Application of Gaussian Impulses and Chaotic Signals in Ultra-Wideband Communications

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Main requirements:

- Operation in indoor environment
  $\Rightarrow$ *multipath* $\Rightarrow$ ultra-wideband carrier
- Operation in a frequency band already allocated to narrowband systems
  $\Rightarrow$ *interference* $\Rightarrow$ low power spectral density of radiated signal

New challenge for circuit and system designers:

- Transmission of ultra-wideband signals with short duration

STRUCTURE OF THE IEEE 802 ORGANIZATION

IEEE 802 LAN/MAN Standards Committee
Wireless applications

- IEEE 802.11: WLAN
- **IEEE 802.15 Working Group: Wireless personal area network (WPAN)**
  - 802.15.1: Bluetooth
  - 802.15.2: Coexistence
  - 802.15.3: High data rate
  - **802.15.4 Task Group: Zigbee**
    - **Task Group 4a**
      Low data rate ultra-wideband radio (UWB)
- IEEE 802.16: WMAN
- IEEE 802.20: MBWA

IEEE 802.15.4a
WPAN LOW RATE ALTERNATIVE PHY TASK GROUP

802.15.4a became an official Task Group in March 2004

Main features of 802.15.4 standard:

- Low data rate (250 kbps, 40 kbps, and 20 kbps)
- Multi-month to multi-year battery life
- Low power consumption and cost
- Very low complexity
- Operation in an unlicensed, international frequency band
- Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation

Special properties and requirement

Ultra-wideband carrier:

- Federal Communications Commission (FCC, USA) determined only the maximum emission limit and minimum bandwidth
- Method for access to UWB frequency band has not yet been fixed

Implementation:

- CMOS Technology

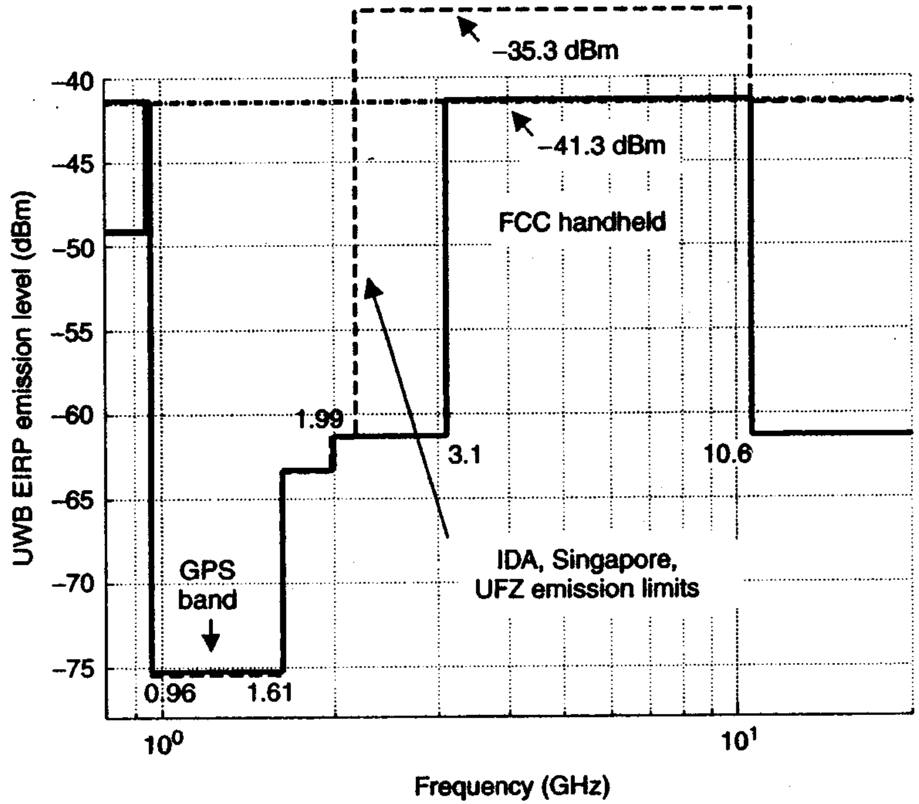
Only the physical layer (PHY) is considered here

- Comparison of impulse radio and chaotic communications system
- Modulation schemes
- System level aspects
- Special requirements arising from the application of UWB signals

CONTENTS

- **UWB signals: Regulations and definitions**
- UWB Impulse Radio
- Chaos-based UWB radio
- Comparison of noise performances
- Conclusions

FCC handheld and Singapore IDA-UFZ emission limits



- Frequency band allocated to UWB: 3.1 GHz to 10.6 GHz
- Bandwidth has to be greater than 500 MHz
- Power spectral density of transmitted signal has to be below -41.3 dBm/MHz

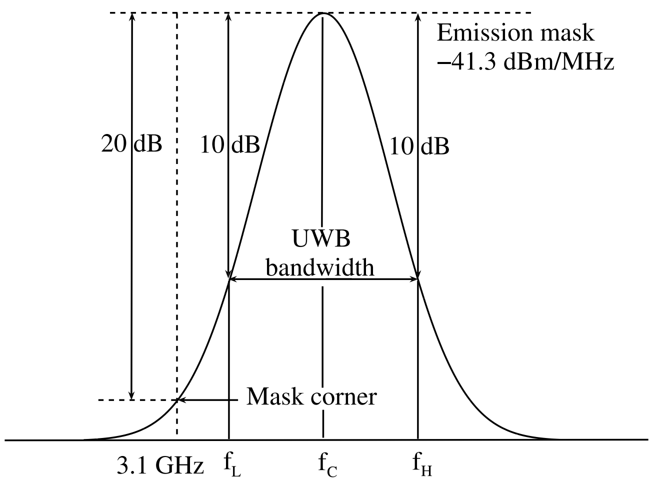
PSD is measured with a resolution bandwidth of 1 MHz

Note: The wider the bandwidth, the larger the UWB radio coverage

Maximum radiated power allowed by UWB regulations

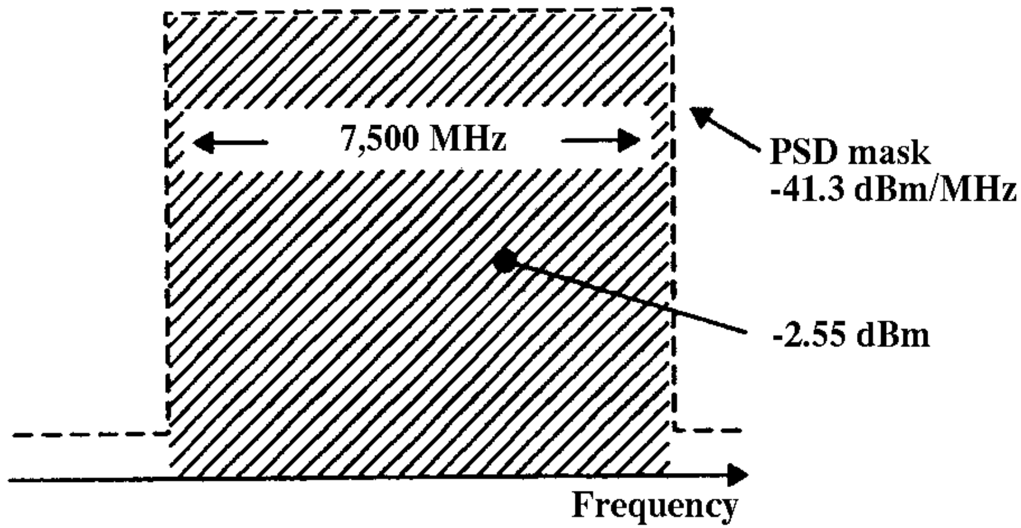
- Maximum coverage of radio communications depends on transmitted EIRP
- Level of transmitted power has the strongest influence on power consumption
- Assuming an isotropic antenna, let the transmitted power be determined

Constraints on UWB signal in the frequency domain:



Note:
Since psd of EIRP is limited, increasing bandwidth is the only way to increase the transmitted power

Absolute maximum allowed radiated power in Ws



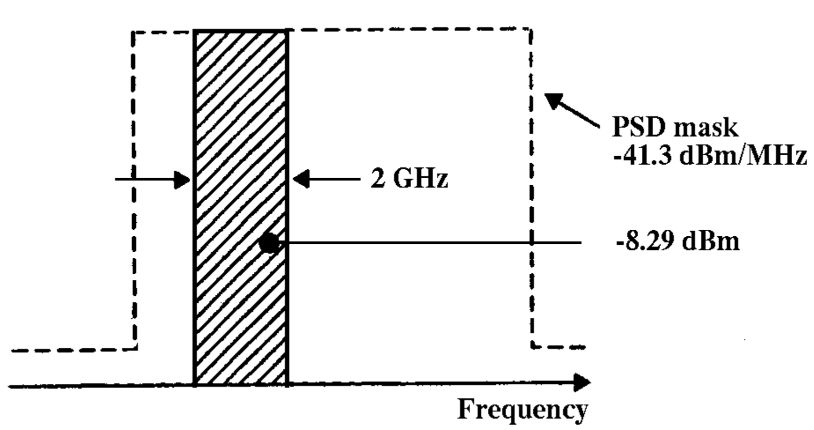
For comparison:
Mobile phone: up to 2W
Wi-Fi: up to 100 mW
tipical nx10 mW

Absolute maximum radiated power:

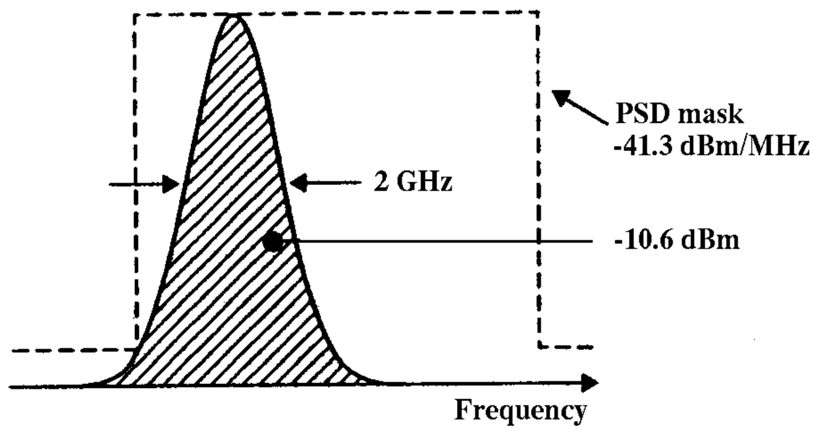
$$P_{tr} = -41.3 \text{ dBm } + 10 \log_{10}\left(\frac{7500 \text{ MHz}}{1 \text{ MHz}}\right) = -2.55 \text{ dBm} \Longrightarrow \mathbf{0.556\ mW}$$

Comparison of max. EIRP for UWB bandwidth of 2 GHz

Chaotic UWB system



Gaussian impulse radio



Maximum allowed radiated EIRP and side-lobe levels

Type of UWB carrier	Radiated power	Highest side lobe (dB)
Bell-shaped Gaussian pulse	-10.6 dBm (87.10 μW)	-34.5 dB
Chaotic communications	-8.29 dBm (148.25 μW)	Not known

Note: Radiated EIRP is as low as $\sim$**100 μW**!

CONTENTS

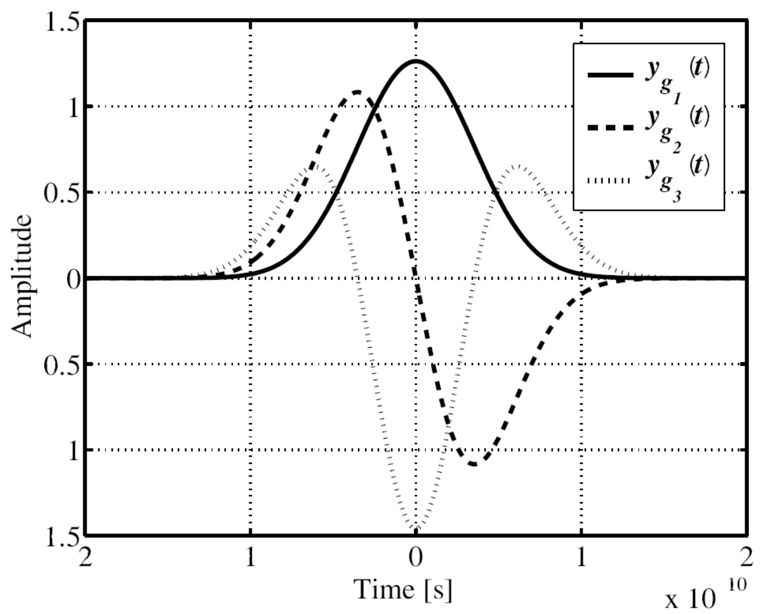
Implementation using fixed waveforms: UWB impulse radio

- **Pulses used as carrier in UWB impulse radio**
  - Gaussian pulse
  - Monocycle
  - Doublet
  - Frequency-shifted bell-shaped Gaussian pulse
- **Modulation schemes**
  - Modulation with one wavelet
  - Modulation with two wavelets
- **Detection techniques**
  - Feasibility of coherent receivers
  - Noncoherent receivers

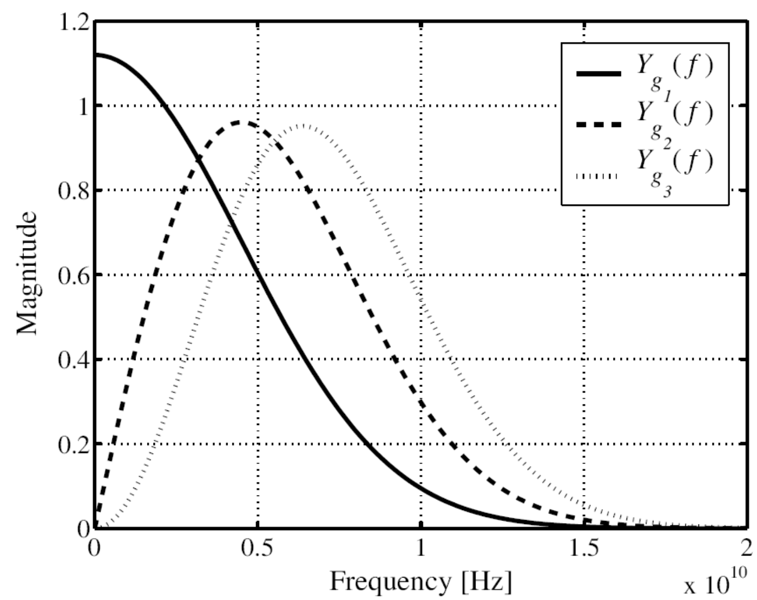
Pulses used as carrier in UWB impulse radio

Gaussian pulse (solid curve), monocycle (dashed curve) and doublet (dotted line)

In the time domain

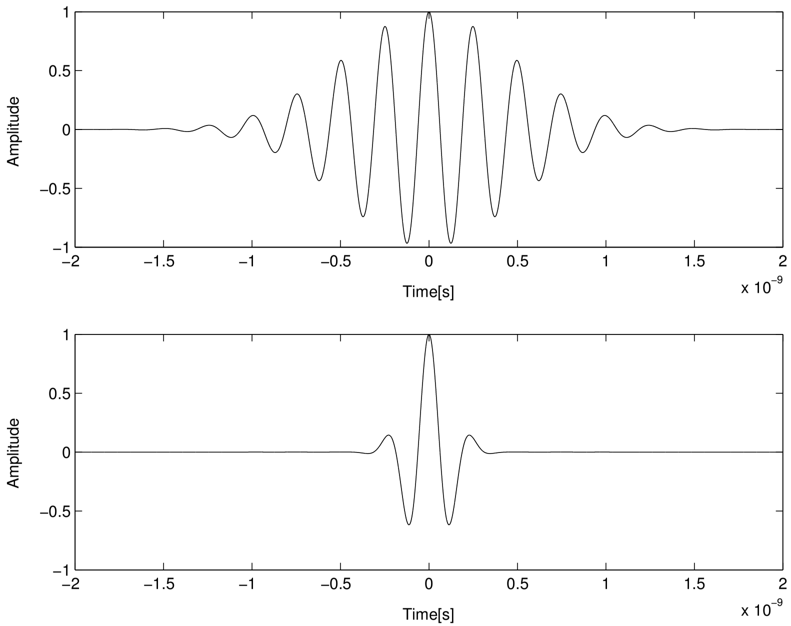


In the frequency domain



Note: Gaussian pulse has a large DC component

To remove DC component:
Frequency-shifted bell-shaped Gaussian pulse



Upper trace: 1-GHz RF bandwidth

Lower trace: 4-GHz RF bandwidth

$$g(t) = \sqrt{\frac{2E_b}{k\sqrt{\pi}\,u_B}}\exp\left(-\frac{t^2}{2u_B^2}\right)\cos(\omega_C t)$$

where

- u_B is calculated from the required RF bandwidth $(2f_B)$ of UWB signal

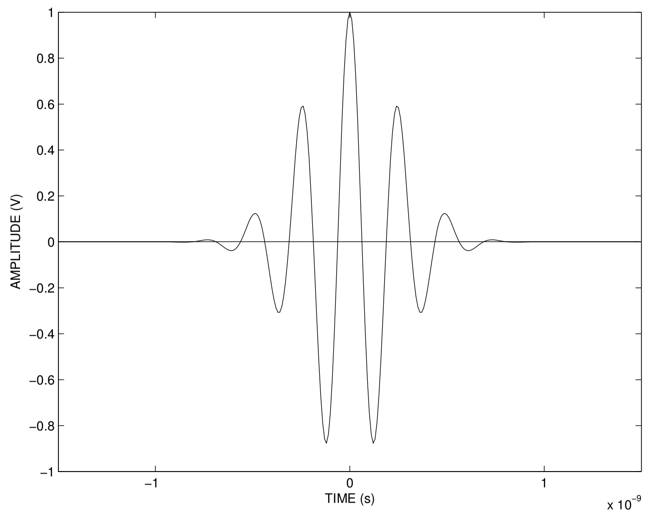
$$u_B = \frac{1}{2\pi f_B\sqrt{\log_{10}(e)}}, \qquad e = 2.718$$

- f_C denotes the center frequency
- E_b is the energy per bit

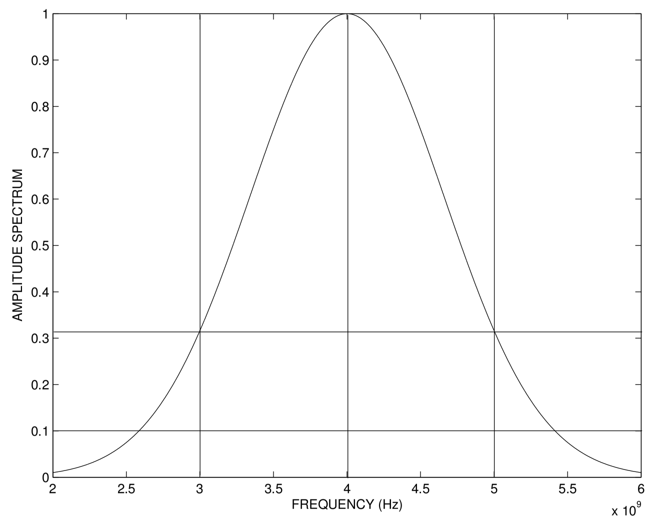
Wideband pulse for the lower UWB band

$$f_C = 4 \text{ GHz} \quad \text{and} \quad BW = 2 \text{ GHz}$$

Wavelet in the time domain



Amplitude spectrum



-10 dB

-20 dB

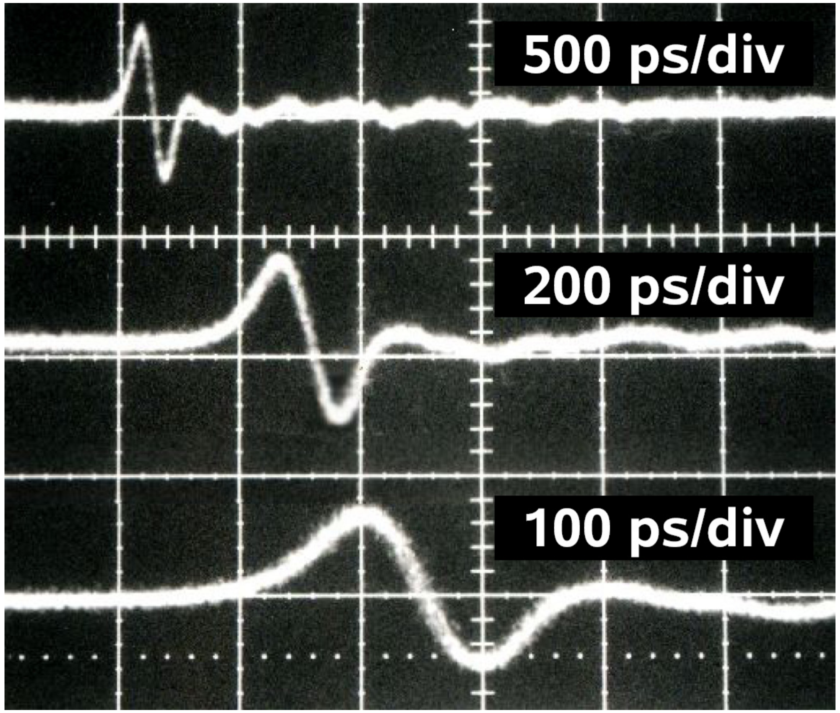
Note:
- Only a few carrier cycles are radiated
- Smooth spectrum
- Only 2.31 dB loss in maximum allowed EIRP
- No side lobe

BUILT MONOCYCLE GENERATOR

AVTECH

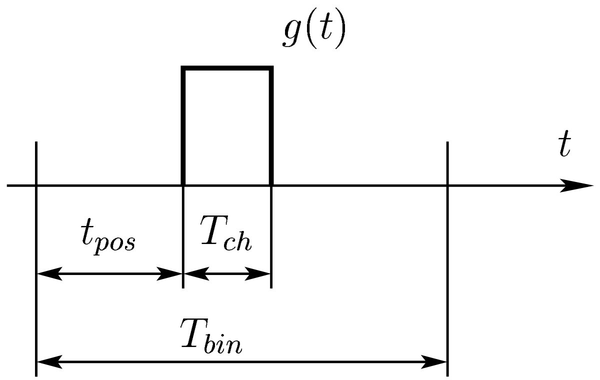
- Fixed tuned, where the pulse duration or center frequency (3 GHz – 5 GHz) may be specified
- Amplitude = 4 V_{pp} @ 50 Ω
- Power consumption:

200 mA @ +15 V (3 W!)



STRUCTURE OF UWB MODULATED SIGNAL

Modulation scheme with one wavelet



where
- $g(t) \Rightarrow$ Wavelet, i.e., carrier
- $T_{ch} \Rightarrow$ Wavelet duration
- $T_{bin} \Rightarrow$ Pulse bin to prevent intersymbol interference
- $t_{pos} \Rightarrow$ Wavelet positioning in T_{bin}

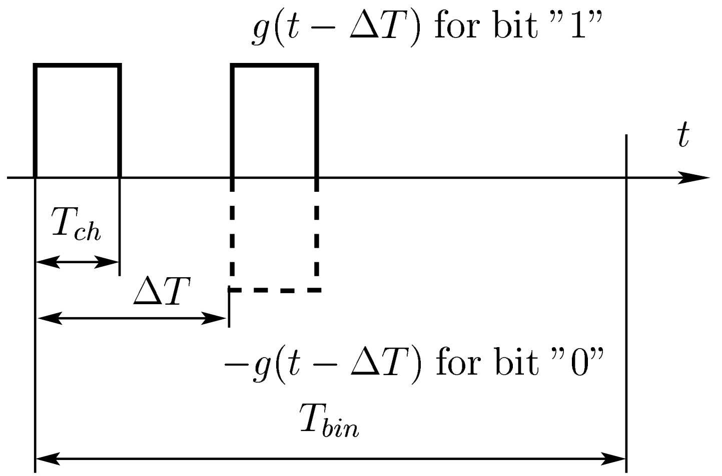
Modulation of wavelet: Varying its **positioning**, **amplitude**, **polarity** or On-Off Keying (**OOK**)

Remarks:
- Arbitrary waveforms may be used in wavelet positioning and OOK modulation
- Wavelet polarity modulation is referred to as Pulse Polarity Modulation (PPoM) in UWB impulse radio. Since it offers the best noise performance only PPoM is considered here

Modulation scheme with two wavelets

Binary information is mapped into two wavelets, called chips

First chip serves as a reference, the sign of second one carries the information



where
- $\Delta T \geq T_{ch} \Rightarrow$ Delay between the reference and information bearing chips

Note:
- Wavelet $g(t)$ may be either a **fixed** (impulse radio) or a **chaotic** waveform

Modulation technique:

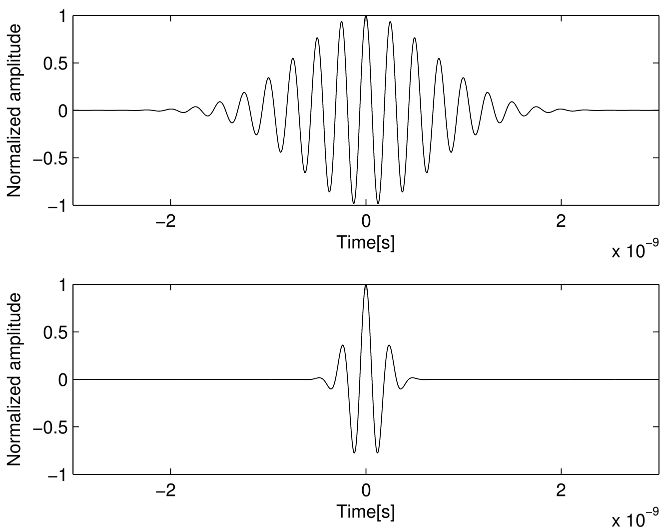
- Bit "1" $\Rightarrow$ Second chip is equal to the delayed reference one
- Bit "0" $\Rightarrow$ Second chip is equal to the inverted and delayed reference one

Note: This modulation is the generalized version of FM-DCSK

DETECTION OF MODULATED UWB WAVEFORMS

Coherent correlation receivers

Autocorrelation of frequency-shifted bell-shaped Gaussian pulse



RF bandwidth = 1 GHz (upper trace) and 4 GHz (lower trace)

Reasons making the application of a coherent receiver very hard:

- Recovery of UWB pulses is not feasible due to the special shape and ultra short duration
- Due to the ultra short transmitted pulses, even a small timing error causes a large performance degradation
- Transmitted pulse is not equal to received one because the transient response of channel (including transceiver) cannot be neglected
- Because of the large pulse amplitude, channel distortion may occur

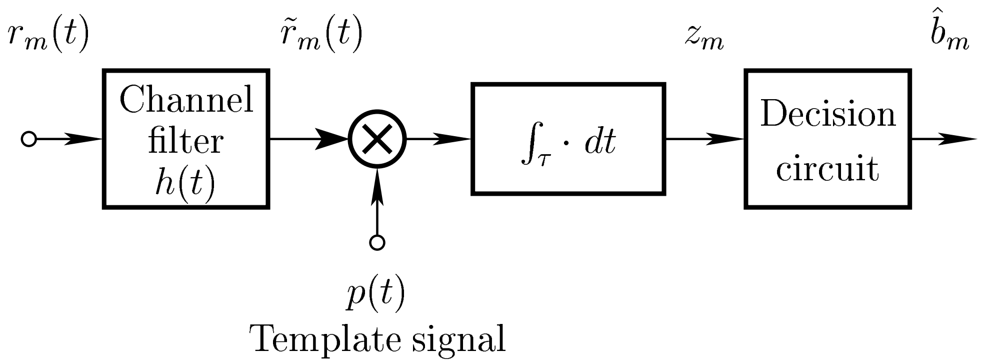
Conclusion: Noncoherent demodulator configuration has to be used

4.3.2 Noncoherent receivers

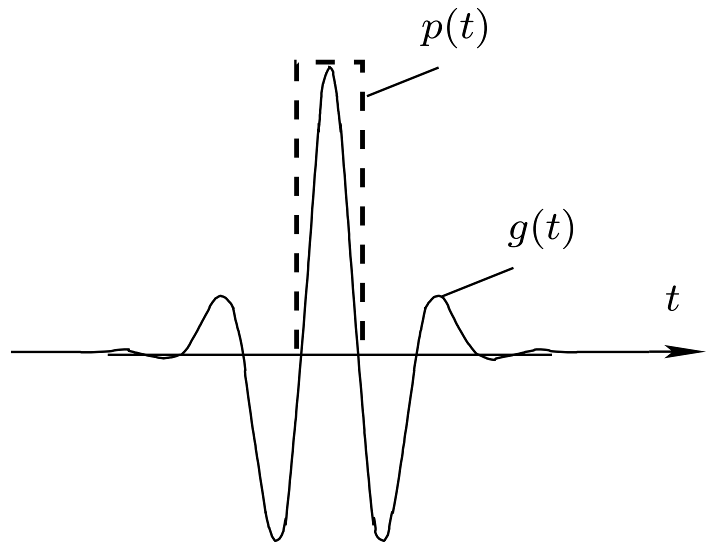
Pulse polarity modulation with rectangular template detection

- No need for UWB pulse recovery but a fixed wavelet is a must
- Suitable for UWB impulse radio only

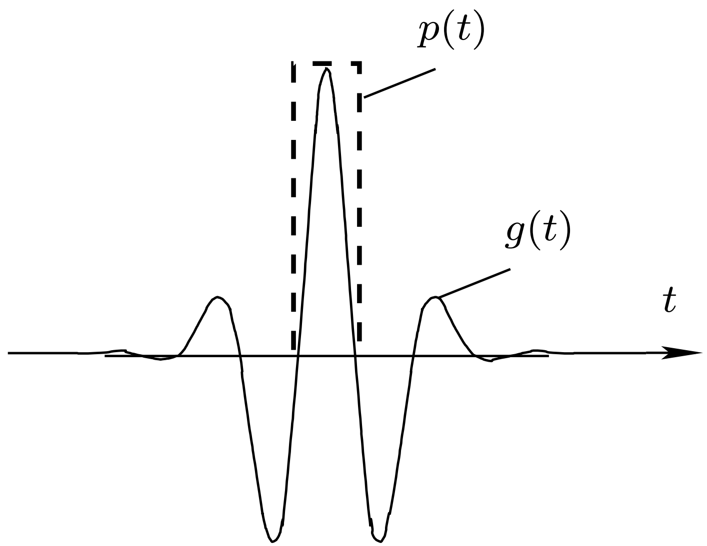
Detector block diagram



Received noise-free $r_m(t) = g(t)$ and template $p(t)$ wavelets in case of perfect matching



Properties of template detection



Rectangular template signal:

$$p(t) = \begin{cases} 1/\sqrt{\tau}, & \text{if } |t| < \frac{\tau}{2} \\ 0, & \text{otherwise} \end{cases}$$

where τ denotes the *energy capture time*

Note, the received signal is correlated by a noise-free template signal

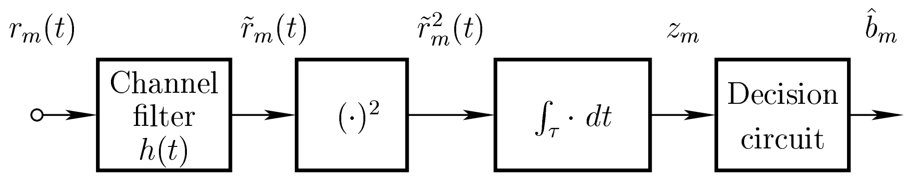
Observation variable

$$z_m = \int_{T_{bin}} \tilde{r}_m(t)p(t)dt = \pm \int_{\tau} \tilde{g}(t)p(t)dt + \int_{\tau} \tilde{n}(t)p(t)dt$$

OOK with energy detector

- Suitable for both UWB impulse and chaos-based communication
- To get the optimum performance, decision threshold must be varied according to the Signal-to-Noise Ratio (SNR) measured at detector input

Detector block diagram



Observation variable:

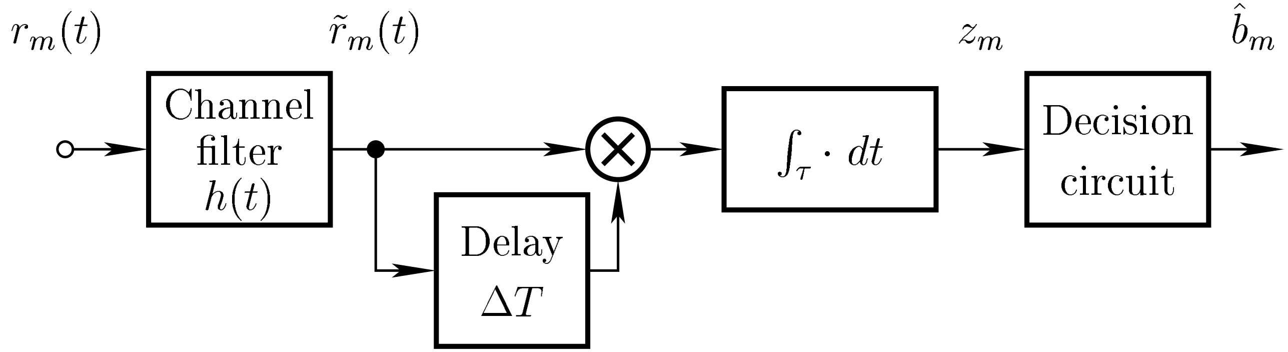
$$z_m = \int_{T_{bin}} \tilde{r}_m^2(t)dt$$
$$= \int_\tau \tilde{g}^2(t)dt + 2\int_\tau \tilde{n}(t)\tilde{g}(t)dt + \int_\tau \tilde{n}^2(t)dt$$

Note term $\tilde{n}^2(t)$ that limits the noise performance

TR-based autocorrelation detector

- In transmitted reference (TR) system, the digital message may be recovered from the sign of correlation measured between the reference and information bearing chips
- Either fixed waveform (impulse radio) or chaotic waveform may be used as carrier
- Source of robustness: Reference chip measures the actual channel characteristics

Detector block diagram



Observation signal

$$z_m = \int_{\Delta T}^{T_{bin}} \tilde{r}_m(t)\tilde{r}_m(t-\Delta T)dt$$
$$= \pm \int_\tau \tilde{g}^2(t)dt + \int_\tau \tilde{n}(t+\Delta T)\tilde{g}(t)dt \pm \int_\tau \tilde{g}(t)\tilde{n}(t)dt + \int_\tau \tilde{n}(t+\Delta T)\tilde{n}(t)dt$$

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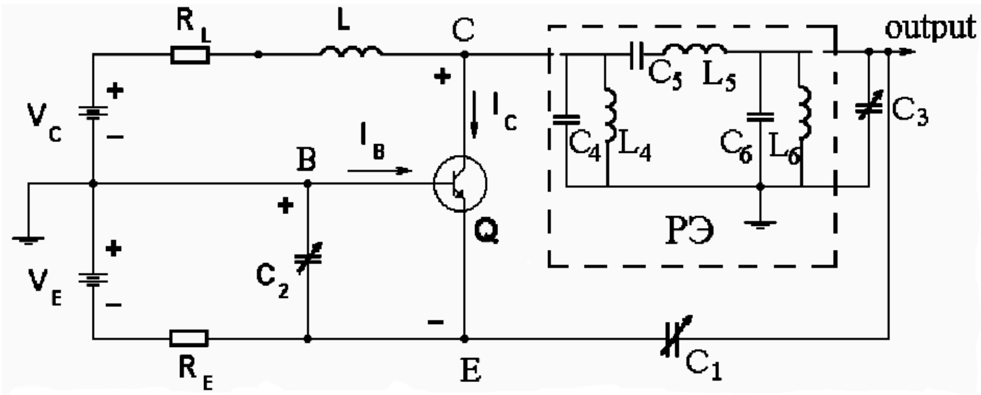
- UWB signals: Regulations and definitions
- UWB Impulse Radio
- **Chaos-based UWB radio**
- Comparison of noise performances
- Conclusions

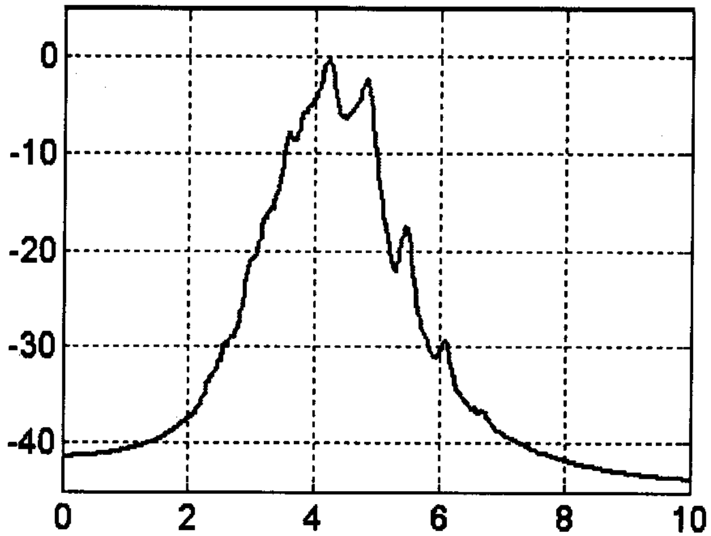
Chaos-based UWB radio

Chaotic carrier generation directly in the microwave frequency region

Circuit diagram



Power Spectral Density (psd) of chaotic signal



Frequency (GHz)

Modulation schemes and receiver configurations

- Chaotic On-Off Keying (COOK) with energy detection
- FM-DCSK with autocorrelation receiver

Open questions in chaos-based UWB radio

- Development of (i) CMOS (ii) high-efficiency (iii) microwave chaotic signal generator
- Variation in energy per bit (E_b) has to be prevented
  Solution: Apply frequency modulation as used in FM-DCSK
- A special problem arising from the application of chaotic waveforms:
  Emission mask must be satisfied by each transmitted waveform
  A power back-off should be used?

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- UWB signals: Regulations and definitions
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Comparison of noise performances: Chaos-based versus impulse radio

ON-OFF KEYING WITH ENERGY DETECTOR AND TR-BASED MODULATION SCHEMES

- If OOK with energy detector and TR-based autocorrelation receiver are considered then the amount of exploited *a priori* information is the same in both UWB impulse and chaos-based communications
- Autocorrelation estimation problem has to be prevented by keeping E_b constant in chaos-based communications
- In both UWB impulse radio and chaos-based communications the same noise term appears in the observation variable that limits the noise performance
  See terms $\tilde{n}^2(t)$ and $\tilde{n}(t + \Delta T)\tilde{n}(t)$ in OOK and autocorrelation receiver, respectively

Consequently, the noise and interference suppression capability of OOK with energy detector and TR-based autocorrelation receivers are **identical** for chaos-based and impulse radio and they are **not studied here**

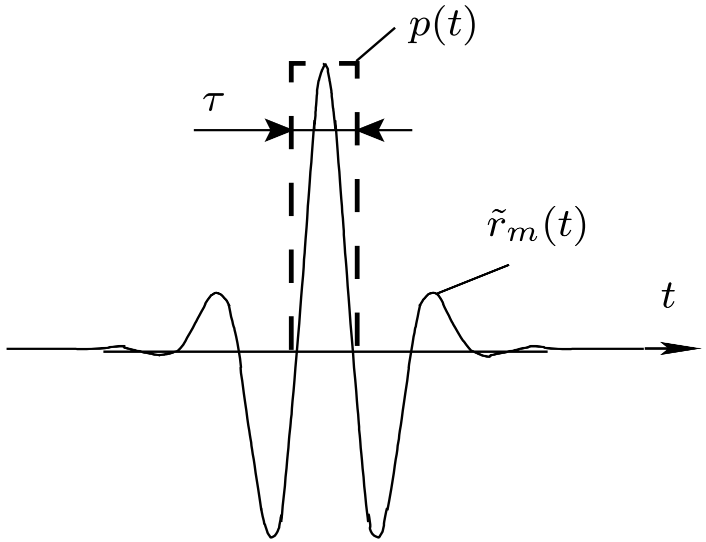
COMPARISON OF PPoM-BASED TEMPLATE DETECTION WITH TR-BASED AUTOCORRELATION RECEIVER

- Since noise-noise term does not appear in observation variable, its variance is much less than that of OOK and TR-based modulation schemes
- The operation of template detection requires a transmitted wavelet having a cycle where energy content is concentrated
- If the signal energy is distributed between cycles then autocorrelation technique must be used
- A mismatch error measured between transmitted wavelet $g(t)$ and windowing template $p(t)$ appears that corrupts the noise performance

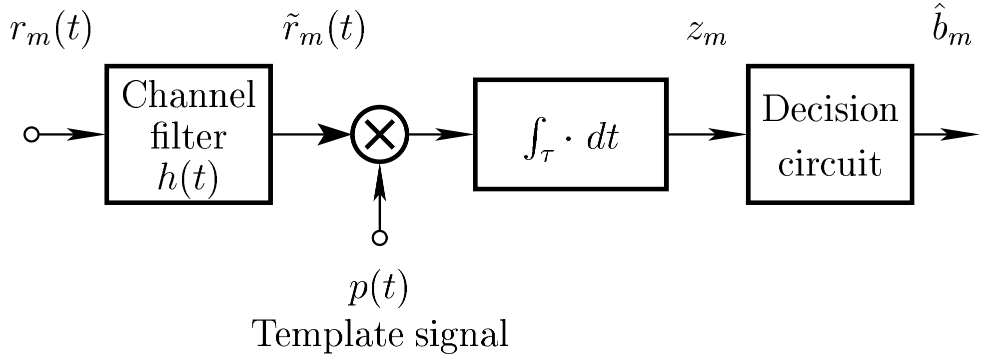
A win-and-lose situation

A comparison between PPoM with template detection and TR-based autocorrelation receiver has to be performed to check if we win or lose more with using PPoM with template detection

Mismatch error between transmitted pulse $g(t)$ and windowing template $p(t)$



Recall: Block diagram of template detector



Sources of mismatch error:

- Simple windowing function, i.e., $p(t) \neq g(t)$
- Alignment error between $p(t)$ and $g(t)$
- Energy capture time τ, i.e., the width of $p(t)$ deviates from its optimum value

Noise performance of PPoM with template detection

Observation variable of the template detector

$$z_m = \int_{T_{bin}} \tilde{r}_m(t)p(t)dt = \pm \int_{\tau} \tilde{g}(t)p(t)dt + \int_{\tau} \tilde{n}(t)p(t)dt$$

First term gives the mean of observation variable

$$E\left[z_m\right] = \int_{\tau} \tilde{g}(t)p(t)dt = \sqrt{\alpha E_b}$$

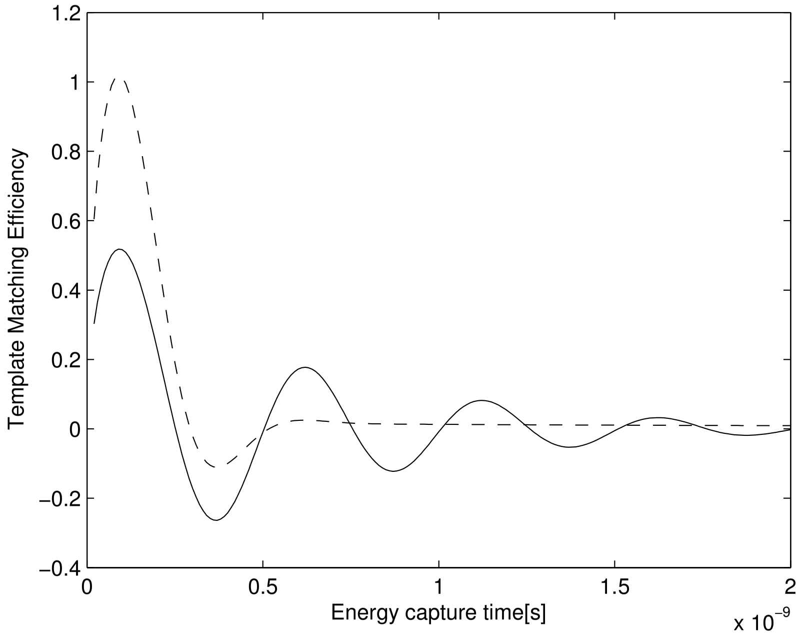
where the **template matching efficiency** is defined by

$$e_{tm} = \sqrt{\alpha} = \sqrt{\frac{E\left[z_m\right]}{E_b}}$$

Second term is a linear integral transformation, consequently, it gives a random variable with a Gaussian distribution, its mean is zero and its variance is $N_0/2$

Template matching efficiency: **Effect of energy capture time τ**

Template matching efficiency for 2 GHz (dashed curve) and 2.5 GHz (solid curve) UWB bandwidths



f_C =4 GHz and perfect alignment

Note:

- Energy capture time has an optimum value
- Due to uncertainty in timing (between the transmitter and receiver clocks), energy capture time has to be increased beyond the optimum value
- Large τ even may cancel the modulation

Comparison of bit error rates

Pulse polarity modulation with template detection

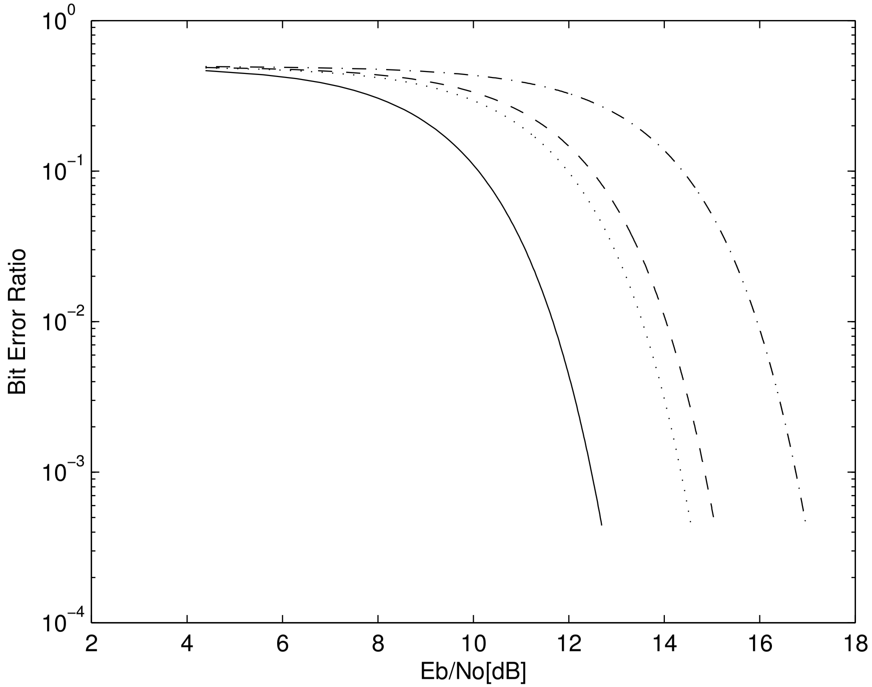
$$P_e = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{\alpha E_b}{N_0}}\right)$$

TR-based autocorrelation receiver

$$P_e = \frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \binom{j+2B\tau-1}{j-i}$$

Noise performance of PPoM with template detection

- Suitable for impulse radio only
- Since the shape of template differs from the transmitted wavelet, compared to BPSK, it has theoretically at least a 3-dB loss

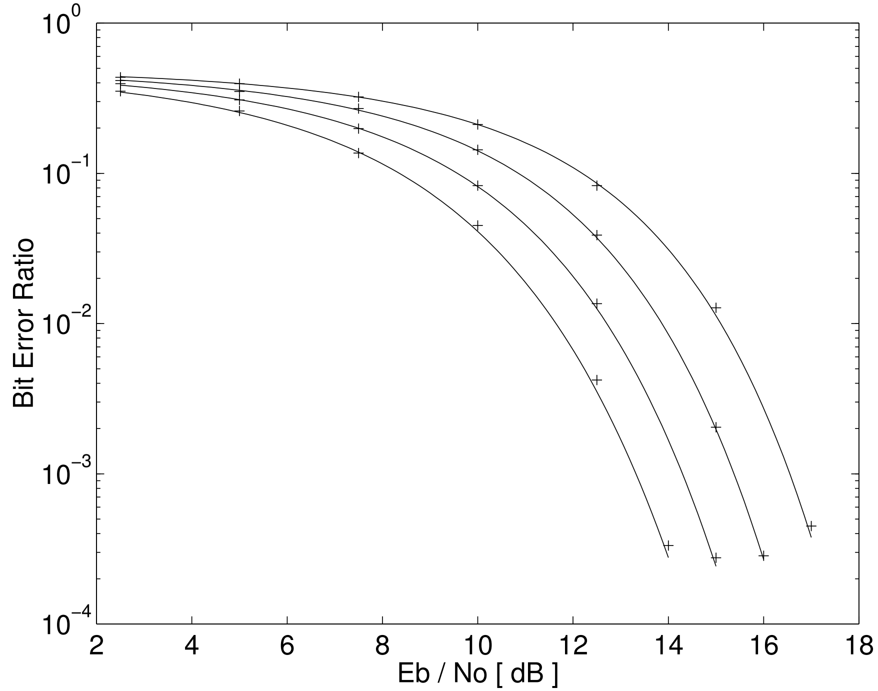


where

- Solid curve:
  BW=2 GHz and e_{tm}=0.69
- Dotted curve:
  BW=2 GHz and e_{tm}=0.42
- Dashed curve:
  BW=500 MHz and e_{tm}=0.35
- Dash-dotted curve:
  BW=500 MHz and e_{tm}=0.20

Noise performance of TR modulation with autocorrelation receiver

- Suitable for both impulse radio and chaotic communications



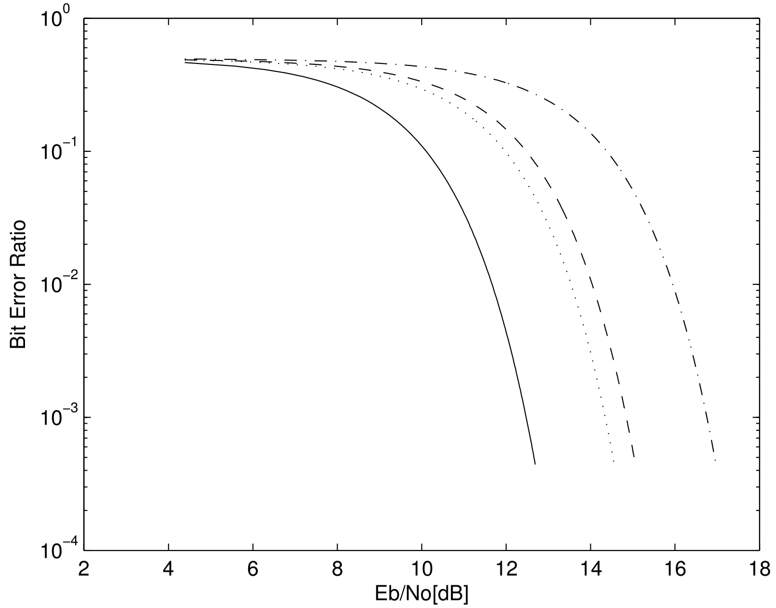
Recall, noise performance of TR-based systems depends on the product of $2B\tau$

where

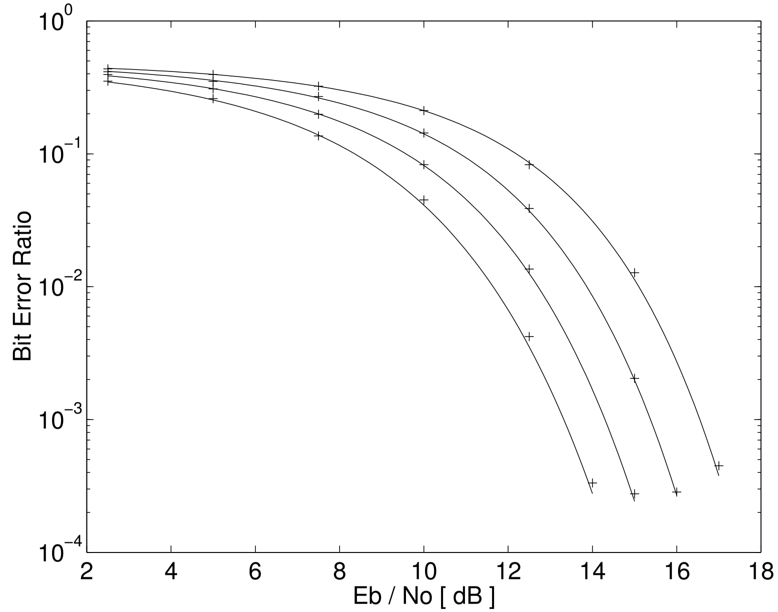
- From left to right: $2B\tau$ is equal to 8.5, 17, 34 and 68

Performance comparison

Pulse polarity modulation with template detection



TR modulation with autocorrelation receiver



Note: Noise performances of the two modulation schemes are almost identical

CONCLUSIONS

1. In chaos-based communications there is an inevitable loss in exploitable *a priori* information, consequently,
   - Worse BER
   - Worse spectral efficiency (i.e., lower data rate)
2. Consider only those applications where these parameters have less importance
   - Forget high data rate-applications where high QoS is required
   - Embedded (control) systems
   - LR systems where QoS is assured by acknowledgment protocol

3. UWB impulse radio offers a solution but
    - High power consumption
      Recall: Power consumption of AVTECH monocycle generator is 3 W
    - Very tight timing requirements must be satisfied with CMOS technology

4. Open questions in chaos-based communications
    - Microwave CMOS chaotic signal generator having ultra-low power consumption is wanted
    - Chaos-based modulation scheme:
        - Prevent variation in energy per bit
        - Exploit more *a priori* information
    - A solution assuring that the emission mask is satisfied by each transmitted waveform is wanted

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