Impulse Radio Overview

by Paul Withington of Time Domain Corporation

Overview

Time Domain Corporation has developed a revolutionary radio technology, impulse radio, for wireless communications. The general characteristics of Time Domain's impulse radios are:

- Ultra-short duration pulses which yield ultrawide bandwidth signals.
- Extremely low power spectral densities.
- Center frequencies typically between 650 MHz and 5 GHz.
- Multi-mile ranges with sub-milliwatt average power levels (even with low gain antennas).
- Excellent immunity to jamming from other radio systems.

Time Domain Corporation has built several prototypes, the most recent being a full duplex 1.3 GHz system with an average output power of 250 microwatts and a variable data rate of either 39 kbps or 156.25 kbps. This radio has been tested to beyond sixteen kilometers (ten miles).

Other prototypes have operated at data rates up to 1.5 Mbps and down to a few bits per second. One prototype was demonstrated to the US Department of Defense and other governmental agencies, who determined that the signal could not be detected at ranges under 30 meters (100 feet) even when the transmission was being received ten kilometers away.

Impulse radios can qualify for type acceptance in the US under the rules of Part 15 for unlicensed applications and can share spectrum without affecting conventional radio transmissions.

Additionally, impulse radios:

- Have exceptional multipath immunity.
- Are relatively simple and should be less costly to build than spread spectrum radios.
- Are expected to consume substantially less power than existing conventional radios.
- Could be implemented as a two integrated circuit chip set with very few off-chip parts, when fabricated using advanced integrated circuit technologies.

Because of these characteristics Time Domain's technology is the optimal technology for a wide variety of applications, including in-building communications systems and personal communications systems.

Technology Basics

Time Domain's impulse transmitters emit ultra-short "Gaussian" monocycle pulses with a tightly controlled pulse-to-pulse interval. Time Domain has been working with pulse widths of between 1.50 and 0.20 nanoseconds (billionths of a second) and pulse-to-pulse intervals of between one hundred and one thousand nanoseconds. These short monocycle pulses are inherently wideband.

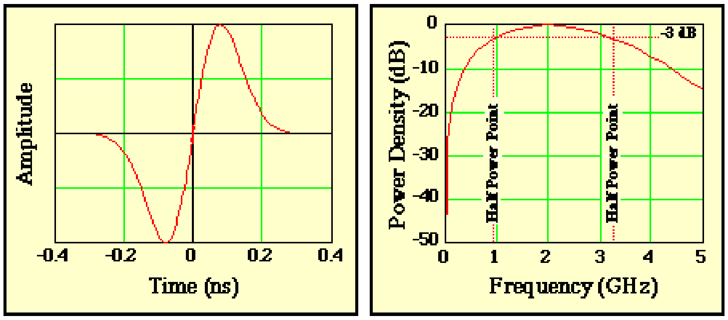
The system uses pulse position modulation. The pulse-to-pulse interval is varied on a pulse-by-pulse basis in accordance with two components: an information signal and a channel code.

The impulse receiver directly converts the received RF signal into a baseband digital or an analog output signal. A front end cross correlator coherently converts the electromagnetic pulse train to a baseband signal in one stage. There is no intermediate frequency stage, the elimination of which greatly reduces complexity.

Gaussian Monocycle

The most basic element of Time Domain's impulse radio technology is the practical implementation of a Gaussian monocycle. Figure 1 shows the monocycle in both the time and frequency domains. (Actual practice prevents the transmission of a perfect Gaussian monocycle. In the frequency domain, this results in a slight reduction in the signal's bandwidth.)

Figure 1



2 GHz Center Frequency Gaussian Monocycle in Time and Frequency Domains

The monocycle is naturally a wide bandwidth signal, with the center frequency and the bandwidth completely dependent upon the pulse's width. In the time domain, the Gaussian monocycle is described mathematically by the first derivative of the Gaussian function, i.e.:

$$V(t, f_c, A) = 2\sqrt{e}\, A \pi t f_c\, e^{-2(\pi t f_c)^2}$$

Where, A determines the peak amplitude of the pulse; fc determines the pulse's center frequency; and t is time.

In the frequency domain, a Gaussian monocycle is given by:

$$V(f, f_c, A) = \frac{1}{2}\sqrt{\frac{2e}{\pi}}\,\frac{A}{f_c^2}\, e^{-\frac{1}{2}\left(\frac{f}{f_c}\right)^2}$$

There is a direct relationship between the pulse's center frequency and its duration, which is given by:

$$Tau = \frac{1}{\pi f_c}$$

Where Tau represents the time between the maximum and minimum amplitudes.

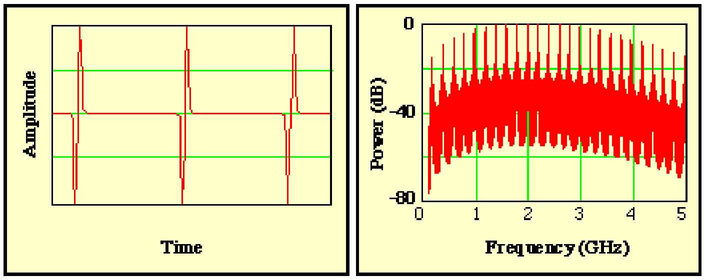
The half power bandwidth is 116% of the center frequency and since fc defines the pulse width, then the pulse width specifies both the center frequency and bandwidth. In practice, the center frequency of a pulse is approximately the reciprocal of the pulse's length and the bandwidth is approximately equal to the center frequency. Thus, for the 0.5 ns pulse shown in Figure 1 the center frequency and the half power bandwidth are approximately 2 GHz.

A Pulse Train

Impulse systems use long sequences of pulses, not single pulses, for communications. Time Domain's prototypes have pulse repetition frequencies of between 1 and 10 million pulses per second (Mpps). Figure

2 contains an illustration of a Gaussian pulse train. In the frequency domain, this highly regular pulse train produces energy spikes ("comb lines") at regular intervals; thus, the already low power is spread among the comb-lines. This pulse train carries no information and, because of the regularity of the energy spikes, might interfere with conventional radio systems at very short ranges.

A Pulse Train in the Time and Frequency Domains
Figure 2



Impulse systems have very low duty cycles and Figure 2 exaggerates the typical duty cycle found in Time Domain's prototypes. In actual implementation the actual duty cycle is less than 1%.

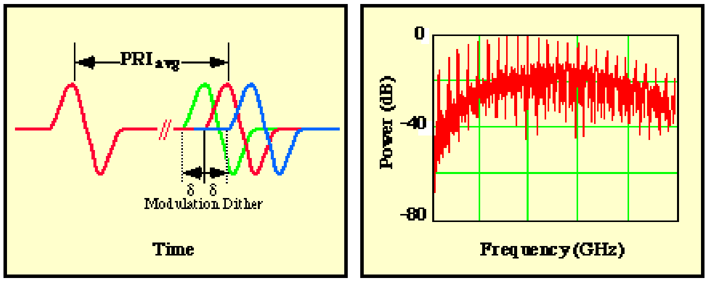
Modulation

Additional processing is needed to modulate the pulse train, so the system can actually communicate information.

Time Domain's systems use pulse position modulation as it allows the use of an optimal receiving matched filter technique. Time Domain's receivers use a cross correlator which gives the receiver the ability to find the signal well below the ambient noise level.

As illustrated in Figure 3, pulse position modulation varies the precise timing of transmission of a pulse about the nominal position. For example, in a 10 Mpps system, pulses would be transmitted nominally every 100 ns (represented in Figure 3 as the time period PRI avg). In such a system a "0" digital bit might be represented by transmitting the pulse 100 ps early and a "1" digital bit by transmitting the pulse 100 ps late.

Pulse Position Modulation
Figure 3

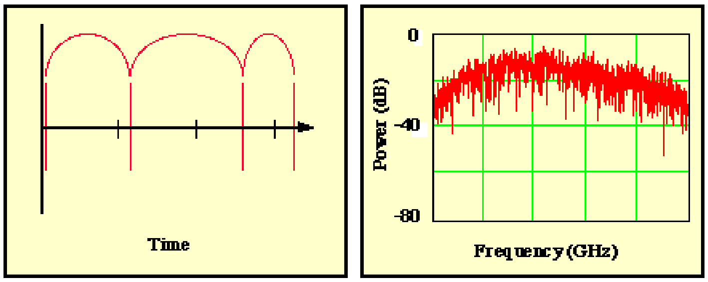


As shown in the right hand graph in Figure 3, pulse position modulation distributes the RF energy more uniformly across the band (it smooths the spectrum of the signal), thus making the system less detectable. However, because information modulation only moves the pulses only a fractional part of a pulse width, this spectral smoothing impact is small.

Pseudo-random Noise Coding - Coding for Channelization

At this point any modulated pulse train looks like any other pulse train; it is not channelized. However, by shifting each pulse's actual transmission time over a large time frame in accordance with a code one can channelize a pulse train. As illustrated in Figure 4, Time Domain applies a relatively large time offset (many nanoseconds) to each impulse. Time Domain uses "pseudo-random noise" codes (PN codes) for this purpose. For a multiple access, each user would have their own pseudo-random noise code sequence. Only a receiver operating with the same pseudo-random noise code sequence can decode the transmission.

Pseudo-Random Noise Coding
Figure 4



In the frequency domain, this PN code make Time Domain's signal appear like noise. As a result, anyone attempting to detect the presence of the signal would have to be very close to the transmitter and even then would not be able to decode the transmission.

A system can be implemented for the highest communications security requirements.

Besides channelization and energy smoothing, the pseudo-random noise coding also makes impulse radio highly resistant to jamming from all radio communications systems, including other impulse radio transmitters. This is critical as all other signals within the band occupied by an impulse signal act as jammers to the impulse radio. Since there are no unallocated 1+ gigahertz bands available for impulse systems, they must share spectrum with other conventional without being adversely affected. The pseudo-random noise code helps impulse systems discriminate between the intended impulse transmission and transmissions from others.

Jam Resistance and Process Gain

Process gain is a measure of the radios resistance to jamming. Impulse radio has a huge processing gain. One definition of processing gain is the ratio of the bandwidth of the signal to the bandwidth of the information signal. For example, Qualcomm's spread spectrum system with a 8 kHz information bandwidth and a 1.25 MHz channel bandwidth yields a processing gain of 156 (22 dB). An impulse system transmitting the same 8 kHz information bandwidth and a 2 GHz channel bandwidth the processing gain is 250,000 or 54 dB.

Alternatively, the process gain for an impulse signal may be calculated from:

- The duty cycle of the transmission, e.g., a 1% duty cycle yields a process gain of 20 dB.
- The effect of integrating over multiple pulses to recover the information, e.g., integrating energy over 100 pulses to determine one digital bit yields a process gain of 20 dB.
- The total process gain is then 40 dB.

Thus, a 2 GHz / 10 Mpps link transmitting 8 kbps would have a process gain of 54 dB, because it has a 0.5 ns pulse width with a 100 ns pulse repetition interval = 0.5% duty cycle (23 dB) and 10 Mpps / 8,000 bps = 1250 pulses per bit (another 31 dB).

System Capacity

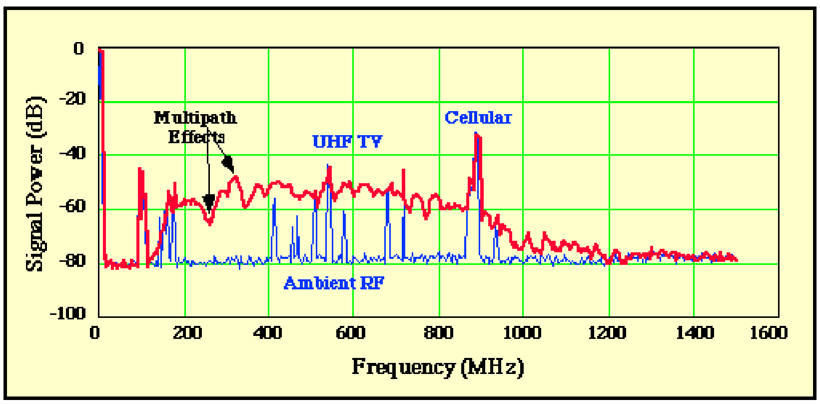
A theoretical analysis, conducted for Pulson by Professor R.A. Scholtz of the University of Southern California ("Multiple Access with Time Hopping Impulse Modulation"), suggest that Time Domain's

impulse radio system could have thousands of voice channels per cell without special signal processing algorithms [1]. Others have analyzed the system, and using more realistic assumptions, estimate the capacity to be between 200 and 1000 simultaneous telephone conversations per base station, depending upon numerous environmental factors and also without special signal processing algorithms.
Using a cellular architecture and standard radio engineering practices, Time Domain can achieve very high densities of simultaneous users.

Performance in the Real World - Time Domain's Test Systems

An early prototype built by Time Domain has an average radiated power of 450 microwatts. The center frequency was 675 MHz and smoothed by a pseudo-random code with 256 positions. Figure 5 shows the signal measured at 3 meters as well as ambient signals. The power spike just below 900 MHz is from two cellular base stations, one at about 400 meters distance, another about 1.6 kilometers distance. The spikes between 360 MHz and 720 MHz are predominantly UHF television stations. The 720 MHz spike is a 2.2 megawatt EIRP channel 54 station approximately 7 miles distant. (The "bumpiness" of the impulse spectral measurements reflects the impact of frequency domain multipath. Moving the receive antenna causes the location of nulls and peaks to move. This does not impact the performance of the impulse system. See "Multipath and Propagation" below.)

675 MHz Impulse Signal At 3 Meters*
Figure 5



**Measurements not adjusted to compensate for antenna performance.*

Time Domain also built a 1.3 GHz / 2 Mpps prototype with an average output power of 33 µW. Its performance has been measured over two paths:

1. With a -9.6 dBi transmit antenna buried in a highly conductive medium which had a total loss of 36 dB over a 6 cm path, Time Domain transmitted a 125 kbps pseudo-random bit stream an additional 4 meters through air to a 10 dBi receive antenna. The bit error rate was better than 0.5 x 10-5. The demonstration took place in an office building.
2. With the same experimental set-up and the same location, the bit rate was lowered to 7.8 kbps and range was increased to 10 meters. The bit error rate was better than 10-6.

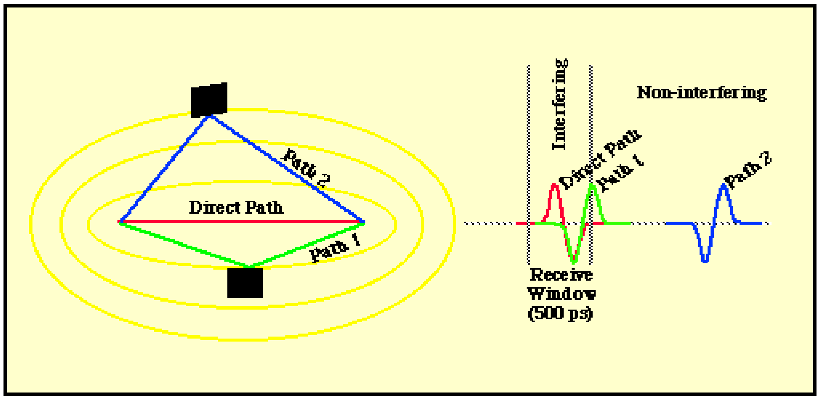
Most recently, Time Domain's engineers have constructed a full duplex 1.3 GHz system operating at 5 Mpps. The system transmits at either 39 kbps or 156.25 kbps. The system has been tested successfully on long range links exceeding sixteen kilometers (ten miles) and within buildings.

Multipath and Propagation

Multipath fading, the bane of sinusoidal systems, is less of a problem for impulse systems than for conventional radio systems. In fact Rayleigh fading, so noticeable in cellular communications, is a continuous wave phenomenon, not an impulse communications phenomenon. In an impulse system in order for there to be multipath effects, special conditions must persist. Either:

* The path length traveled by the multipath pulse must be less than the pulse width times the speed of light. For a 2 GHz pulse, that equals 0.15 meters or about 1/2 foot, i.e., [1/2 ns] x [300,000,000 meters/second]. (See Figure 6, in the case where the pulse traveling "Path 1" arrives one half a pulse width after the direct path pulse.); or
* The multipath pulse travels a distance that equals the interval of time between pulses times the speed of light might interfere times an integral number with the next pulse. (For a 1 Mpps system that would be equal to traveling an extra 300, 600, 900, etc. meters.) However, because each individual pulse is subject to the pseudo-random dither, these pulses are decorrelated.

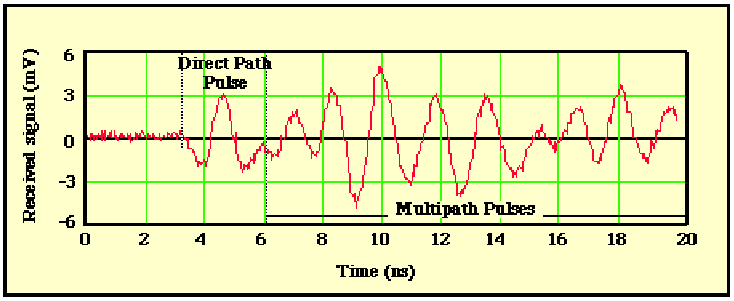
Multipath in an Impulse System
Figure 6



Pulses traveling between these intervals do not cause self-interference (in Figure 6, this is illustrated by the pulse traveling Path 2). While pulses traveling grazing paths, as illustrated in Figure 6 by the narrowest ellipsoid, create impulse radio multipath effects.

Figure 7 shows how easy it is to resolve multipath impulse signals in the time domain. These measurements were made in a single story office complex. The laboratory contained many feet of steel shelving, test equipment, and metal filing cabinets. One adjacent office space was occupied by a metal fabricating company. The other was occupied by a personal computer sales offices along with that company's warehouse (using steel shelving). (Note: The receive antenna's characteristics convert the Gaussian monocycle into a "W" waveform.)

Time Domain Measurement of 675 MHz Impulse Signal at 12 Meters
Figure 7



The first arriving pulse (between 3 ns and 6 ns) is of lower amplitude because it traveled through more walls than some later arriving pulses, e.g., the pulse arriving at between 8 ns and 11 ns.

Key Components in Constructing a Time Domain System

Time Domain Corporation has expended significant resources to develop its impulse communications systems and determined that while all components must be very carefully designed, certain components determine the ultimate feasibility of producing impulse communication systems in mass quantities.

Time base	Because this system uses picosecond deviations of the pulse position, an accurate clock is an absolutely necessity. Just a few years ago sufficiently accurate clocks were too expensive for consumer products; this is no longer true as technology has improved and new consumer products demand high performance clocks, e.g., cellular telephones and consumer GPS receivers.
Antenna	Most antennas are designed to operate over very narrow bandwidths. Time Domain Corporation has a small, effective broad band antenna. The dimensions for an 1.9 GHz center frequency Time Domain system would be about 5 cm x 7 cm x 0.7 cm or 2 in. x 3 in. x 0.3 in. (Time Domain's antenna is patented.)
PN codes	Codes must be orthogonal with respect to other codes as well as to themselves, i.e., there must be neither cross- nor auto- correlation. Additionally, the codes must smooth the energy distribution effectively and allow fast signal locking. There has been extensive research in the area of coding, which shows a large numbers of codes do have the proper qualities required by Time Domain's impulse system.

Simplicity

Time Domain's impulse radios are much simpler to build than equivalently sophisticated conventional radios.

The transmitter is much simpler than a narrowband transmitter, it is simply a single transistor that operates in a digital mode - it flips from a "0" state to a "1" state. This transition produces a step waveform that can be easily filtered to produce a monocycle. Thus, unlike conventional transmitters it does not contain a linear amplifier, which reduces cost and power consumption.

The receiver is also simpler than a narrowband receiver as it does not require IF stages. And unlike spread spectrum receivers, the control loop operates at very low frequencies, which also saves cost.

Preliminary studies suggest the impulse transmitter and receiver front end can be built on a single chip. In addition to this chip a complete impulse radio would include a time base and a microcontroller. Time Domain Corporaiton sees no impediments to producing an impulse radio cordless telephone system for an under $200 retail price.

Summary

Time Domain's impulse radios have far superior performance in high multipath environments than narrowband radios, including spread spectrum technologies from such manufacturers as Qualcomm and Omnipoint. Multipath is a critical problem for most radio system because people live in environments where there are lots of objects that reflect radio signals. In these environments, impulse radios can operate at high data rates with lower bit error rates and with lower transmit powers. Moreover, it can do all this within the regulatory limits established by the FCC in their Part 15 regulations.

Sources

[1] R.A. Scholtz, "Multiple Access with Time Hopping Impulse Modulation" (Invited Paper), MILCOM'93, Bedford, MA, October 11-13, 1993.