Principles of Ultra Wideband Communication

Overview

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Introduction

- History
- What is Ultra wideband technology
- Main principlee
- Difference from WCDMA
- Signal & Spectral characteristics
- Channel statistical characteristics
- Modulation & demodulation
- Transceiver
- Antenna
- Applications
- Reference

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History

- The earliest UWB system, Spark-gap transmitter in 1897 by *Guglielmo Marconi*
- UWB as a technology began developing in 1950s
- *Larry Fullerton* is the first who conceived the idea of UWB in 1973 and founded the Time Domain Corporation
- Modern UWB system, is done at Sperry Research Center in the 1980's by Ross
- in 1980's and 1990's the principle of *time-domain electromagnetics* were applied to wireless communications

Difference from WCDMA

- It is not the traditional spread spectrum technique.
  - Lower interference
  - Without dedicated frequency
  - Inherent covertness in secure
  - Using a unique timing code for a pair of specific transceivers
  - Multiple pulse comprise each bit, + timing code make this technology suitable for noisy radio environment
- Same advantage: enhance process gain on received signal, operate in the presence of other higher-powered radio system

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UWB characteristics (1)

- UWB shares the same spectrum with existing users
- A revolutionary wireless technology
- UWB systems make use of narrow pulse (Impulse) and time-domain signal processing.
- Transmitting digital data over a wide spectrum of frequency with very low power (Ptx<50mw)
- At very high transmission rate (WLAN) (short distance); At very low transmission rate (telemetry applications)
- Ability to carry huge amount of data through doors or other obstacles

UWB characteristics (2)

- Time modulation
- UWB technology is not a continuous sine wave technology
- Does not require an assigned frequency or a power amplifier
- This technology does not interfere with regular radio services
- The invention potentially opens up an almost limitless number of new channels for communication
- Low probability of intercept/detection and anti-jam properties: ideal for covert communication links
- No interference to the narrowband system in deicated bands

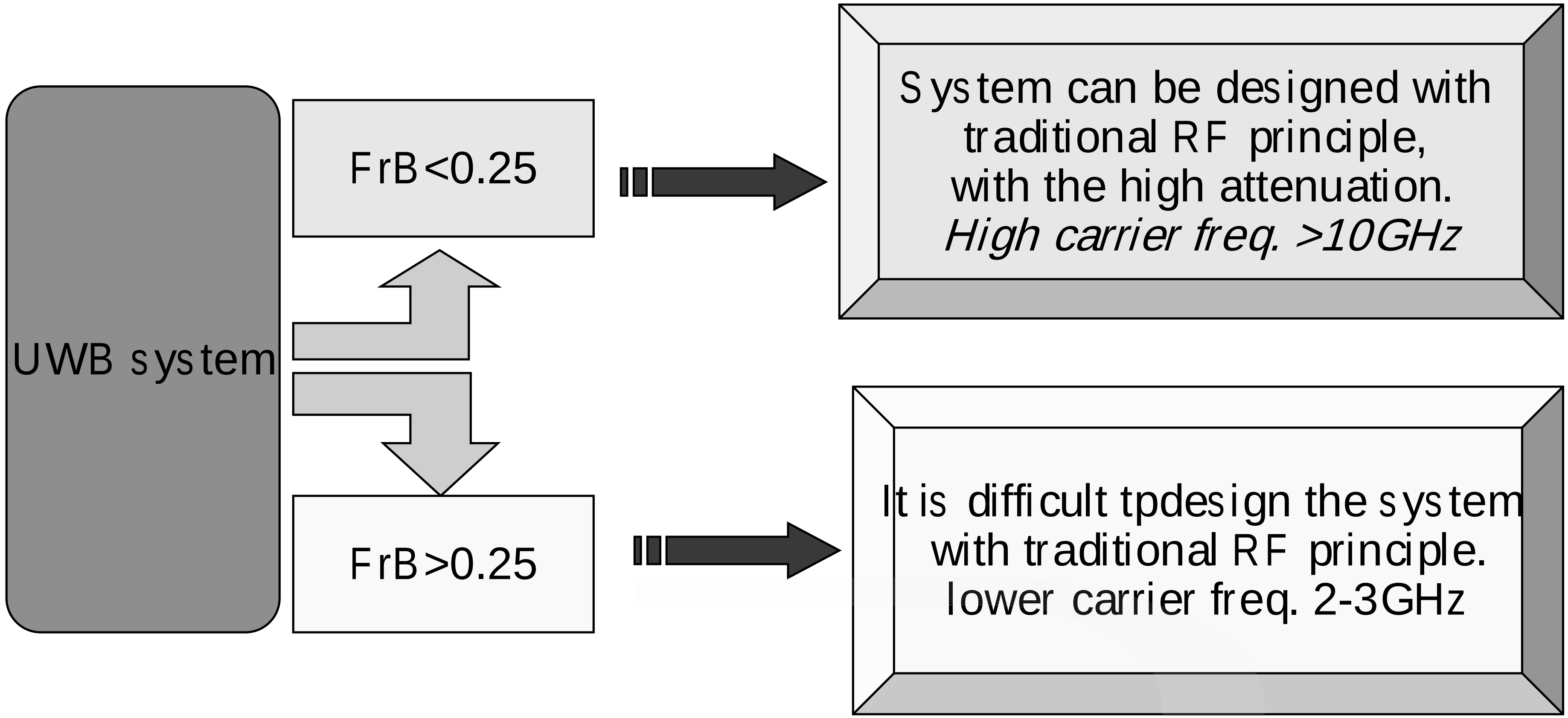
Principle (1)

- Time Domain's founder, *Larry Fullerton* discovered that single RF monocycles could be transmitted through an antenna and by precisely positioning these monocycles in time and then using a matched receiver to recover the transmissions created a whole new wireless medium.
- Utilizing narrow Gaussian mono-pulses and time hopping spread the signal spectrum over a wide frequency range
- Pulse timing within the allotted pulse frame is controlled by a time PN code.
- The PN code determines the time bin assoiated with each pulse's niominal time.
- Time modulation (TM) is utilized to transmit each data bit by precisely controlling the timing of each pulse within its designated time bin.
- Time hopping spread the signal spectrum -> RF energy to distribute more uniformly across the frequency band. -> channelization for multiaccess systems

Principle (2)

- In traditional fashion, the communication system alway uses the some frequency band, and the radio spectrum is divided into band and the channel. and then the signal transmitted in the channel can be tractable, and the signal is said carrying by the ”carrier”.
- UWB sysytem operates as spread spectrum systems: i.e. bandwidth>> minimal effective data rate
- Very short duration of pulse -> The duration of the pulse is typically short that the interval corresponding to a single bit.
- UWB does not rely on a spreading sequence or a hopping sequence to produce a wide bandwidth signal -> short duration of basic pulse
- It has always been possible to generate the signal without the carrier.
- Carrierless -> Anttena is excited with baseband signal directly.
- UWB works in the *power-limited regime*.

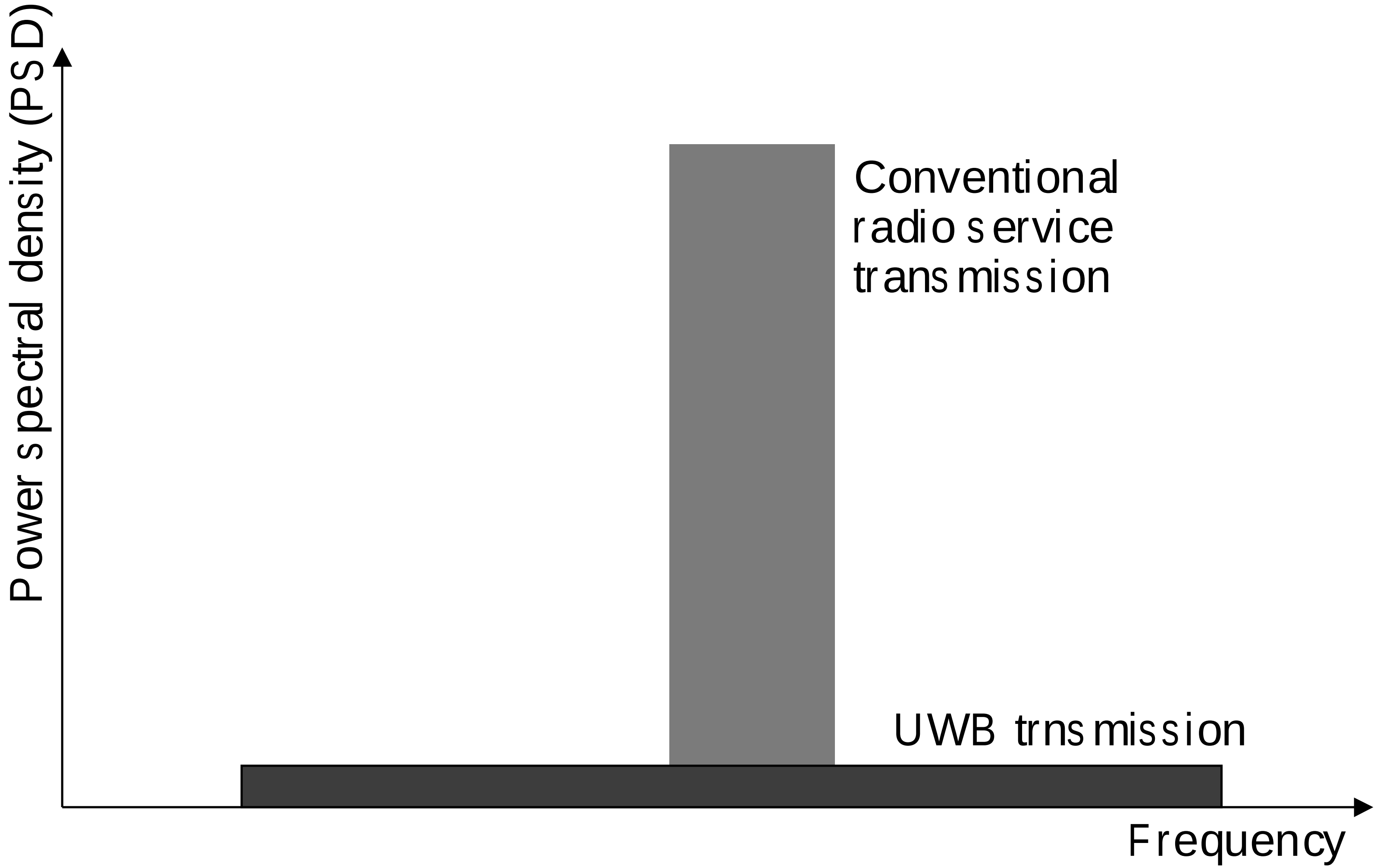
UWB systems



Fractional bandwidth (FrB): is the ratio of the bandwidthof a signal to the center frequency of transmission.

Time-domain modulation
i.e. *impulse radio*

Spatial Spectrum



Spatial Capacity

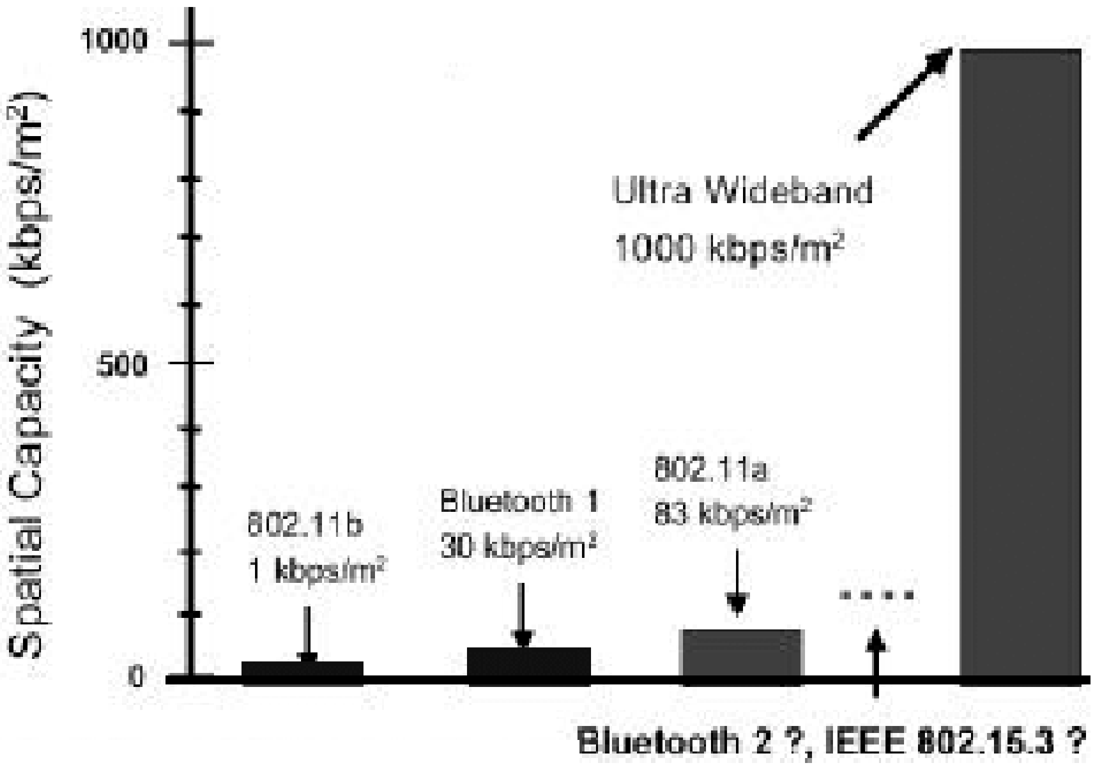


Figure 1. UWB transmissions provide the highest spatial capacities because of their inherently wide bandwidths. Source: [4].

Signals

- A general UWB pulse train signal cab be presented as a sum of pulses shifted in time:

$$s(t) = \sum_{k=-\infty}^{\infty} a_k p(t - t_k)$$

- where, *s(t)* is the UWB signal; *p(t)* is the basic pulse shape; a_k and t_k are the amplitude and time offset for each individual pulse.
- Due to the short duration of the pulse, the spectrum of the UWB signal can be several gigahertz or more in bandwidth.
- FCC proposes that UWB system be permitted to operate on an unlicensed basis at extremely low transmit power levels.

Signal - monocycle

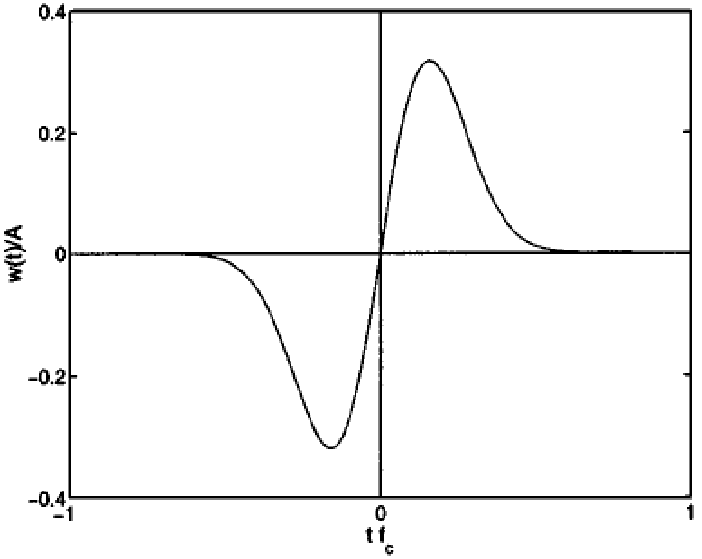


Fig. 5. Plot of the Gaussian monocycle $w(t)$ in normalized units. The pulse duration τ is defined as the time interval between the pulse's maximum and minimum amplitudes.

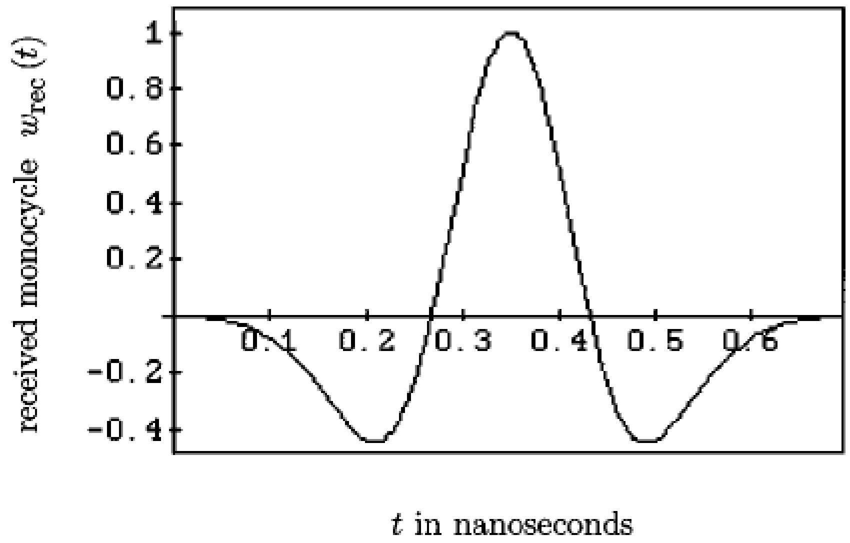


Fig. 1. A typical idealized received monocycle $w_{rec}(t)$ at the output of the antenna subsystem as a function of time in nanoseconds. The model used in this plot is $w_{rec}(t + 0.35) = [1 - 4\pi(t/\tau_m)^2] \exp[-2\pi(t/\tau_m)^2]$ with $\tau_m = 0.2877$.

Monocycle in TD and FD

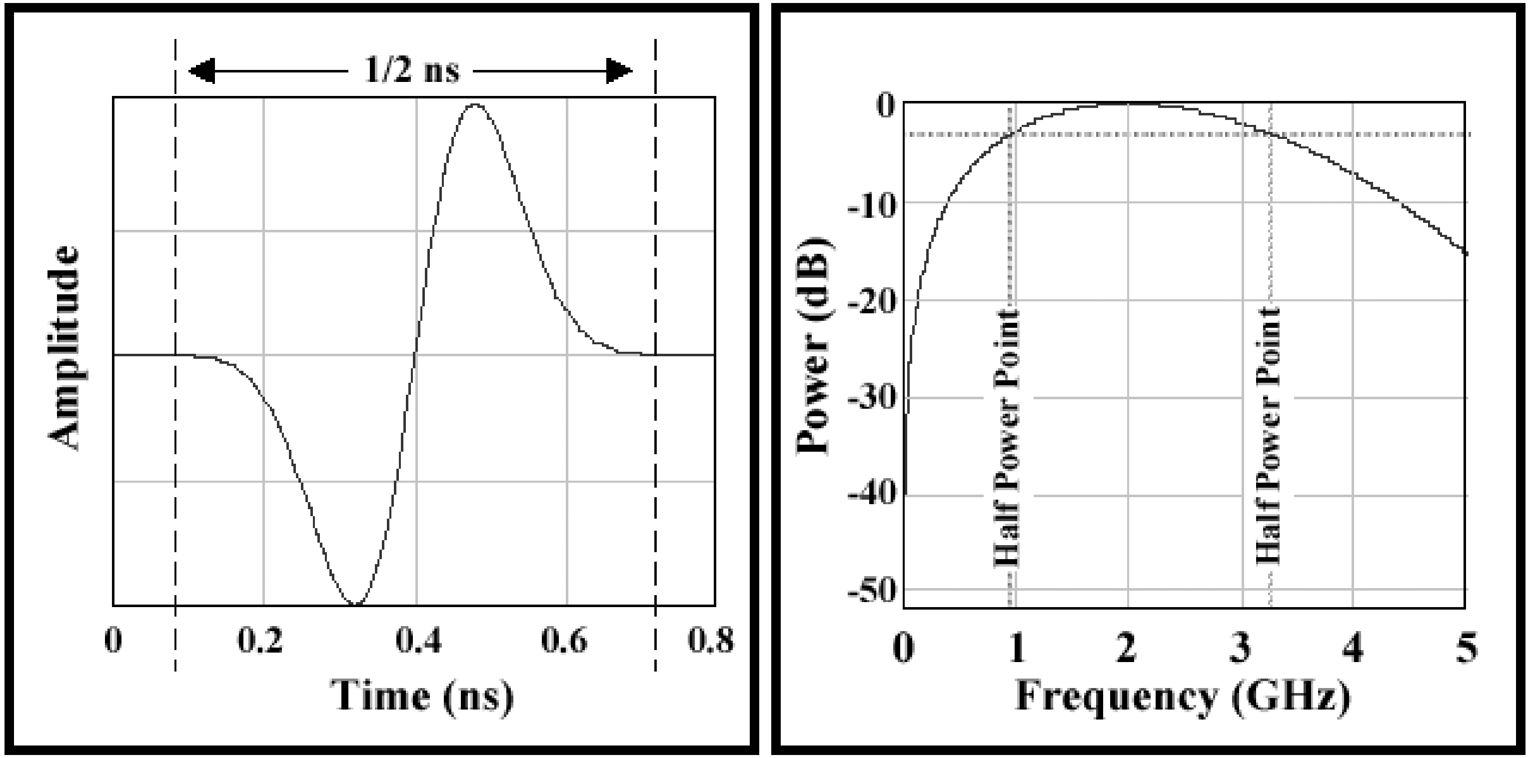


Figure 1. 2 GHz Center Frequency Gaussian Monocycle in Time and Frequency Domains

Pulse train in TD and FD

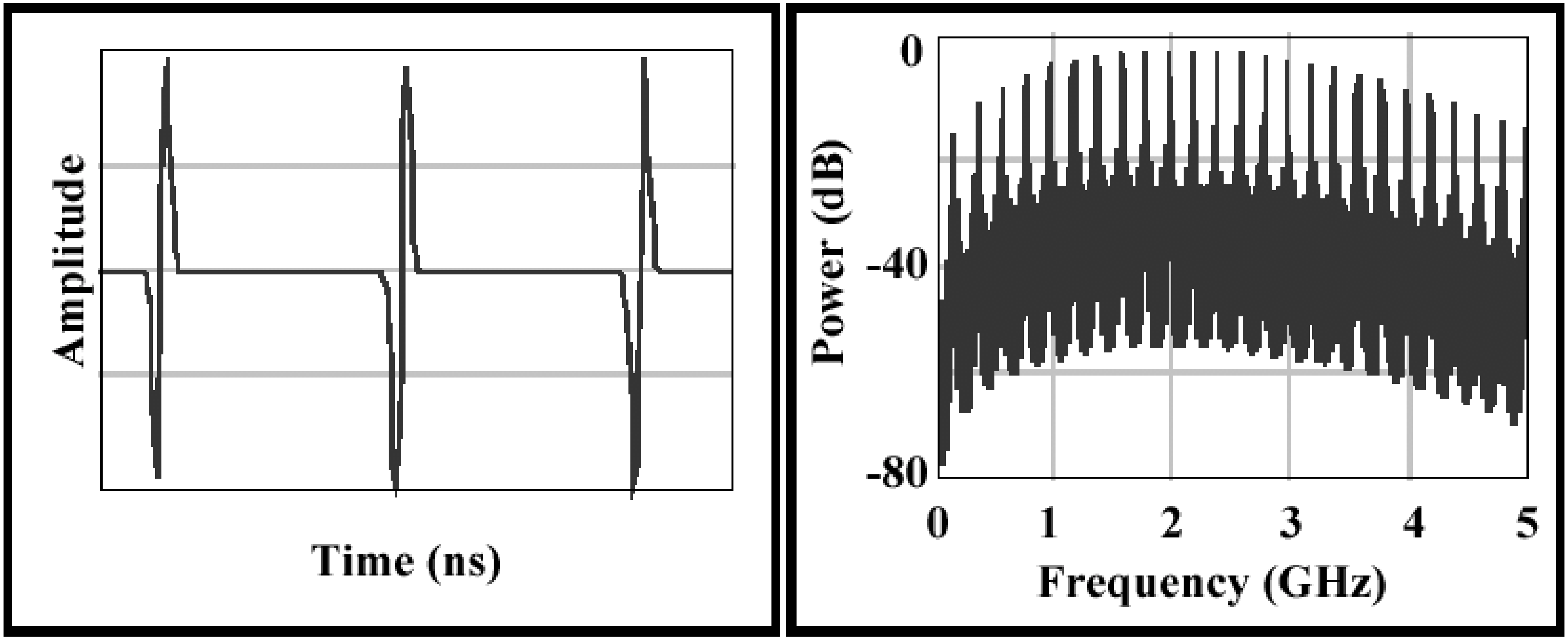


Figure 2. A Monocycle Pulse Train In The Time and Frequency Domains

Generate the long sequence

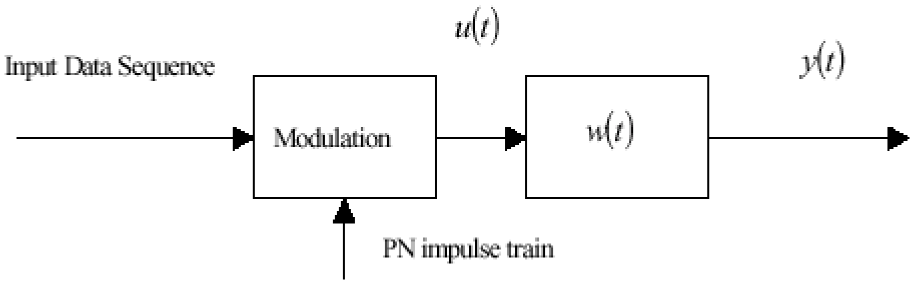


Figure 1. The simplified block diagram of UWB transmitter.

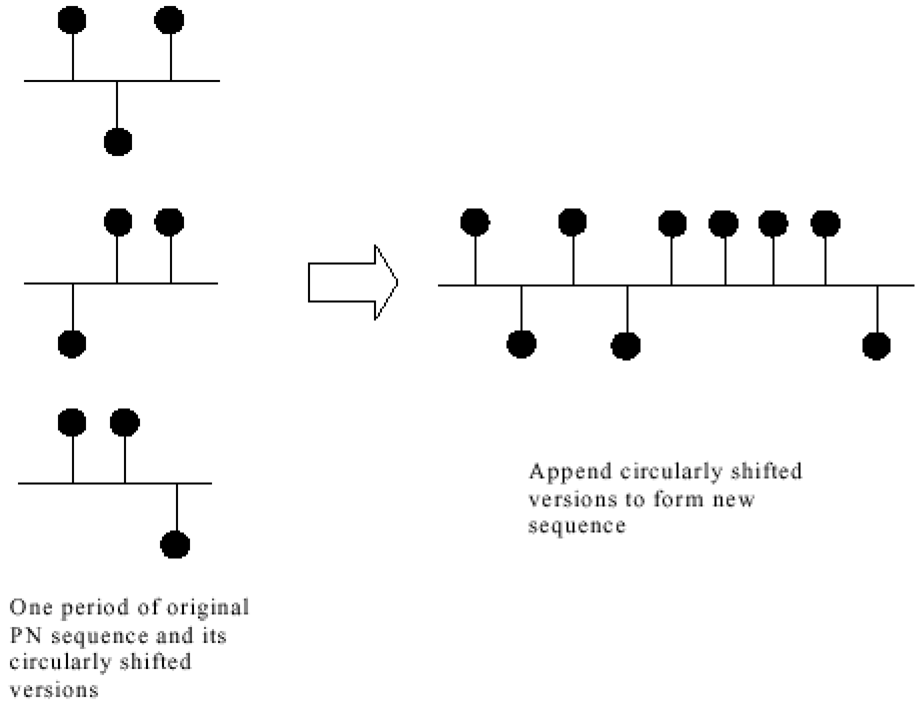


Figure 2. Example of period extension to form longer period PN sequence.

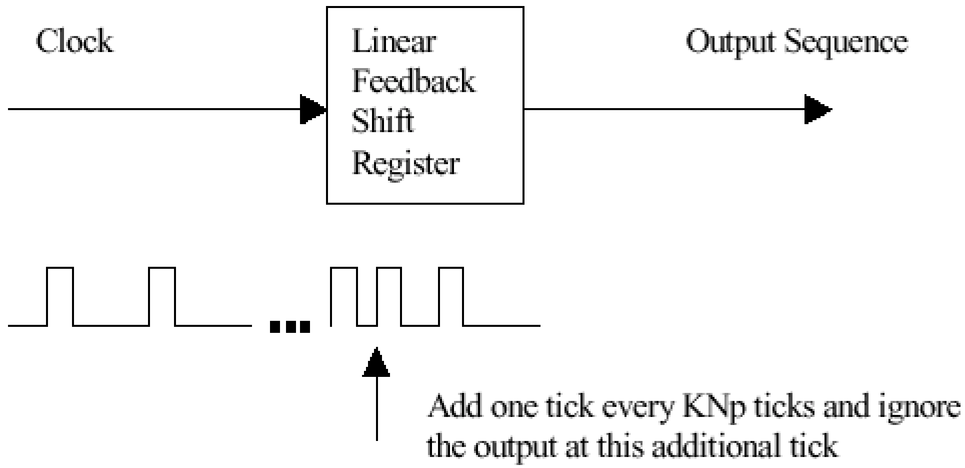
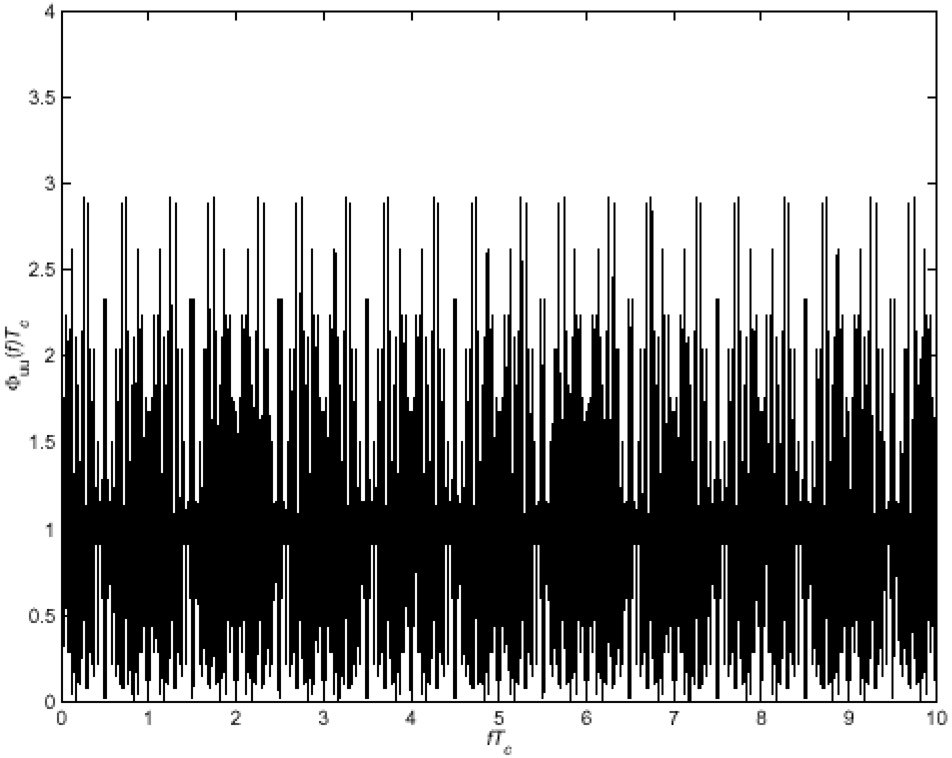


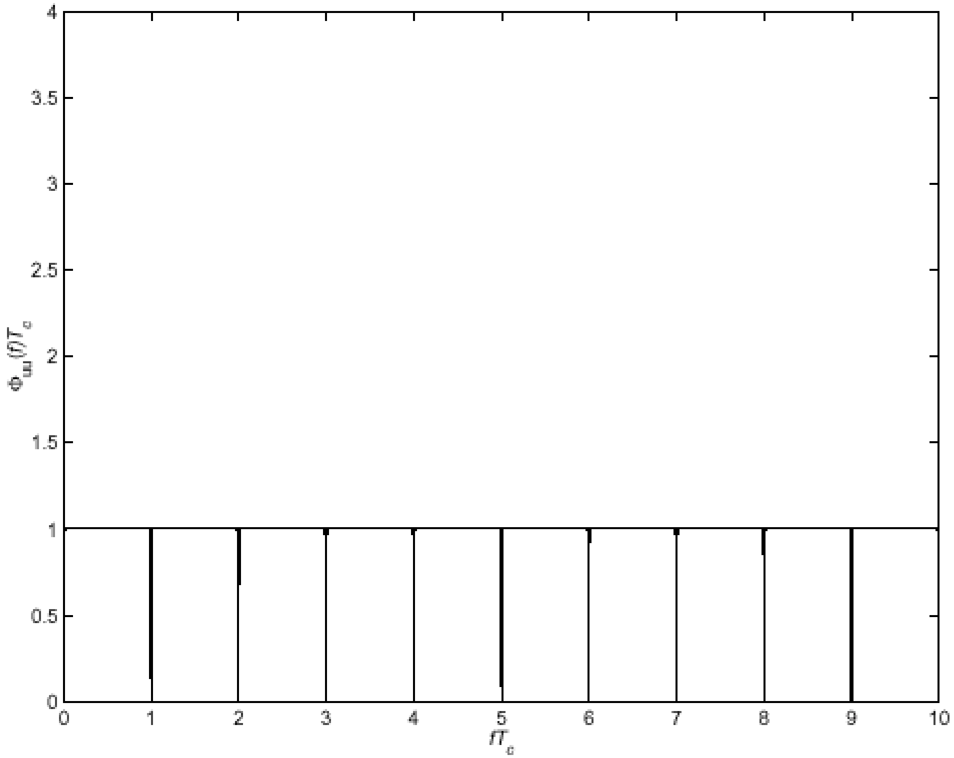
Figure 3. Linear feedback shift register implementation of extending the period of a PN sequence.

Near-white UWB signal spectrum



(a)

$$c(t) = \sum_{i=-\infty}^{+\infty} c_i \delta(t - iT_c),$$



(b)

Figure 4. The comparison of normalized PSDs of (a) UWB signal generated by original PN sequence and (b) UWB signal generated by period extended PN sequence. The normalized frequency is defined as fT_c.

Modulation (1)

- ***BPSK*** (*Binary phase-shift keying*) modualtion: if data sequence is random and i.i.d. with zero mean, the spectrum will vanish. (Spectrum lines will incur the reduction of the total transmit power.)
- ***Pulse-position modulation*** (PPM): Time–domain signal processing:
  - The pulses are not uniformly paced in time.

$$s(t) = \sum_{k=-\infty}^{\infty} p(t - kT + a_k \beta T)$$

  - where, a_k is the data $a_k \in \{-1,1\}$ and βT is the amount of pulse advance or delay in time relative to the reference (unmodulated) postion
  - Whenever $1/\beta$ is an interger greater that two, then there are no spectrum lines.
- Others:
  - OOK: *On-off keying*
  - PAM: *Pulse-amplitude modulation*

Modulation (2)

- Consider the transmission of a train of pulses equally spaced in time. the receiver processing determines whether each received pulse is located where expected or arrives early or late.
- With PPM, a slightly retarted pulse could represent a ”0” and a slightly advanced pulse could represent a ”1” when transmitting digital information.
- The important point in Modulation’s selection is to consider the spectral properties in order to archieve maximum power efficiency.
  - i.e. to select a power efficient modulation scheme with a smooth PSD (power sprectrum density).

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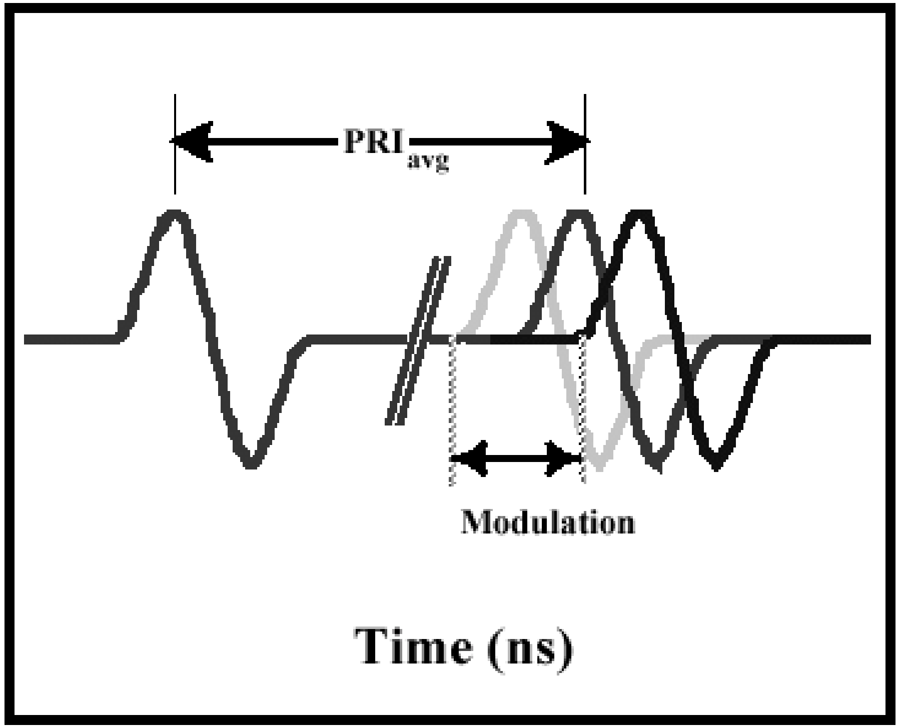
Pulse Position Modulation



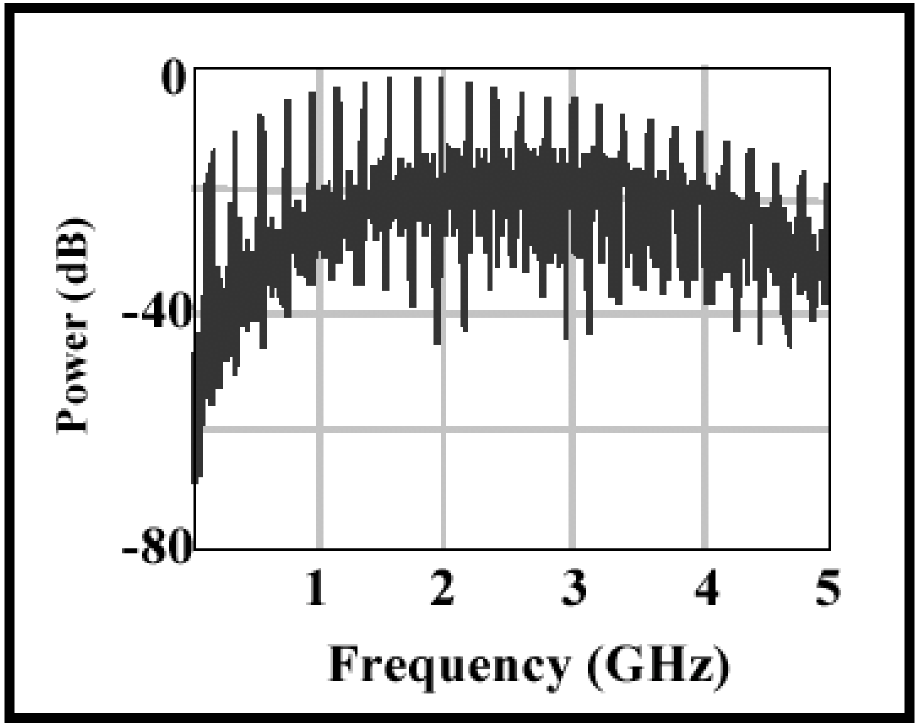
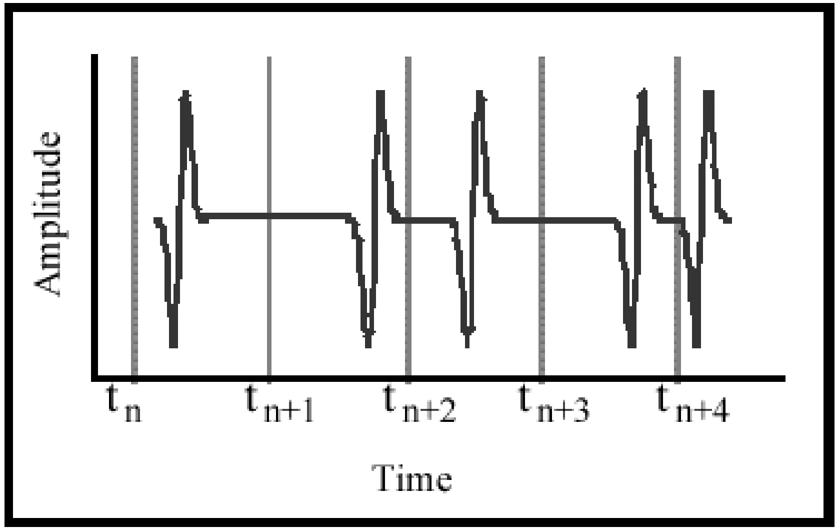


Figure 3. Pulse Position Modulation

Coding and channelization



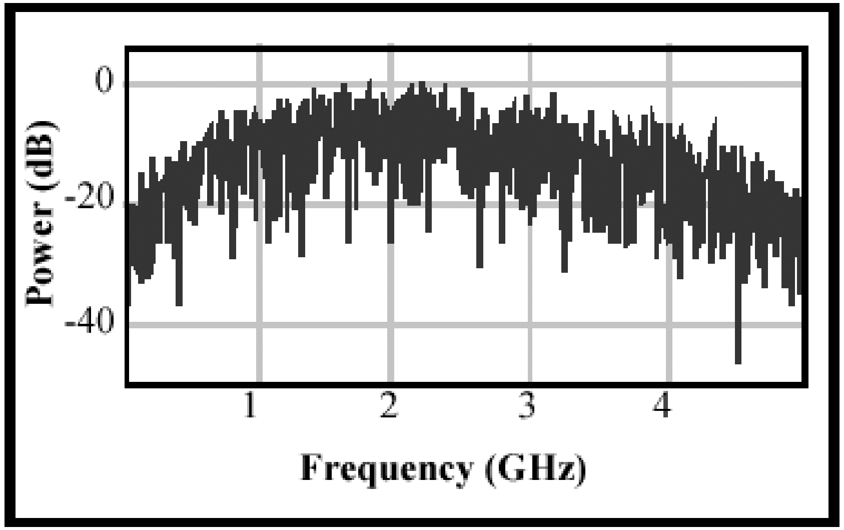
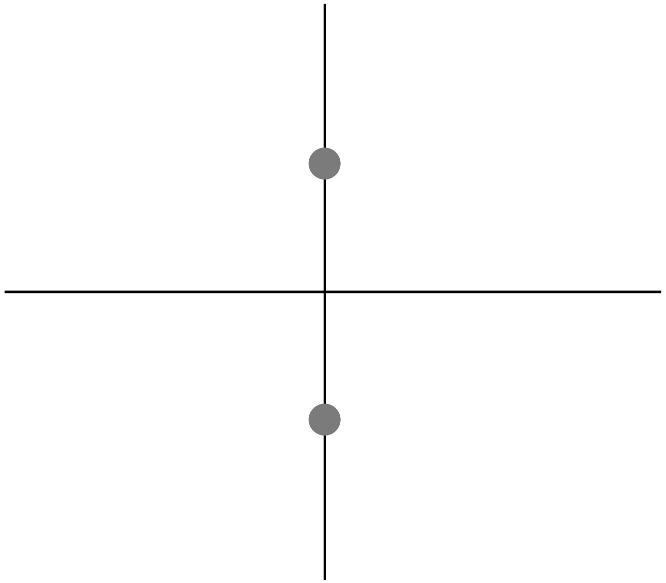


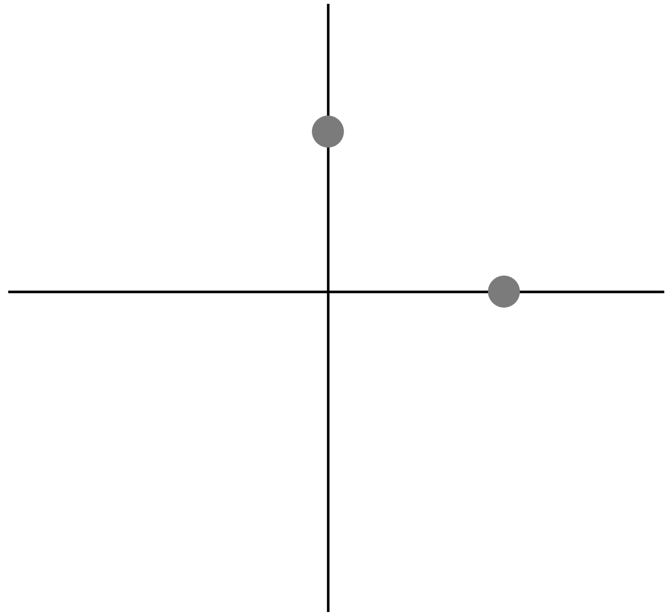
Figure 4. The Impact of Pseudo-Random Time Modulation on Energy Distribution in the Frequency Domain

Constallation disgrams



BPSK

Greatest inter-symbol distance:
- 3 dB advantage in efficiency than PPM.
- It seems the best selection from this viewpoint.



PPM

Time offsets for the pulses are chosen to make two possible pulses orthogonal at the receiver.
PPM must use 2 times bit energy to archieve the same bit error rate compared to BPSK

Spectrums

BPSK:

$$\Phi_{BPSK}(f) = \frac{1}{T}\left|P(f)\right|^2$$

OOK: (*PPM: when 1/β is an integer greater than two*)

$$\Phi(f) = \frac{1}{T}\left|P(f)\right|^2 + \frac{1}{T^2}\sum_{k=-\infty}^{\infty}\left|P(\frac{k}{T})\right|^2 \delta(f - \frac{k}{T})$$

discrete spectral lines

where $P(f)$ is the Fourier transform of $p(t)$
$\delta(f)$ is the unit impulse

Demodulation

- Scheme selection: Target is to reduce the complexity of structures.
- Non-coherent (an envelope detector) demodulation is based on
  - Simplify timing requirement
  - Bandwidth required of samplers or A/D converters
- UWB has had many properties to reduce the design complexity:
  - No requirement on carrier recovery or frequeny translation
  - UWB transmitter will not require a power amplifier.
- Coherent demodulation:
  - BPSK must use a coherent demodulation: every pulse looks the same out of the envelope detection.
  - Possible to use the optimal RAKE combining to improve the S/I.

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Forward error correction and coding

- Operation in a power-limited regime has implications for forward error correction techniques.
- Signal-space codes, such as Trelli codes, that increase the alphabet size are good for band-limited applications, but not as appropriate for UWB systems.
- Appropriate coding technique for power-limited regime also has the potential to significiantly improve the UWB system performance.

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Transmitter/receiver

- **UWB trnsmitter:** operates in baseband, no power amplification, baseband mono-pulse is directly apllied to the antenna
- **UWB receiver:** operates in baseband, no IF stage
- **Entire UWB transceiver systems** have been fabricated on CMOS chips.

PulseON® TM UWB transceiver

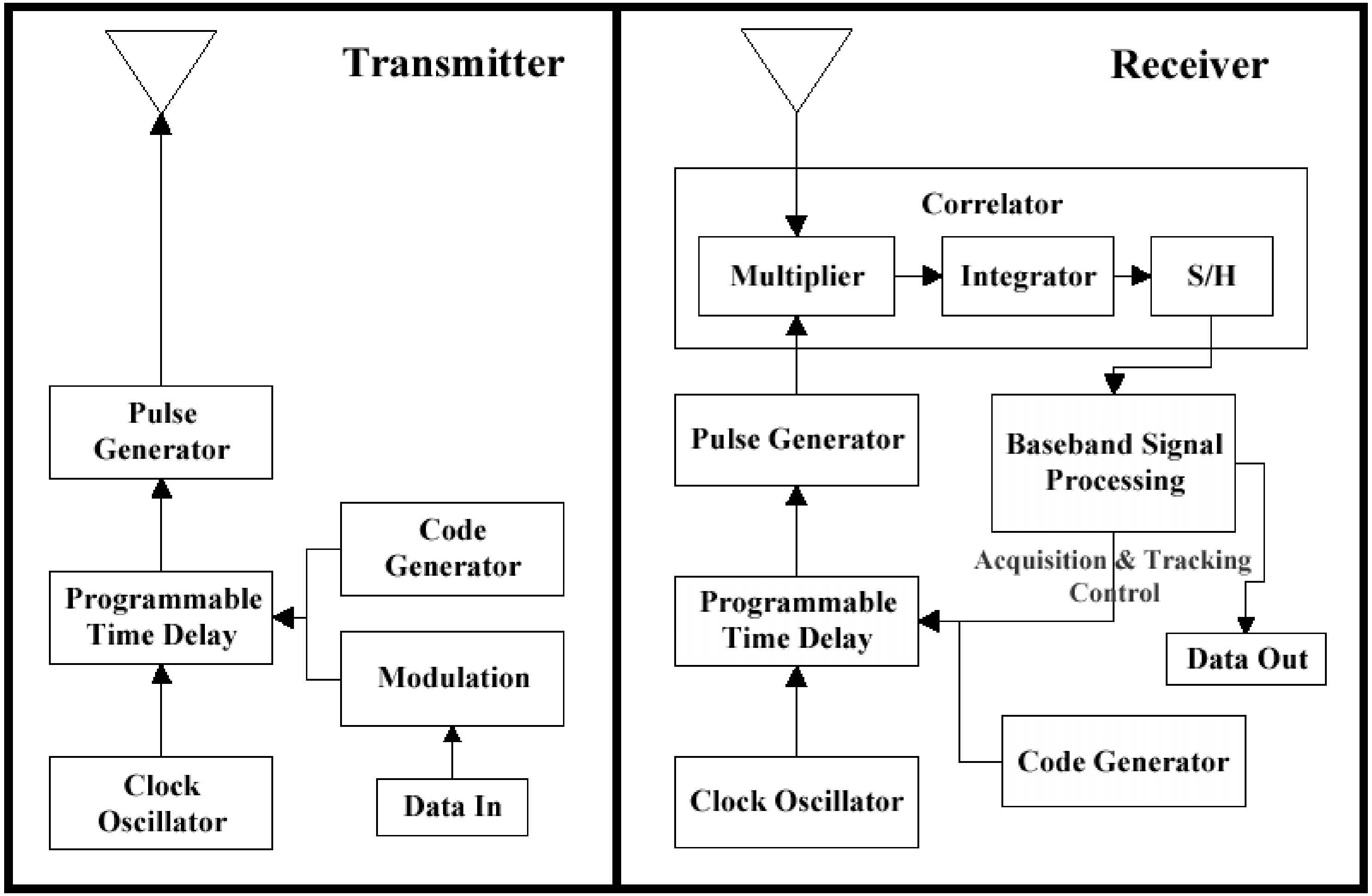

Figure 6. PulsON® Transceiver Block Diagram

Correlator Output

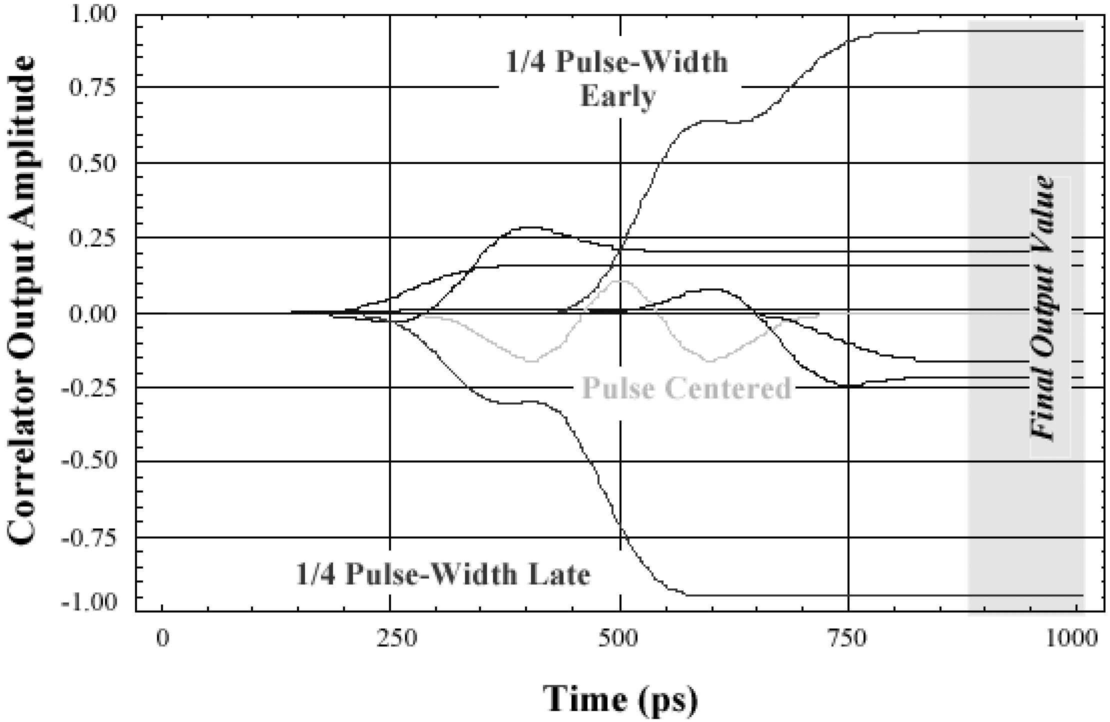

Figure 5 : Correlator Output

•A correlator is a correlation receiver

•A correlator multiplies the received RF signal with a "templete" waveform, and then integrates the output of that process to yield a single DC voltage.

•This multiply-Integrate process occurs over the duartion of the pulse

•Correlator is an optimal earlt/late detector:

•when the received pulse is ¼ of a pulse early, the output is "+1"

•when the received pulse ise ¼ of pulse late, the output is "-1"

•when the received pulse arrives centered in the correlation window, the output is "0"

• The pulse-integration process will pick up the transmitted signal below the nois e floor

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Antennas

- Antenna technique has a challenge for UWB system, especially for one in which the fractional bandwith is greater than 0.25.

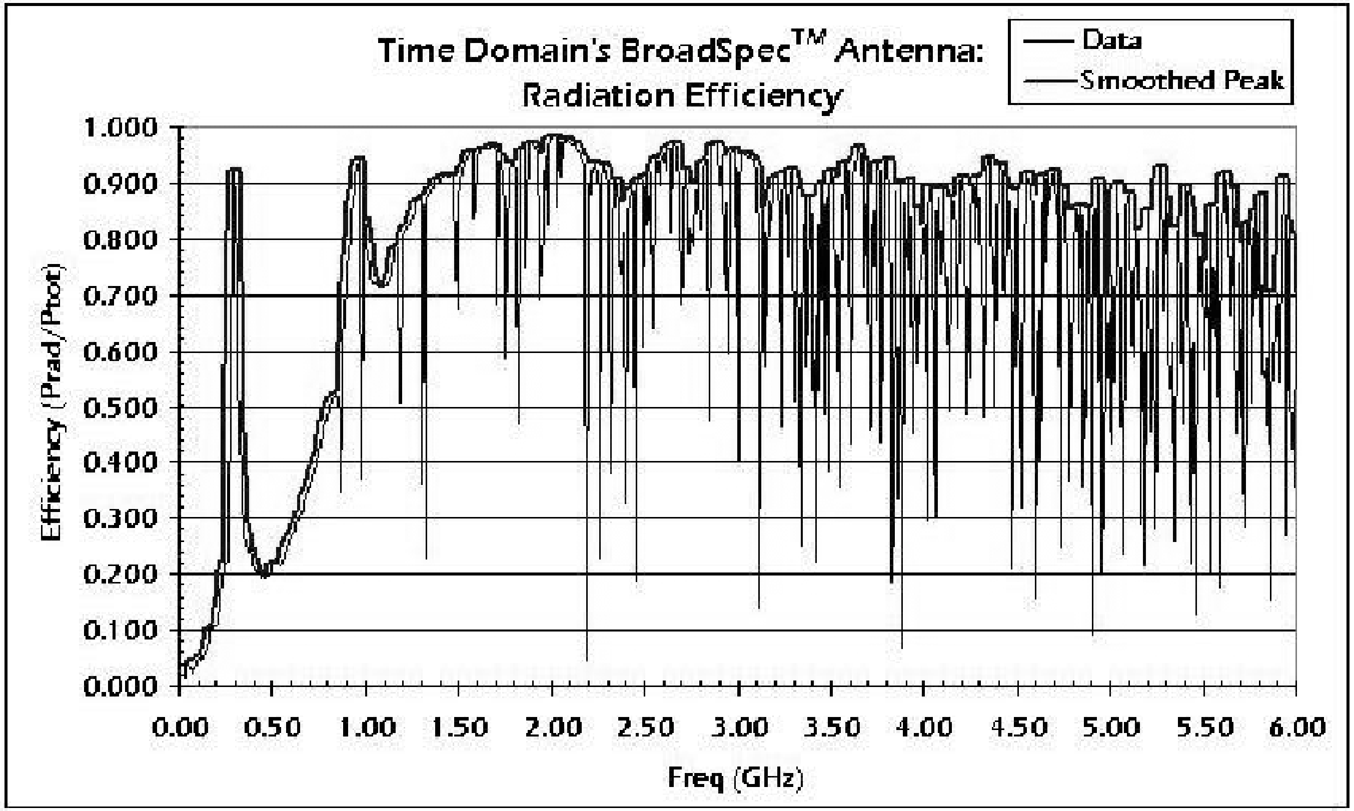

Figure 2: Radiation efficiency of a Time Domain Corporation BroadSpec™ Antenna.

An indoor channel model

- Indoor communication is the main use of UWB in communication field now.
- The channel can be modeled by the signal (last slide)
- Main parameters to characterize the indoor channel model
  - Multipath delay spread
  - Multipath idensity profile
  - Multipath fading distribution
  - Multipath arrival times

Indoor UWB channel statistics (1)

- A UWB channel can be defined by the SNR of the LOS path.

$$SNR = 10\log\frac{\sum_{n=0}^{N-1} s^2(n,\theta)}{\sigma^2} dB$$

- where, *s(n,θ)* is the normalized largest incident signal; N is the numer of time samples where the signal is assumed to be nonzero, θ is the angle-of-arrival, and σ^2 is the variance of the noise floor.
- The temporal-spatial distribution of signal energy is charaterised by the first moment and the root of second moment of power delay profile:

$$\overline{T}_k = \frac{\sum_{n=0}^{N-1} n r^2(n,k)}{\sum_{n=0}^{N-1} r^2(n,k)}$$

$$\sigma_{T,k} = \sqrt{\frac{\sum_{n=0}^{N-1}(n-\overline{T}_k)^2 r^2(n,k)}{\sum_{n=0}^{N-1} r^2(n,k)}}$$

- where, *r(n,k)* is the k^{th} received signal (based on discrete time signals)

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Indoor UWB channel statistics (2)

- Delay spread is often reported as the median of the collection of measurement
- The spatial distribution of the signal energy can be measured by the first and root of second moments of received *angular profile:*

$$\overline{\Phi} = \frac{\sum_{n=0}^{N-1} \Phi_k \beta^2}{\sum_{n=0}^{N-1} \beta^2}$$

$$\sigma_k = \sqrt{\frac{\sum_{n=0}^{N-1} (\Phi_k - \overline{\Phi})^2 \beta^2}{\sum_{n=0}^{N-1} \beta^2}}$$

- where β_k is the amplitude of the signal component incident from angle *k*, $\overline{\Phi}$ is the power-weighte average AOA, and σ_k is the RMS AOA
- β_k^2 can be interpreted as the energy accumulated at the angle *k* during the measurement time window.

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Multipath components

- One of potential benefits of UWB radio is its multipath resolution.
- The multipath components can be distinct identified in UWB system, but may not be resolved in more narrow system.
- Traditional spectrum analyzers cannot be used to measure the UWB channel response at a meaningful distance. A receiver using a time modulated ultra-wideband rake receiver concept, scanning receiver, has been deveploing in *Time-Domain Ltd.*
- Diversity is applied for improving the system performance

Power delay profile

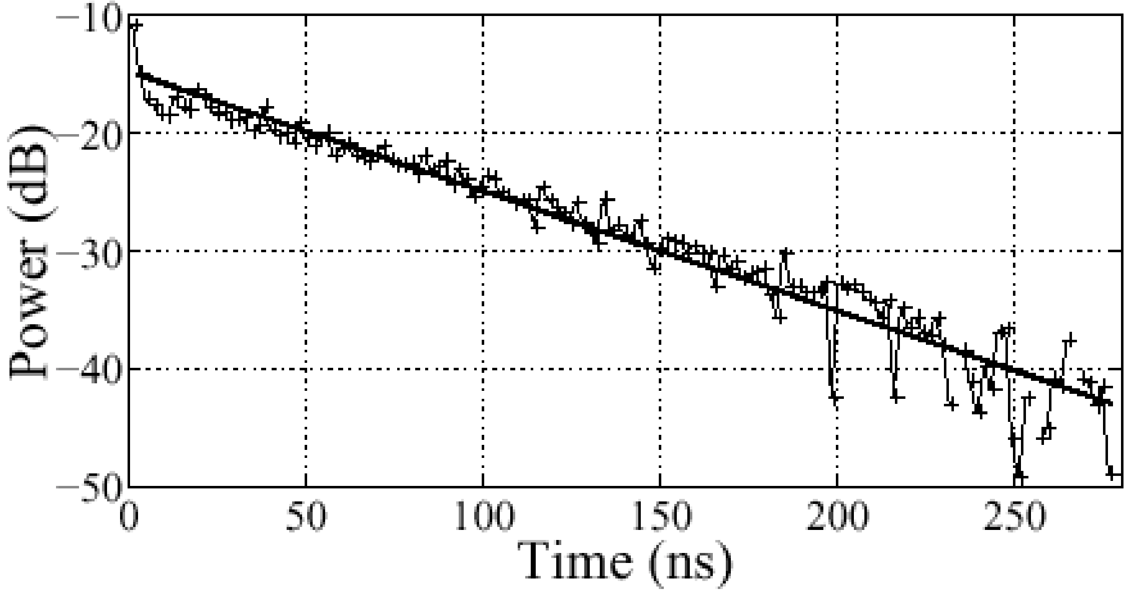

Figure 1. The average power delay profile vs. the excess delay in semi-logarithmic scale for a typical high SNR room. The wavy line is the measured profile, the straight line is the exponential decay obtained by a best fit procedure.

Propagation properties

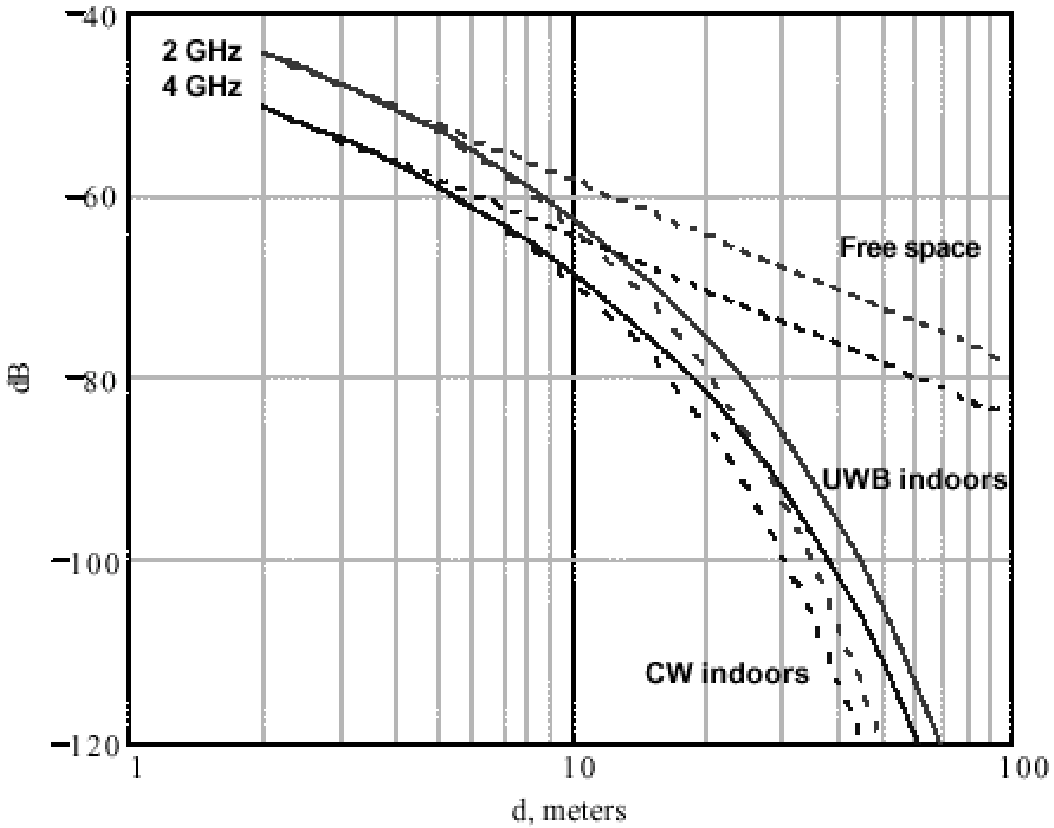

Figure 5. Propagation of CW (continuous wave) systems and UWB systems indoors, compared to the free space law.

Multipath

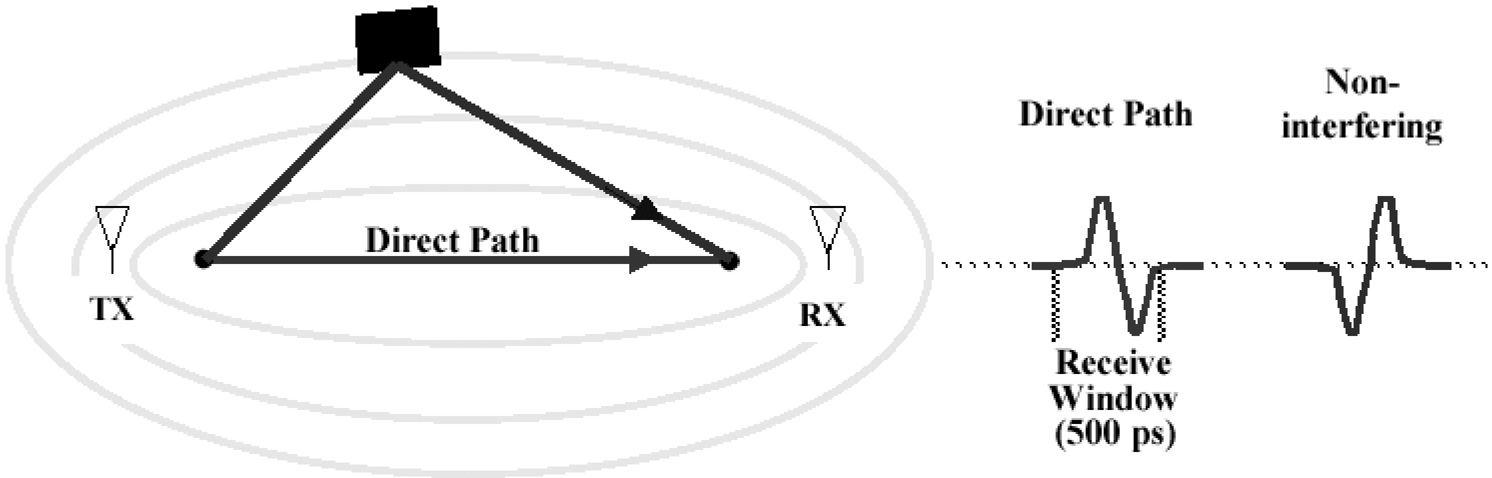

Figure 7. Multipath in a PulsON® System

Multipath reflection

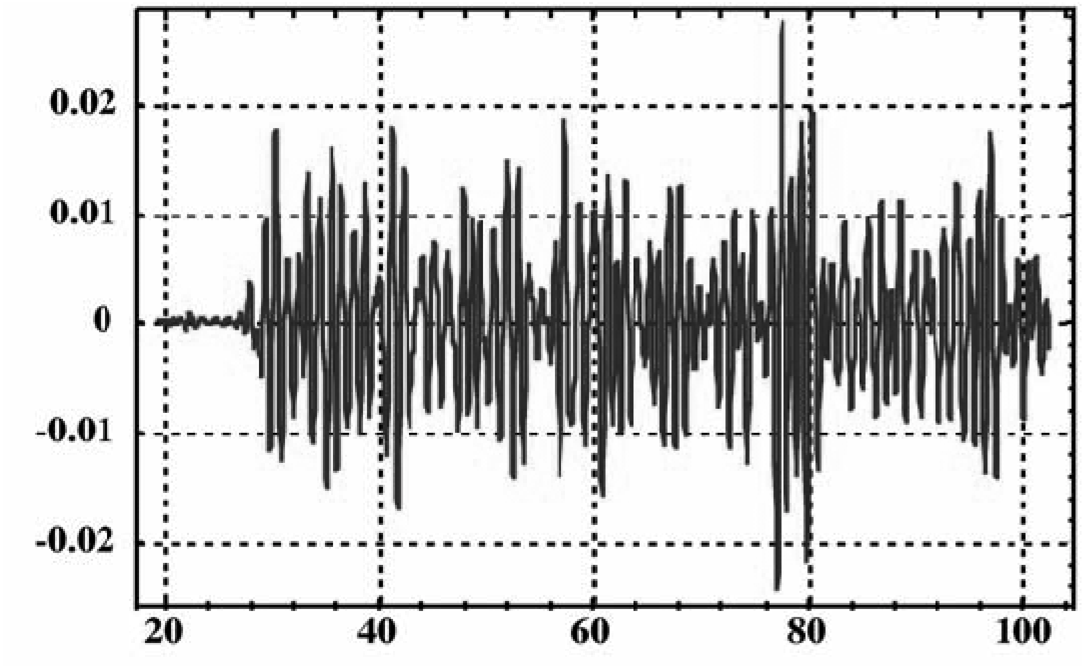

Figure 8: Multipath Reflections in a Complex Environment (Relative Amplitude vs. Time in ns)

System capacity

- PulsON® radio system
- Thousands of voice channels per cell without special signal processing algorithm
- 200-1000 simultaneous duplex 64 kbps telephone conversation per bae station
- Using sectored base station antenna technique, more capacity can be achieved

Applications

- Geo-loaction system
- Radar, position locator, tracking, ranging
- Indoor wireless communication (short range) with
  - Unlicensed operation
  - Resistance to multipath interference
  - Low transmit power
- …

Reference

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