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Ultra-Wide (UWB) Communications: New Paradigms and Opportunities.

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The *UWB* communication problem

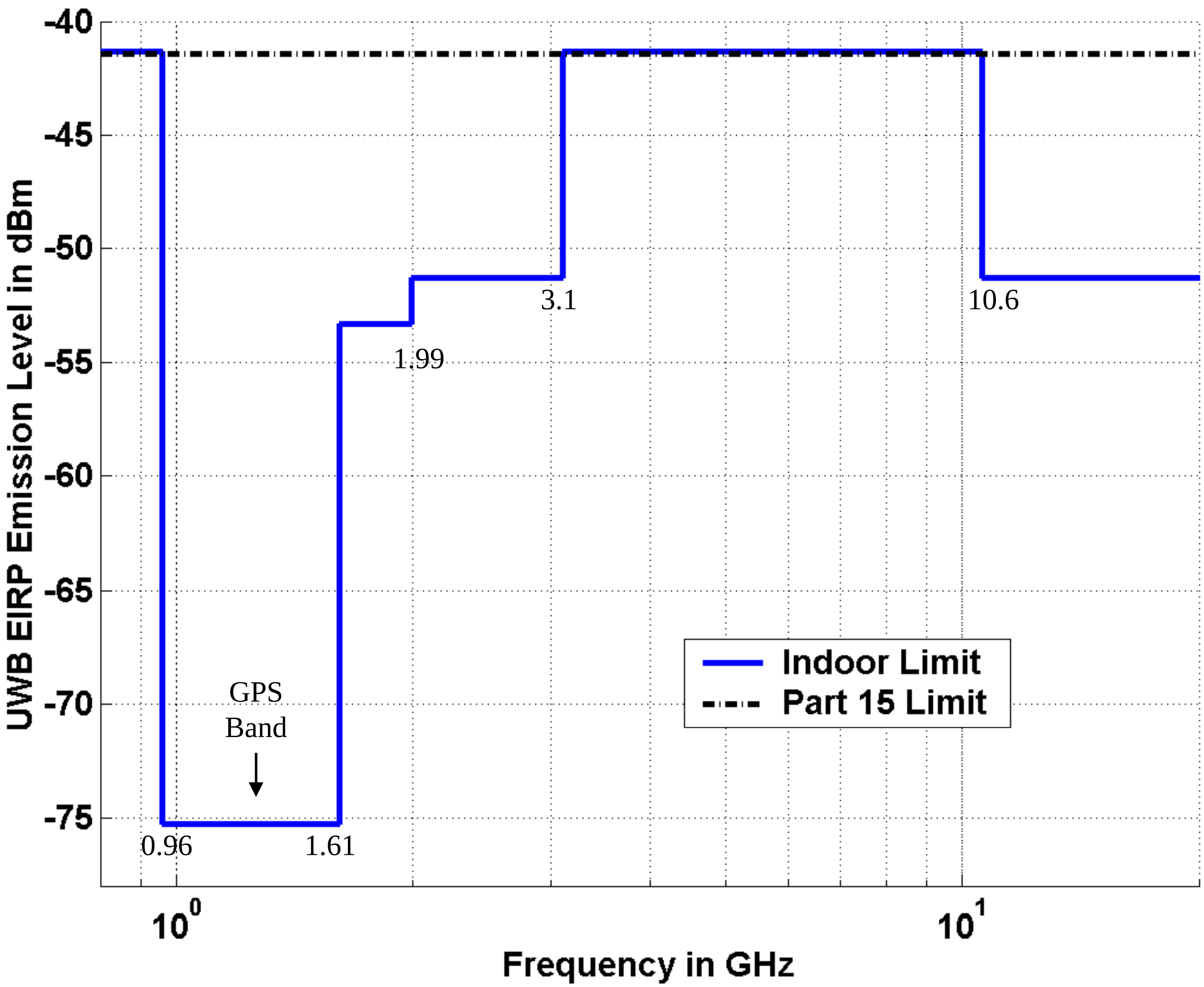
- Truly ***Ultra-wide***: 3.1 GHz to 10.5 GHz (FCC approved in 2001)
- The usable bandwidth is 7.4 GHz (!!)

- Multipath components are resolvable
  - Could use a **RAKE receiver**

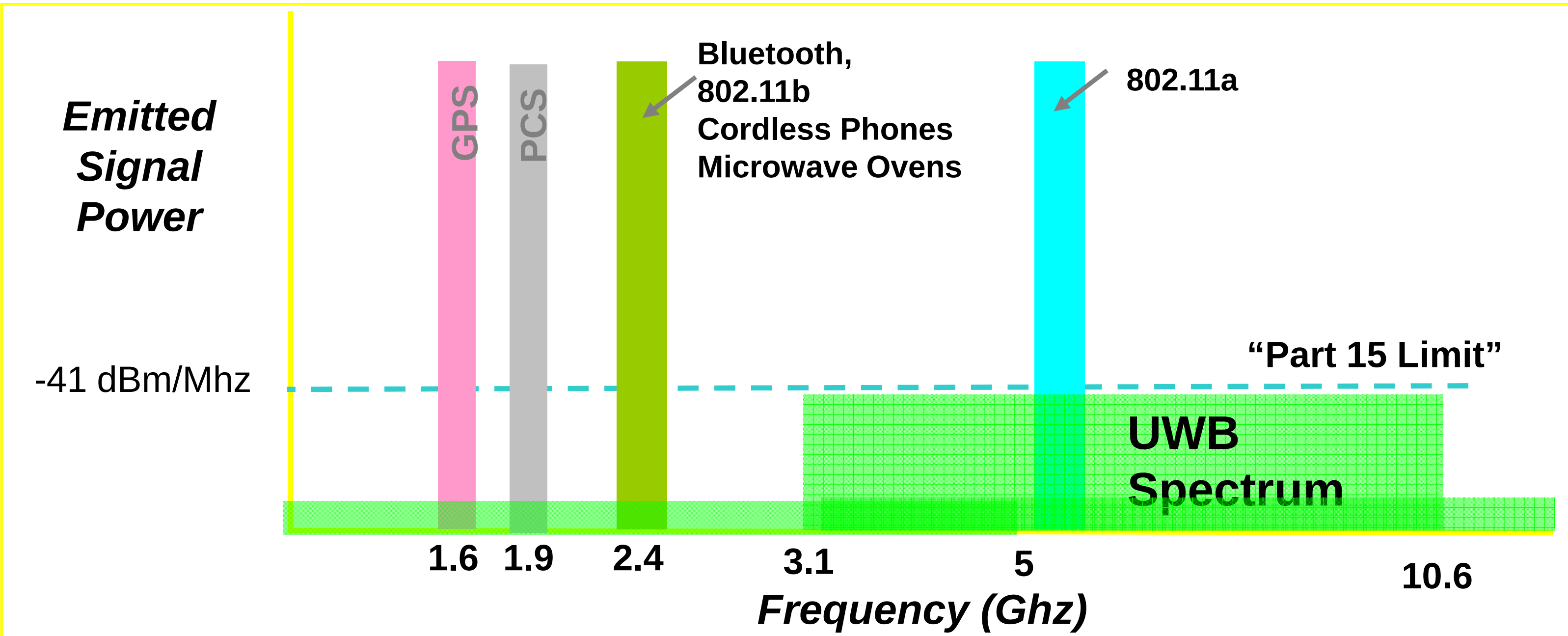
- However, at high information rates (in excess of 100 Mbps), inter-symbol interference (ISI) is present
  - An **equalizer** is needed

- This type of situation has never been studied before
  - **New channel model** needed
  - Cannot rely on CDMA/spread-spectrum experience
  - IEEE 802.15.3a study group (Intel, Time Domain and Mitsubishi)

UWB Emission Limit for Indoor Systems



UWB Spectrum and Narrowband Systems



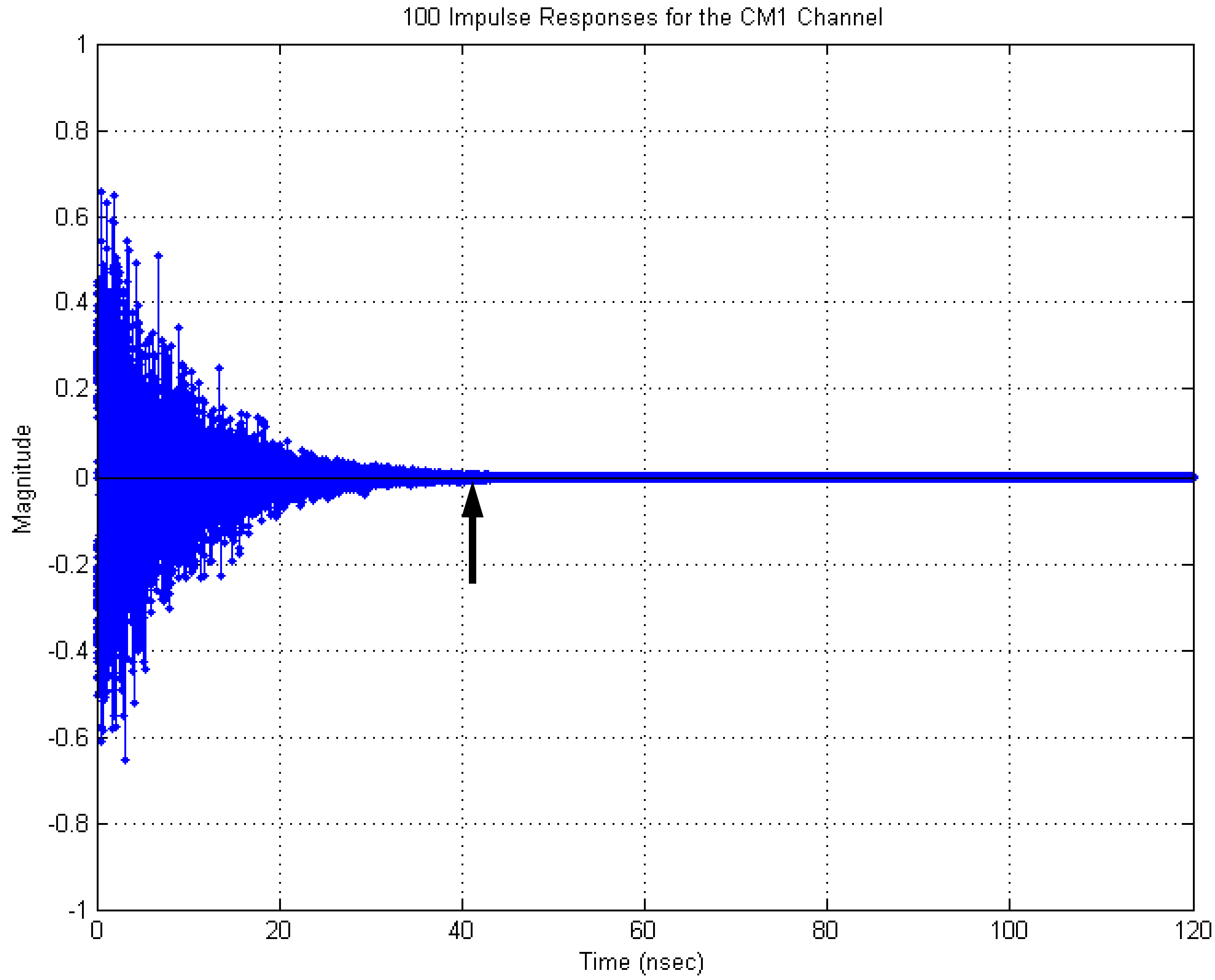
Channel Model from IEEE 802.15.3a group (Nov. 2003)

Parameter	CM1	CM2	CM3	CM4
Λ [1/nsec] Cluster arrival rate	0.0233	0.4	0.0667	0.0667
λ [1/nsec] Ray arrival rate	2.5	0.5	2.1	2.1
Γ Cluster decay factor	7.1	5.5	14.0	24.0
γ Ray decay factor	4.3	6.7	7.9	12.0
σ_1 [dB] Cluster lognormal fading term	3.3941	3.3941	3.3941	3.3941
σ_2 [dB] Ray lognormal fading term	3.3941	3.3941	3.3941	3.3941
NP_{10dB} *MERL*, TR-2003-73	**12.5**	15.3	24.9	**41.2**
NP_{10dB} (*) ***SJSU***, *12/13/2004*	***<u>14.57</u>***	*15.0*	*23.5*	***<u>32.2</u>***

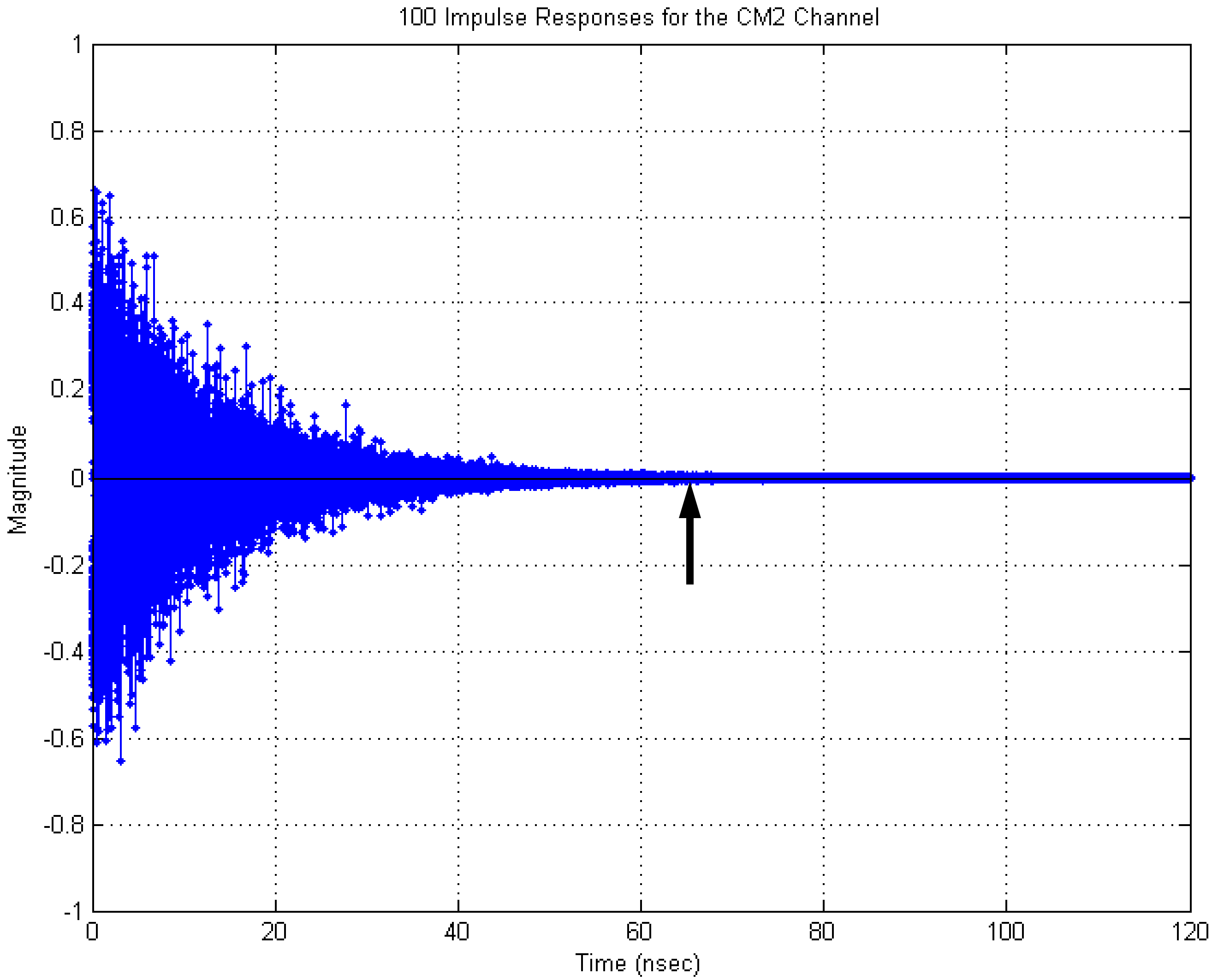
(*) Average over 200 channel realizations with T. Becker's Matlab model.

Matlab model simulation results (February 13, 2004)

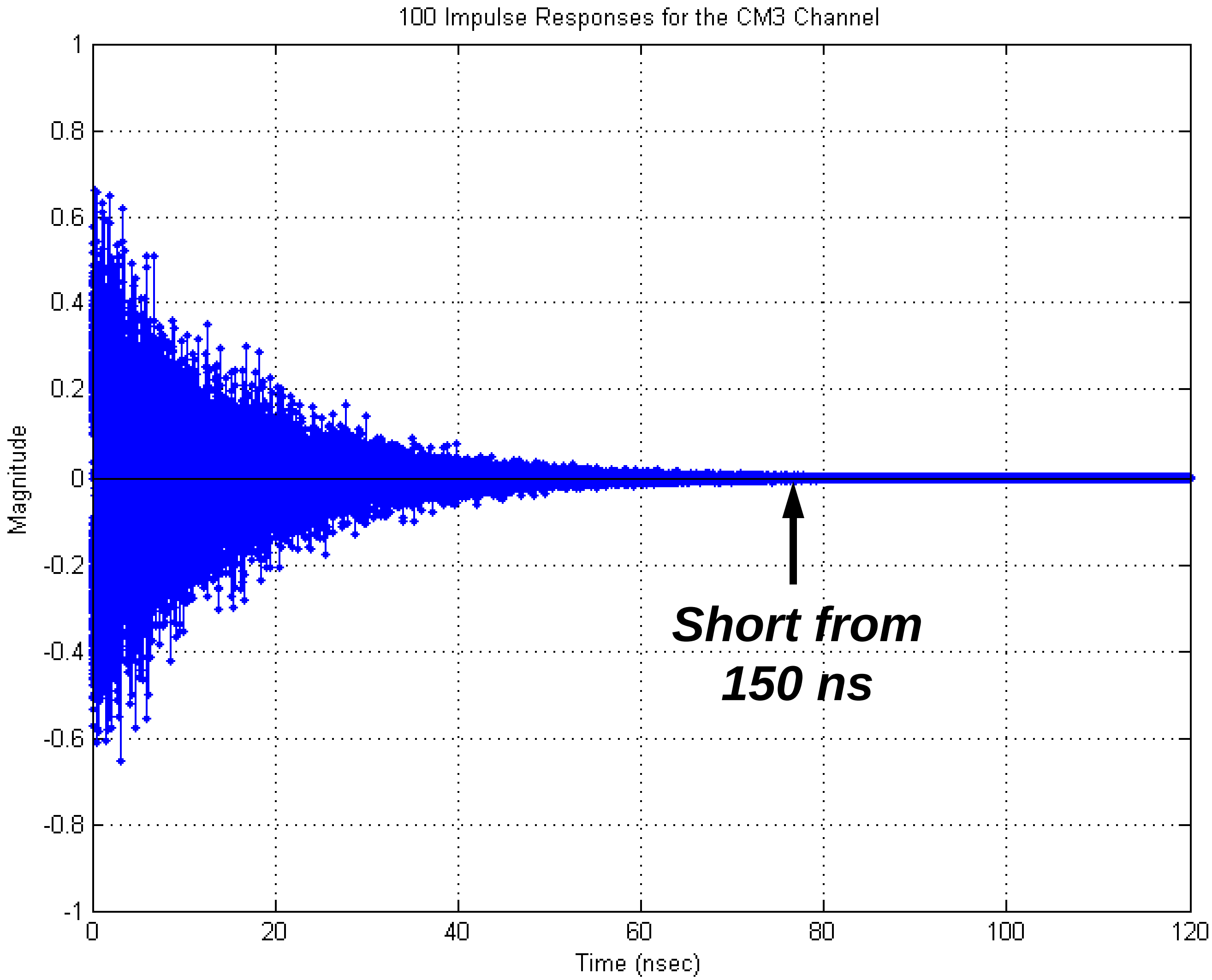
The CM1 Channel: LOS, 0-4 m



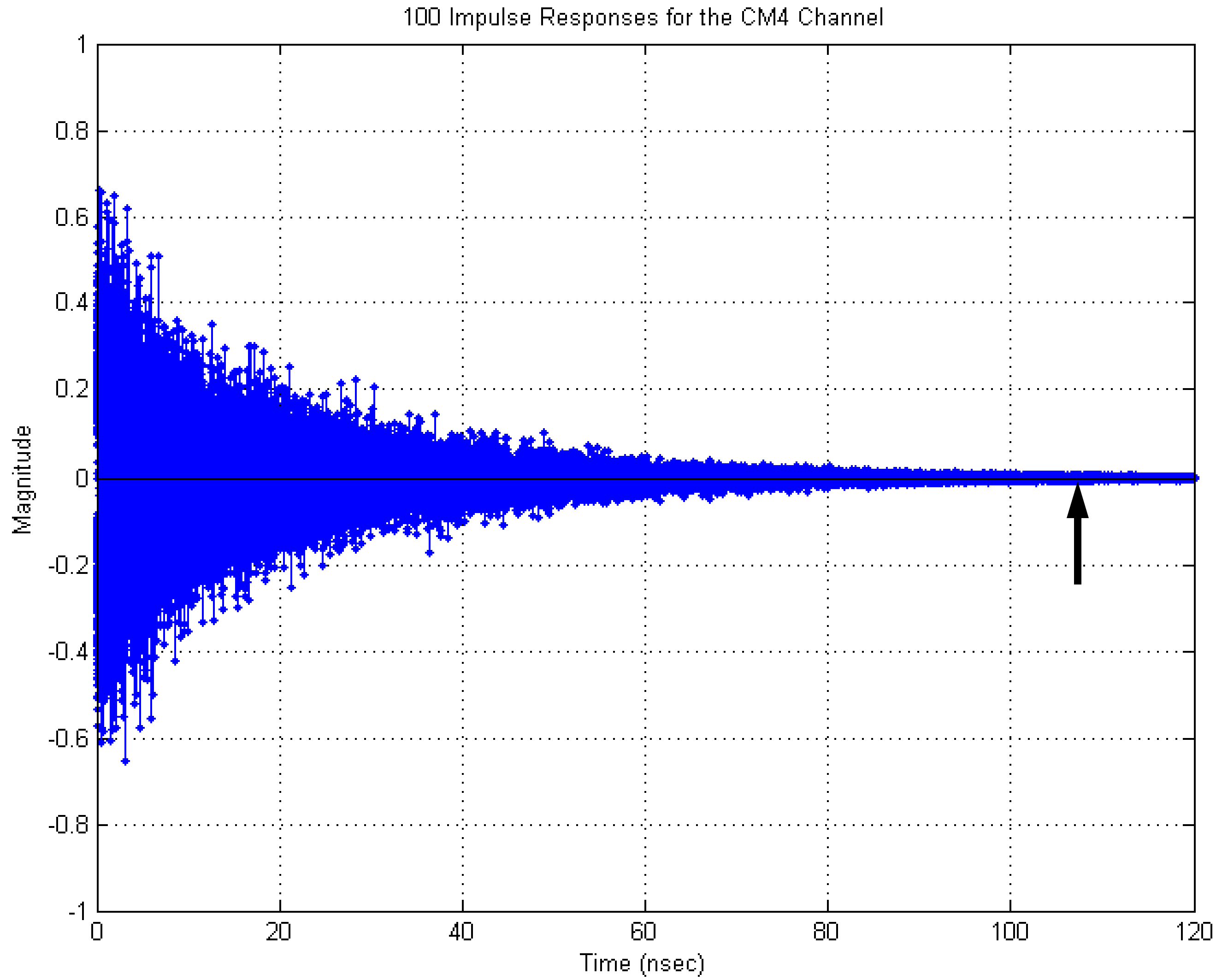
The CM2 Channel: NLOS, 0-4 m



The CM3 Channel: NLOS, 4-10 m



The CM4 Channel: Strong Multipath



Some receiver design considerations

- FCC mandates the use of at least 500 MHz of UWB bandwidth
- This translates into a pulse duration of the order of 2 ns
- Data rates of the order of 100 Mbps translate into symbol periods of the order of 10 ns. The larger the data rate, the longer the symbol duration.
- This means that **spectral peaks** will appear in the spectrum, unless some form of “**dithering**” is used
- Even for line-of-sight (LOS) conditions, with high data rates, the **maximum delay spread is greater than the symbol period**

When to "RAKE" the received signal?

- Signal with very narrow pulses and relatively long symbol period
  - Pulse-based modulation: PPM, PAM

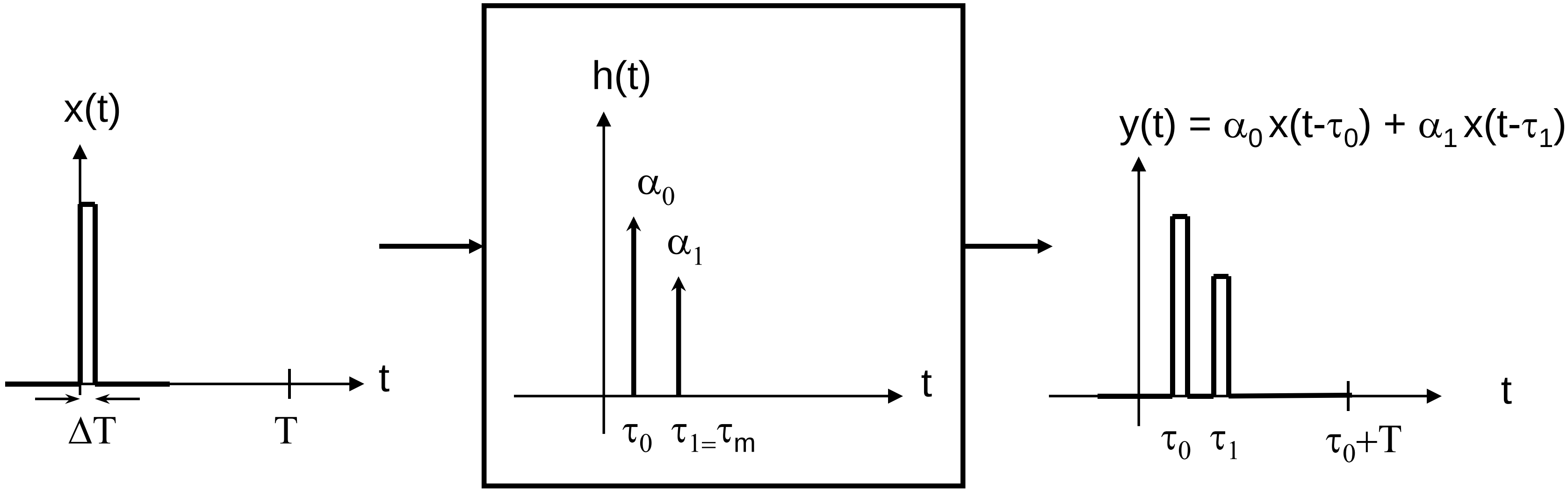
- Spread the symbols using pseudo-noise (PN) sequences with good autocorrelation properties
  - Spread-spectrum modulation (as in CDMA)
  - Chip duration short enough to resolve the multipath components

- [Proakis] Rake receiver improves reliability of the communication link provided that

$$\boxed{T \gg \tau_m\,,}$$

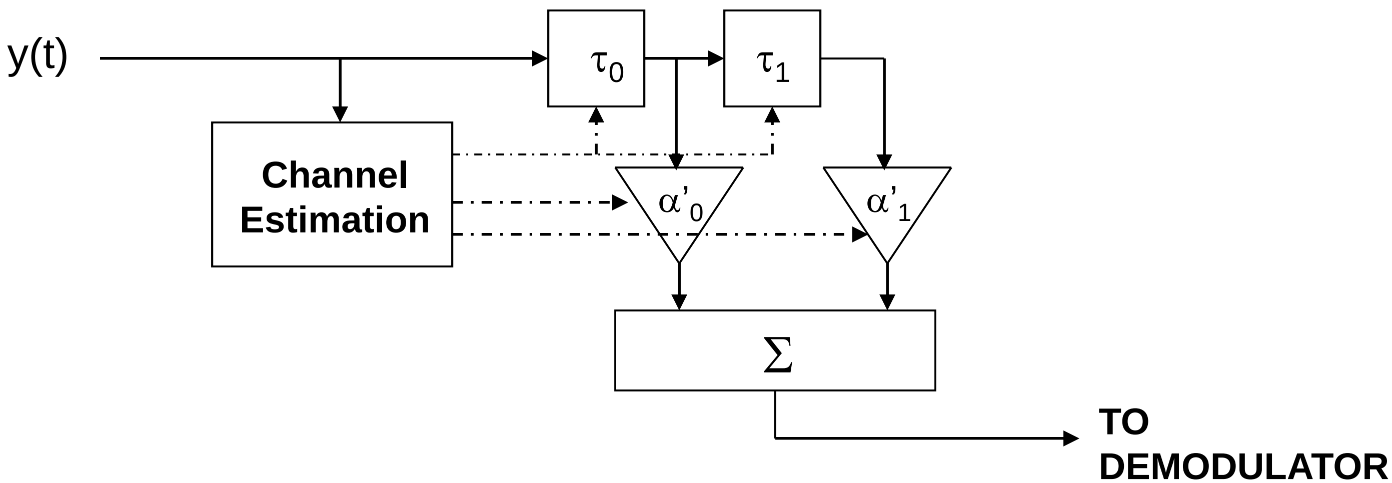
where T is the symbol period, and τ_m is the maximum delay spread of the channel

Example 1:
Pulse-based modulation and two-path channel



<u>Rake receiver</u>: Combines the two components in a constructive manner, to increase the signal energy, prior to the demodulation process

Example 1 (cont.): Rake receiver

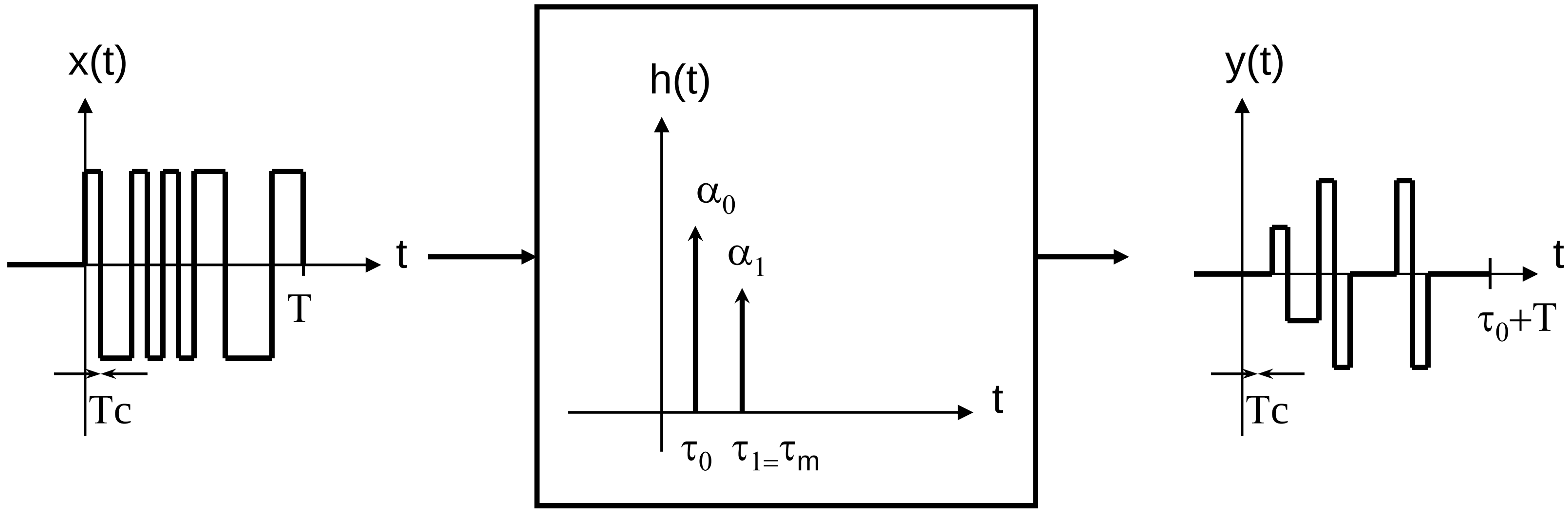


Maximum-likelihood channel gain estimator:

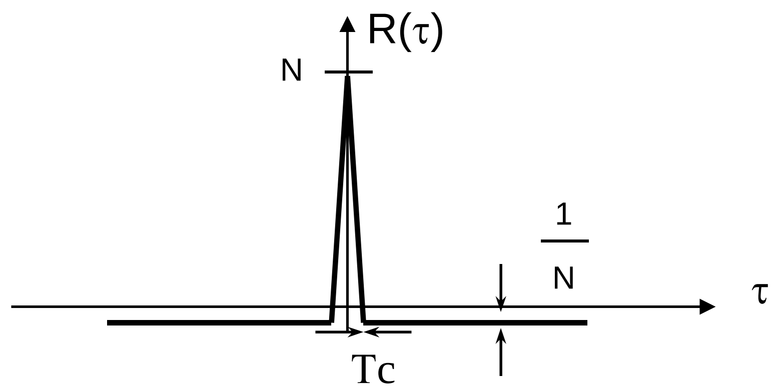
$\alpha'_i = \alpha_i^* + W_i$, where W_i is Gaussian distributed, i=1,2

Estimation Error

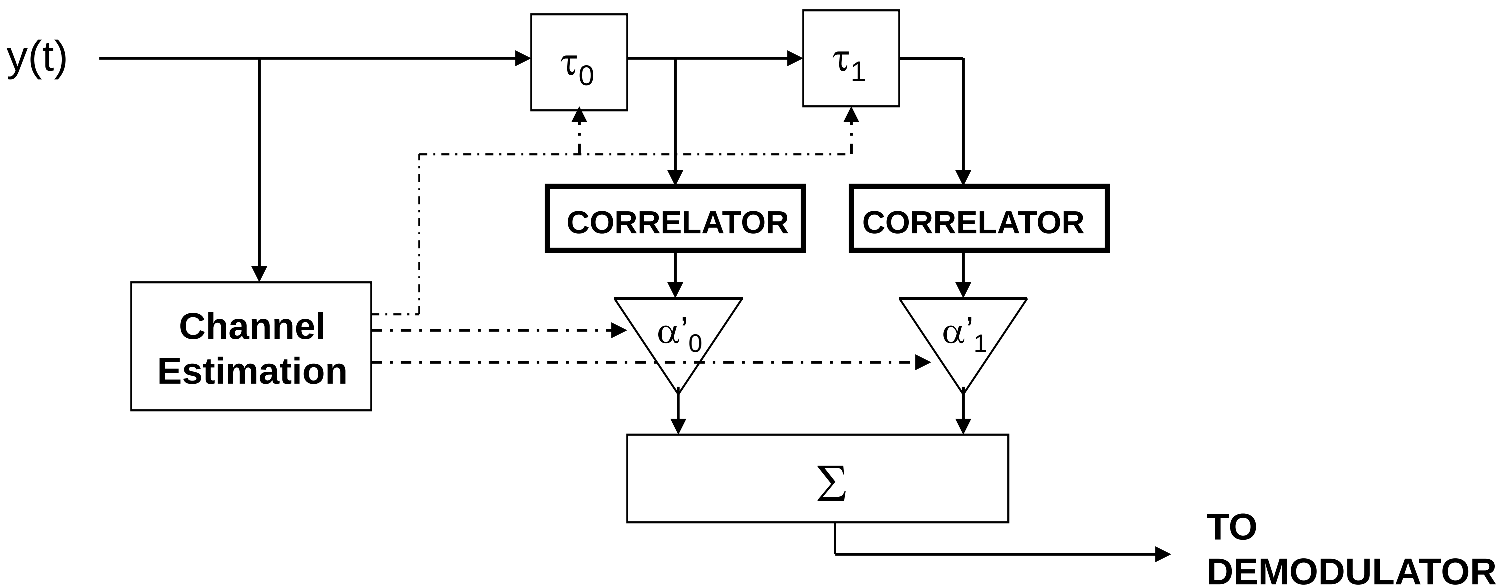
Example 2:
Spread-spectrum modulation and two-path channel



Autocorrelation function of a PN sequence of length N:



Example 2 (cont.): Rake receiver



PN sequence correlators are used in order to resolve (i.e., estimate the delay and gain of) the paths

When to “equalize” the received signal?

- The maximum delay spread of the channel, τ_m, exceeds the symbol period T

$$\boxed{T << \tau_m ,}$$

- A Rake receiver is no longer able to resolve <u>independent paths,</u> no matter how many “fingers” it has.

- Paths span several symbol periods and therefore symbols interfere with each other: **Inter-symbol interference (ISI)**

- ISI in turn mean that the channel is no longer “flat” over the signal bandwidth

- An **equalizer** can be used to “flatten” the channel
  - Multi-carrier (OFDM) signalling with frequency-domain equalization is an option

To RAKE or to equalize?

- In conventional (narrowband) digital communication systems, multipath channels can be classified as either “flat” or “frequency-selective”
- A **Rake receiver** is applicable in “flat” (or mildly frequency-selective) channels. Example: Cellular systems.
- An **equalizer** can be used in frequency-selective multipath channels. Example: Wireless LANs.
- However, the **UWB channel** contains such **large number of multipath components** that the models and receivers designed for narrowband systems are (highly?) suboptimal.

The UWB paradigm and joint RAKE-equalization

- The solution lies between the energy-capture capabilities of a **Rake receiver** and the ISI-removal properties of an **equalizer**

- A new type of digital receiver will emerge to handle the promises of high-data rates in very-large-bandwidth UWB systems

- The biggest challenges at this point in time appear to be
  - Short-time accurate estimation of (correlated) channel paths
  - Low-complexity (low-power) solutions to the joint optimization of Rake and equalizer:
    - Number of Rake fingers
    - Number of equalizer taps
    - Linear or nonlinear structures?
    - Data-aided or decision-directed?