the high data rate wireless link. Each video streams has a data rate of 19.4 Mbps.

The use-case for the system is a Multimedia Client-Server scenario where we have one Media Server (transmitter) and several Media Players (receivers).

Since the above implementation of the UWB connection is unidirectional, TCP/IP communications on top of 802.11a/b/g or 100Base-T PHY is used as the feedback channel for command and control.

The system consists of one Media Server and two or more Media Players. The Media Server uses a Linux OS based Pentium-4 PC and one UWB Transmitter module. Each Media Player consist of a Linux OS based Pentium-4 PC and one UWB receiver module. UWB hardware is attached to the PC via PCI bus.

The multimedia content in the server are MPEG2-TS HD files. Each Media Player is connected to an HDTV Monitor via an IEEE-1394 interface. It uses the 1394 AV/C protocol for command and control and uses the ISO 61883-4 protocol for the MPEG2-TS data transmission. An HDTV's built-in user interface *NetCommand* allows the display of a list of available content and the selection of certain items for viewing. Also simple commands such as "Play" and "Stop" are implemented.

As shown in Figure 2, the system is consisted of two types of connections between the Server and Players:

UWB unidirectional connection: This is used for video stream data transmission.

TCP/IP bi-directional connection: This is used to control data flow and as a quality feedback channel for error recovery. The PHY layer could be wireless 802.11 or wired 100Base-T Ethernet. Current system uses 100Base-T.

To utilize TCP/IP functionality, the standard Socket API provided by Linux OS is used. From networking point of view, it is a typical Client-Server scenario where the Media Server acts as a server and the Media Player acts as a client. The Server opens a listening socket and waits for the client to connect. The Player initiates all communications.

Upon receiving a request for a connection, the Media Server creates a separate thread to handle the client's request. It assigns an ID to the Player and passes that ID in the response. The Player configures the UWB receiver with the assigned ID.

The Media Server's client thread is terminated if the Media Player does not send any request within the timeout interval (10 seconds), or closes connection to the server.

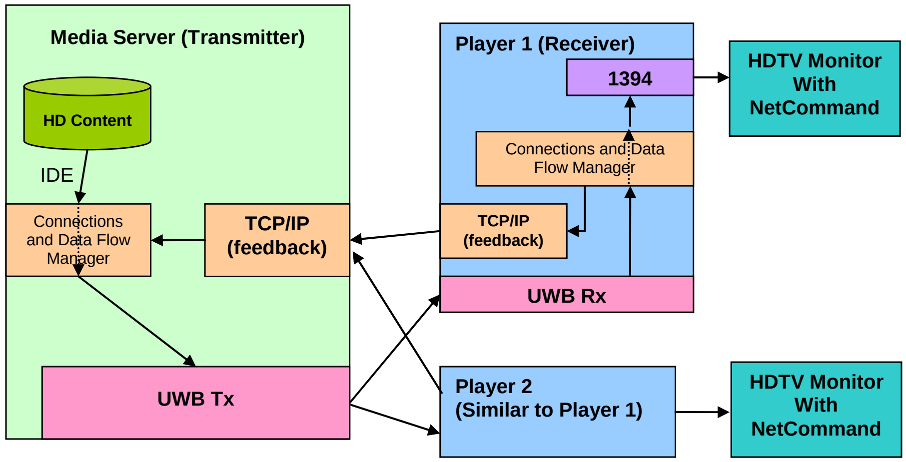

Figure 2. Application block diagram

The current command set consists of the following:

GetContentList – This command is used by the Player to get a list of the content available on the Server. Upon the receipt of the **GetContentList** request, the Server enumerates the content and generates a response to the Player that includes the stream name, length, and creation time.

GetStreamData – This command is used by the Player to get a portion of the video stream. Upon receiving this command, the Server sends the requested portion of the content over UWB to the Player or response to the Player that includes an Error Code.

StopStreamData – This command is used by the Player to immediately stop the UWB transmission of the content. Usually in the case of user interaction when one has decided to stop watching or switch to different video content.

Figures 3 and 4 show the transmitter and receiver data flow. When the Server receives a GetStreamData command, it reads a portion of the content from the PC's hard drive, creates a queue of packets and puts it into the transmitter buffer. The size of the Host Buffer is a variable that is a multiple of 6016 (least common multiple of 188 and 128) bytes. In the current implementation, it is 30080 bytes for storage of 160 packets. 128 bytes are transferred for each DMA interrupt. Therefore, it takes 235 DMA transfers to pass the packets to the DSP Buffer.

The DSP checks the Host Buffer status. When there is data available, the DSP transfers data from the HOST Buffer to the DSP Buffer. The size of the DSP is the same as the Host Buffer. After the data transmission has completed, the Server goes back to a waiting state. After the DSP receives the stream data, it checks the Tx Buffer. If the Tx Buffer is ready, the DSP writes one UWB frame at a time to the Tx Buffer, which contains up to 5 packets. After the Tx Buffer (1024 bytes) is filled, the transmitter then transmits the data in its Tx Buffer as one UWB frame. After the DSP sends all data to the transmitter, DSP will go back to check the host if any new data available.

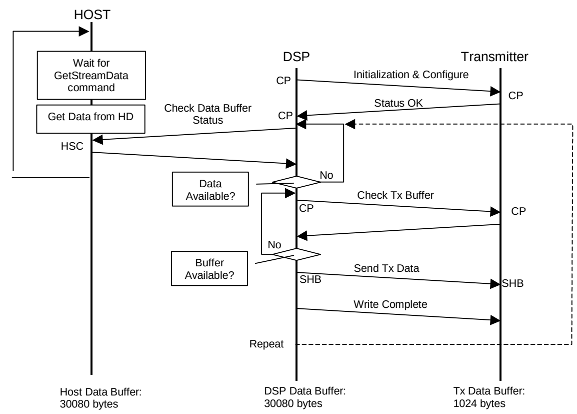

Figure 3. Transmission data flow

On the receiver side, after the Player requests a portion of the content from the Server over TCP/IP, it configures the DSP to listen for incoming data for the Player ID that has been assigned by the Server. Once a data packet is received, it is transferred to the Host over the High Speed Channel (HSC).

When the stream data is available in the Rx Buffer, the DSP gets data from the Rx buffer for one UWB frame each time and puts it into the DSP Buffer. After the DSP receives a total of 160 packets, it will send them to the Host and put into one of the blocks in the Host Buffer.

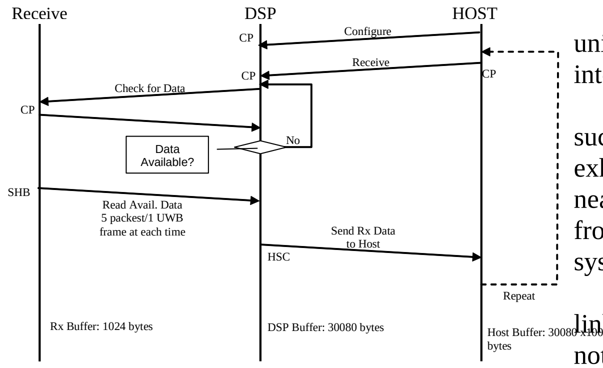

Figure 4. Receiver data flow

3. System Performance

The performance of the implemented UWB link was first checked with the bit error rate test.

With hopping mode disabled, the link bit error rate is close to 10^{-7} over the range of 4 meters.

With hopping mode turned on, we noticed that our synchronization logic occasionally misses packets. This is the result of the carrier leak-through in the transmitter RF circuit. Such a leak-through becomes a DC offset at the outputs of the receiver demodulator. Without hopping, this DC component is blocked by the following stages and therefore has no impact on the performance of the receiver. Since the receiver LOs are not phase locked to the transmitter, values of the DC component are different for each band. Once hopping is on, the leak-through induced DC offsets manifest as plateaus with the symbol duration of ~0.3μs and at hopping repetition frequency. Therefore this signal has a frequency of 3.2MHz and is not blocked by the following receiver circuit and is passed through into baseband. In the worst case, the DC offset can saturate the analog circuit and results in signal distortion and performance degradation. Also our synchronization algorithm is sensitive to the DC content in the symbols, and this carrier leak through causes occasional missed frame detection.

Even with this particular imperfect RF design, test results indicate that the average BER is $\sim 10^{-5}$.

It is plausible that while maintaining an acceptable BER, the range of the system can be extended by adding more gain in our RF front end. Currently the RF circuit is being modified to improve the link bit error rate.

With the combination of CRC check in the physical layer and retransmission mechanism in the application software, error free video-streams were received by all receivers.

The deep buffer in the HDTV decoder allows uninterrupted display when the physical link is interrupted briefly. (e.g. blocked antenna).

The system was tested in different environments such as a hardware lab, office cubical area and exhibition hall with other operating UWB systems nearby. The performance is robust under interference from narrow band wireless systems and other UWB systems.

When transmitting two video streams, the average link utilization is less than 60%. Even though we did not test the performance of the system with 3 receiver nodes due to the lack of hardware, we believe that our system is capable of handling at least 3 HDTV streams.

4. Conclusions

A complete UWB based wireless communications system was developed by combining both UWB PHY link hardware and application software.

Despite the minor imperfection in the RF hardware, the overall performance of the system was satisfactory. The system achieved desired BER of better than 10^{-6} at 110Mbps with the range over 4 meters.

More importantly, the system demonstrated simultaneous transmission of multiple HDTV video streams. An error-free transmission of video streams was achieved by using the CRC check provided in the physical layer and retransmission mechanism designed in the software.

The success of this development proves that UWB-based high-speed wireless link can serve as an excellent platform for applications that demand large wireless bandwidth.

References

[1] MultiBand OFDM Alliance, “MultiBand OFDM Physical Layer Specification”, Release 1.0, January 2005.

[2] I. Ramachandran, Y.-P. Nakache, P. Orlik, A. F. Molisch, J. Zhang, “Symbol spreading for UltraWide Band System Based on MultiBand OFDM”, PIMRC 2004

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