Red
Mountain
Radio

www.RedMountainRadio.com

Thanks for your interest in my technical paper. If you find this work to be interesting, or have additional questions, please contact me at the address below. Red Mountain Radio LLC offers professional RF, optical, and microwave design services, and problem solving.

Regards,
Eric Funk, Ph. D.
Partner, Red Mountain Radio LLC
eric@redmountainradio.com
970-325-2158 ×12

A Wireless Photoconductive Receiver Using Impulse Modulation and Direct Sequence Code Division

Scott Ramsey, Eric E. Funk* and Chi H. Lee
Laboratory for Atomic, Molecular, and Optical Science and Engineering and Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742
**now with EER Systems, 10289 Aerospace Road, Seabrook, MD 20706*
scramsey@eng.umd.edu, yag@eng.umd.edu, chlee@eng.umd.edu
John Craven
Department of Defense

Abstract: Direct sequence code division is used to enhance an ultrawideband impulse modulated communication system using a photoconductive switch-based receiver. Experimental results show an aggregate processing gain of 44 dB using a 750 MHz spreading bandwidth.

I. Introduction

Impulse modulation is a wireless transmission format recently proposed [1-2] for multipath and interference environments. In such environments, spread-spectrum techniques are commonly employed to broaden the bandwidth of the transmitted signal relative to its underlying data rate. This provides protection against the frequency-selective fading is present in multipath environments as well as giving a processing gain against non-coherent signals, whether they are noise, interference or overlaid channels with orthogonal encoding schemes.

In a high-interference environment that requires large processing gains, the receiver front end must have a large dynamic range over broad bandwidths. Electronic receivers will often employ mixers in the front end before any processing gain is realized that have limited dynamic range.

We have previously proposed a photoconductive switch as the front end correlation element in an impulse modulation receiver[3]. The photoconductive switch [4] has the large bandwidth and dynamic range required for the front end of an interference - limited impulse modulation system.

We recently reported [5] error-free performance for data rates up to 38 Mb/s and spreading bandwidths of over 750 MHz using a photoconductive-based impulse modulation receiver. In this paper we present a hybrid receiver that combines impulse modulation with direct sequence to achieve an total processing gain in excess of 44 dB.

II. Processing Gain

Direct sequence code division [6] systems use N data chips to represent a single data bit. The chips are formed by modulation with a pseudo-random sequence at N times the data rate. The bandwidth is spread by a factor of N, and the ideal processing gain against non-coherent signals is:

$$G_p = 10\log_{10}(N) = 10\log_{10}\left(\frac{\text{chip rate}}{\text{data rate}}\right) \qquad (1)$$

Impulse modulation uses time-division to achieve a similar processing gain. Impulses consisting of 1-3 RF cycles are modulated and transmitted using pseudo-random timing. The receiver gates the impulses using either a mixer or high-speed switch to perform the correlation in the front end [7]. This isolates the decision circuits from any interference during the majority of time when impulses are not transmitted.

The bandwidth is set by the shape of the impulse. Spreading bandwidths of 1 GHz and higher can be achieved using sub-nanosecond

0-7803-5558-X/99/$10.00

impulses. The ideal processing gain of an impulse modulated signal is approximately:

$$G_p \approx 10\log_{10}\left(\frac{\text{bandwidth}}{\text{data rate}}\right) \qquad (2)$$

While it is theoretically possible to achieve arbitrarily high processing gains in impulse modulation with low data rates, it is not always feasible. Reducing the data rate affects synchronization because of the longer drift periods. In addition, reducing the data rate does not increase the range unless the peak power of the impulses is increased, but excessive peak powers are inefficient to transmit and may pose interference to other systems.

A solution employed in other impulse radio systems[2] is to coherently combine several impulses to form a single bit in a method analogous to direct sequence. This combines the multipath resistance and front-end processing gain of impulse modulation with the more uniform transmit power and multiple access characteristics of direct sequence code division.

III. Experimental System

As a proof of principle experiment, we added direct sequence to a photoconductive impulse modulation system in our laboratory. The system is shown in Fig. 1.

A low-jitter, 38 MHz timing signal from our laser system is used to drive a step-recovery diode circuit to generate wide-band impulses. An 85 kHz signal is coherently divided down from the 38 MHz reference and is used to gate individual impulses using an on-off keyed pseudo random sequence.

The RF impulses are amplified and radiated by a broadband low-directivity bowtie antenna. The impulses have a bandwidth of approximately 750 MHz and a center frequency of 1 GHz.

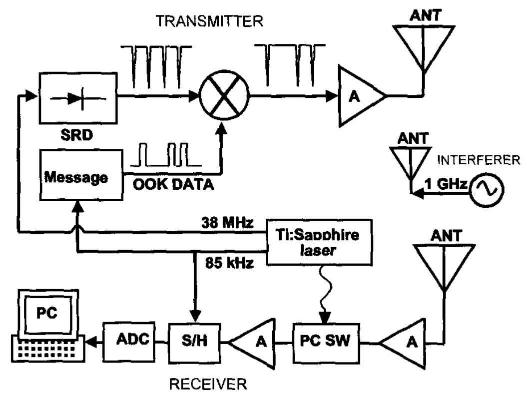


Fig. 1. Experimental system architecture. SRD: step-recover diode circuit, A: amplifier, ANT: broadband antenna, PC SW: photoconductive switch, S/H: sample-and-hold circuit, ADC: analog-to-digital converter, PC: computer with BER receiver software.

The receiver used an identical bow-tie antenna 3 meters away. The signal was preamplified and fed into a photoconductive switch consisting of an interdigitated gap in a 50 Ω coplanar waveguide on a semi-insulating GaAs substrate. The gap width was 3 μm with a switch area of 50 μm x 50 μm. The switch has an RF isolation (in the dark) of more than 30 dB at 1 GHz, and was triggered with 120 pJ laser pulses at 810 nm from a Ti:Sapphire laser. This optical trigger energy is low enough that in the future laser diodes can be employed.

Because our current laser is passively mode-locked, a timing signal to synchronize the transmitter to our receiver is required. Acquiring and maintaining synchronization is a critical challenge for impulse modulated systems because of their narrower pulse widths and lower duty cycles as compared to constant - envelope modulation. In the case of our photoconductive receiver, if a phase-locked laser source were used then a pair of switches in a delay-locked loop configuration could be used to lock the receiver.

Fig. 2 shows the received impulse signal, the gating response of the photoconductive switch, and the sampled output, which is a

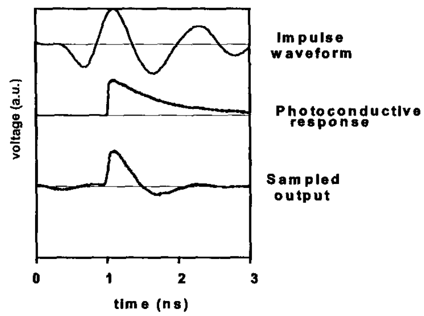


Fig. 2. Photoconductive sampling of the received impulse waveform. The switch can be modeled as a time-varying conductive response in parallel with a capacitor that allows some leakage in the dark state.

combination of the sampled peak and a smaller leakage waveform.

At this point the impulse modulation processing gain has been realized, and only a bandwidth of approximately the chip rate is required for later processing. An electronic circuit operating at the chip rate can sum the signal levels from individual impulses to perform code correlation and thresholding for bit decisions. For this experiment, the flexibility of a software receiver was desired to allow more rapid prototyping of different receiver approaches.

The sampled output was therefore amplified and fed into an Avtech AVS-105 sample-and-hold integrator to hold the sample level long enough to be acquired by a data acquisition board on a personal computer. The sample window of the AVS-105 was chosen to be broader than the photoconductive sampled output so that it did not perform any additional gating.

The data acquisition board converted the analog levels from the AVS-105 using a 12-bit ADC for processing by the computer. The maximum sampling rate of this ADC limited the system chip rate in this experiment to 85 kHz. Commercial ADCs are available that would allow direct sequence at the 38 Mb/s rate of our previous system[5] and higher.

A software bit error receiver was programmed that was configurable for different code lengths. The receiver would average N consecutive impulse levels to make a single decision, reducing the data rate in proportion to the code length.

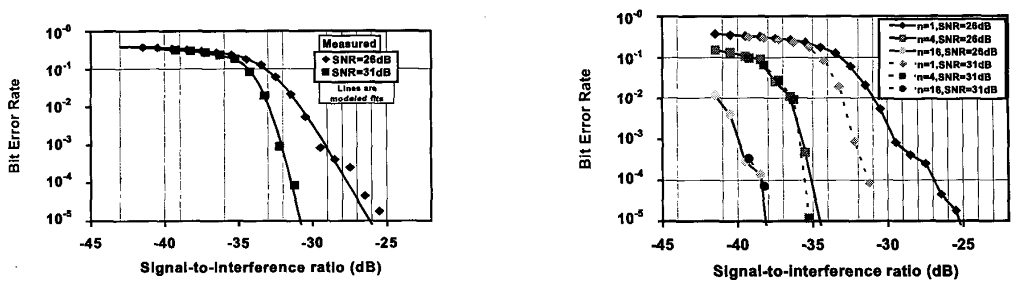
A third antenna was used to transmit a narrowband interference tone at 1 GHz, near the center frequency of our system. The bit error rate (BER) was then measured as the interference level was varied. The level of interference is characterized by measuring the signal-to-interference ratio (SIR) at the output port of our receive antenna.

IV. Results

Fig. 3(a) shows the BER curves vs. interference for two different levels of white noise. The line shows the results from an ideal model that fits the data assuming gaussian noise and a narrowband interferer. The model achieved best fit using values for signal-to-noise ratio (in the absence of interference) and peak signal power that were within 1.5 dB of direct measurements of those parameters. The discrepancy is believed to be due to a combination of model over-simplification and measurement error.

As can be seen, 10^{-5} BER can be maintained even with a SIR of less than -30 dB. Without bandwidth spreading, an OOK signal with high SNR can theoretically achieve 10^{-5} BER with a SIR of 6 dB. Therefore a processing gain of more than 36 dB is achieved using impulse modulation alone.

Using a bandwidth of 750 MHz, our estimated G_P would be 39 dB from Eq. (2). The difference is because our received impulse is not optimally shaped for its bandwidth - it includes some multipath components that are delayed relative to the direct component by several nanoseconds. These reflections do not lead to fading because of the impulse modulation - they are gated out by the photoconductive switch. However, they detract from our processing gain because not all available signal power is used to make decisions.



(a) (b)

Fig. 3. BER results without code division (a) and with code division (b). The chip rate is 85 kHz, the impulse bandwidth is approximately 750 MHz and the interference is a CW tone at the impulse center frequency of 1 GHz.

Fig. 3(b) shows the measured BER curves with the addition of direct sequence. The three pairs of curves correspond to 1, 4 and 16 chips/bits, and therefore data rates of 85, 21.25 and 5.3 kB/s respectively. As can be seen, direct sequence allows operation with higher interference, albeit at lower data rates. For n=16, 10^{-5} BER is maintained with a SIR of less than -38 dB. This corresponds to an improvement of 8 dB and a processing gain of more than 44 dB.

In an actual system, the impulses would be time-hopped. This would affect the spectral properties of the signal, making it more noise-like and less likely to interfere with nearby narrowband systems because no beating could occur between the impulses and a narrowband signal.

This lack of time-hopping in our experimental system does not affect average BER without direct sequence. However, when direct sequence is used, the measured coding gain against the narrowband interferer is not possible to model accurately unless the beating between the interference tone and our periodic impulses is taken into account.

The beating can improve the coding gain of the system. For example, if beating is ignored the model predicts processing gain improvements at a 31 dB SNR of 3 dB and 7 dB for N=4 and N=16 respectively, while we measured improvements of 5 dB and 8 dB.

V. Conclusion

Photoconductive switches can be implemented as front-end correlators in impulse modulated wireless systems. This allows large processing gains without using dynamic range limited components. The switches can achieve large bandwidth, low leakage and moderate insertion loss using low laser pulse energies.

Direct sequence can be effectively combined with impulse modulation to provide high processing gains. A photoconductive-based impulse modulation receiver with direct sequence demonstrated an improvement of 8dB and a 44 dB of processing gain using only 120 pJ/pulse of laser energy.

References

[1] R. A. Scholtz, “Multiple Access with Time-Hopping Impulse Modulation,” *Proc. MILCOM*, Boston, MA, Oct. 11-14, 1993.

[2] Moe Z. Win and R. A. Scholtz, “Impulse Radio: How it Works,” *IEEE Communications Letters*, vol. 2, pp. 36-38, Feb. 1998.

[3] Eric E. Funk, Scott Ramsey and Chi H. Lee, “A Photoconductive Correlation Receiver for Time-Hopped Wireless Spread-Spectrum Radio,” *IEEE Microwave and Guided Wave Letters*. vol. 8, pp. 229-231, June 1998.

[4] C. H. Lee, ed. *Picosecond Optoelectronic Devices*, New York: Academic Press 1984.

[5] Eric E. Funk, Scott Ramsey, Chi H. Lee and John Craven, "A Photoconductive Correlation Receiver for Wireless Digital Communications," IEEE/LEOS Microwave Photonics Technical Digest, pp. 21-23, Oct. 1998.

[6] Andrew J. Viterbi, *Principles of Spread Spectrum Communications*, New York: Addison-Wesley Publishing Company, 1995.

[7] Scott Ramsey, Eric E. Funk and Chi H. Lee, "Photoconductive Receiver Architectures for Impulse Modulation in Interference Environments," in OSA Ultrafast Electronics and Optoelectronics Technical Digest, pp.103-105, Apr. 1999.