Energy Capture of reduced-complexity UWB receivers

ASP Seminar

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Outline

- UWB channel characterization
- Energy capture and UWB benefits
  - High time-domain resolution
  - Reduced fading margin
  - Possible diversity gain
- UWB receiver types
  - Different levels of complexity
  - Energy capture results
  - Integration interval of noncoherent receivers
  - Performance comparison
- Conclusions

UWB channel characterization

- UWB channel is frequency-selective and time-dispersive
- Characterization by channel impulse response (CIR):

$$h(t)=\sum_{k=0}^{K}\sum_{l=0}^{L} a_{k,l} * \delta(t-T_k-\tau_{k,l})$$

K ... Number of Clusters

L ... Number of rays in k^{th} cluster

$a_{k,l}$ ... Tap weight of lth ray in k^{th} cluster

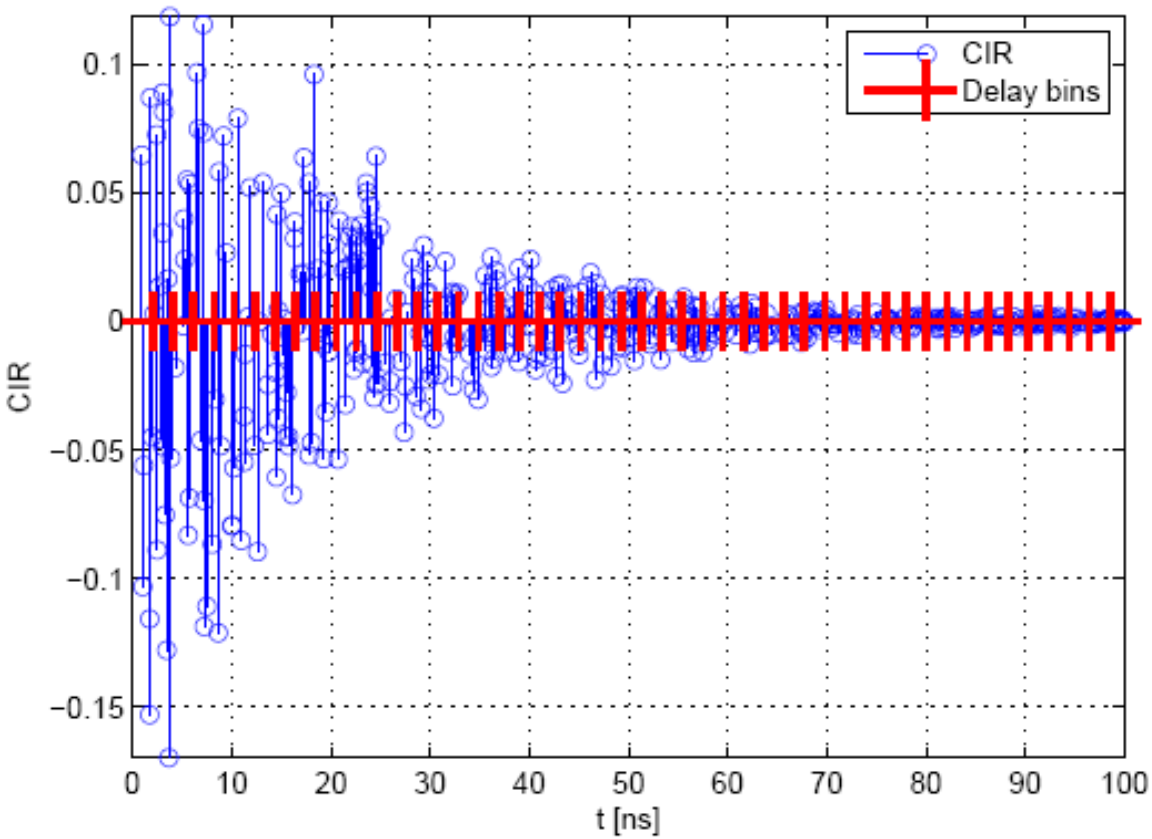
T_k ... Delay of kth cluster

$\tau_{k,l}$ ... Delay of lth ray in k^{th} cluster

- → Received signal: Sum of delayed and scaled copies of transmitted pulse shape
- Number of *resolvable* MPCs depends on system bandwidth

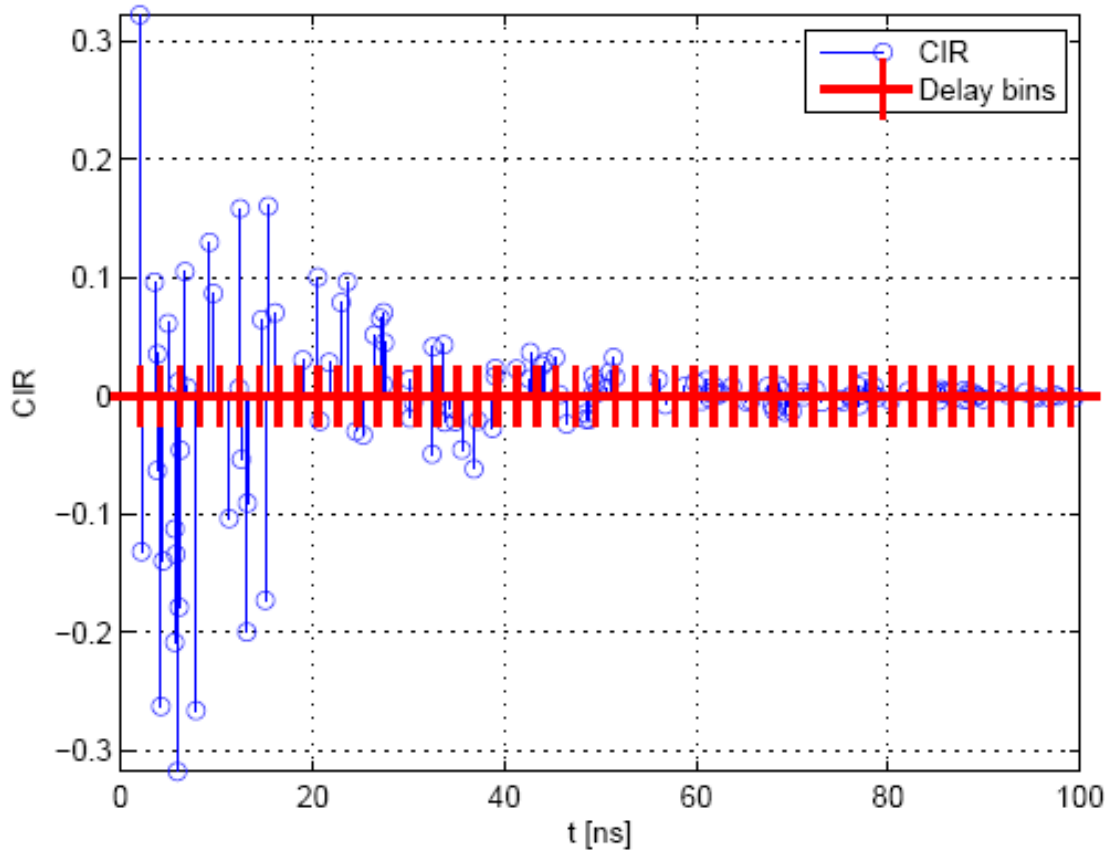
UWB Channel Characterization - CIR

- Several 100 MPCs can be present
- Time-axis divided in delay bins
- Bin width ~ 1/BW
- Here: BW=500MHz
- "Enough" MPCs in one bin→ central limit theorem applies and amplitudes are Rayleigh-fading (*dense* multipath environment)



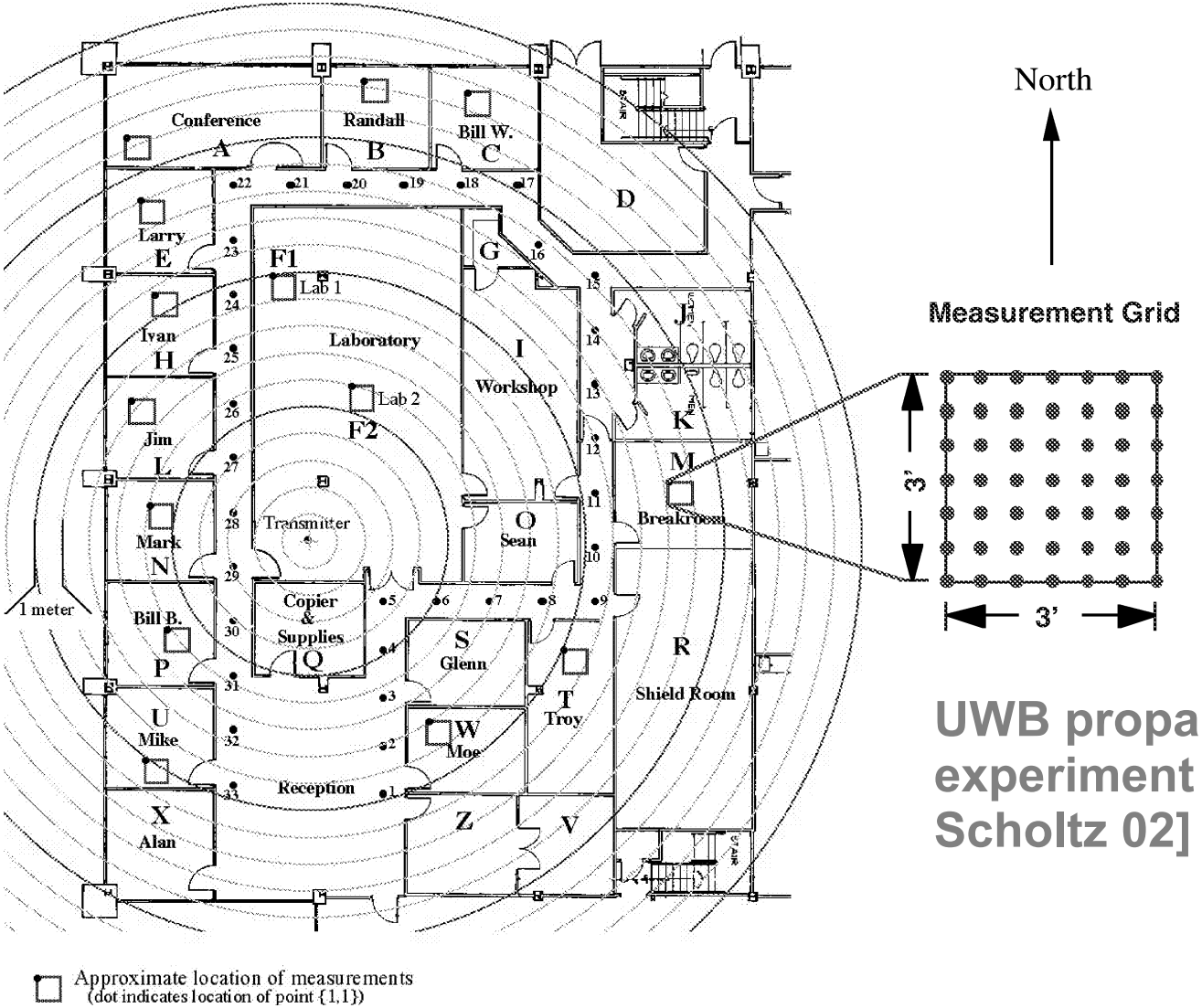
UWB Channel Characterization - CIR

- However, CIR can also be *sparse*
- Due to number of interacting objects
- Due to *bandwidth*
- Higher BW→narrower delay bins →less rays per bin



- CLT might not be applicable → other fading distributions (Nakagami-m, Log-normal)

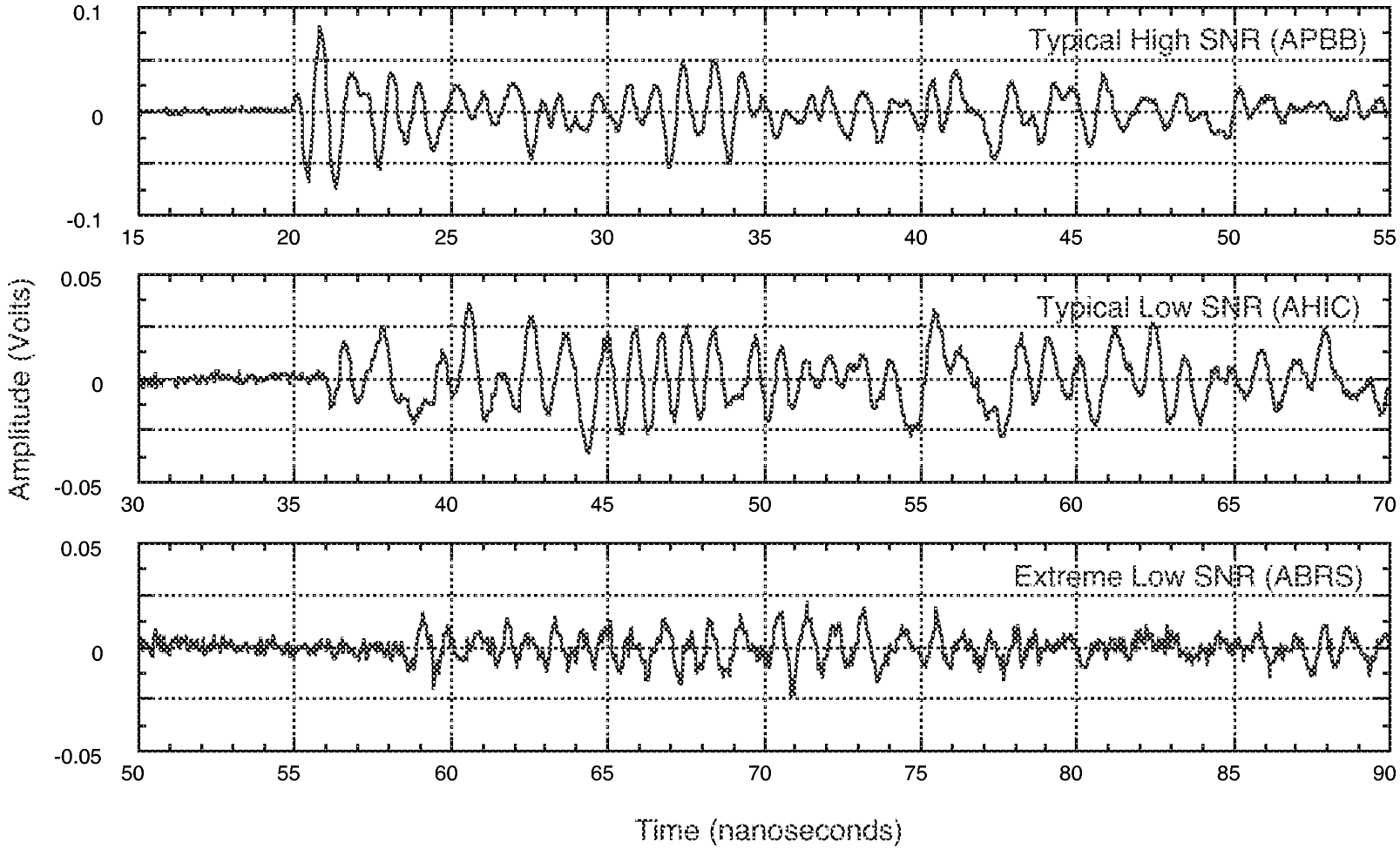
UWB channel characterization - Example



UWB propagation experiment [Win, Scholtz 02]

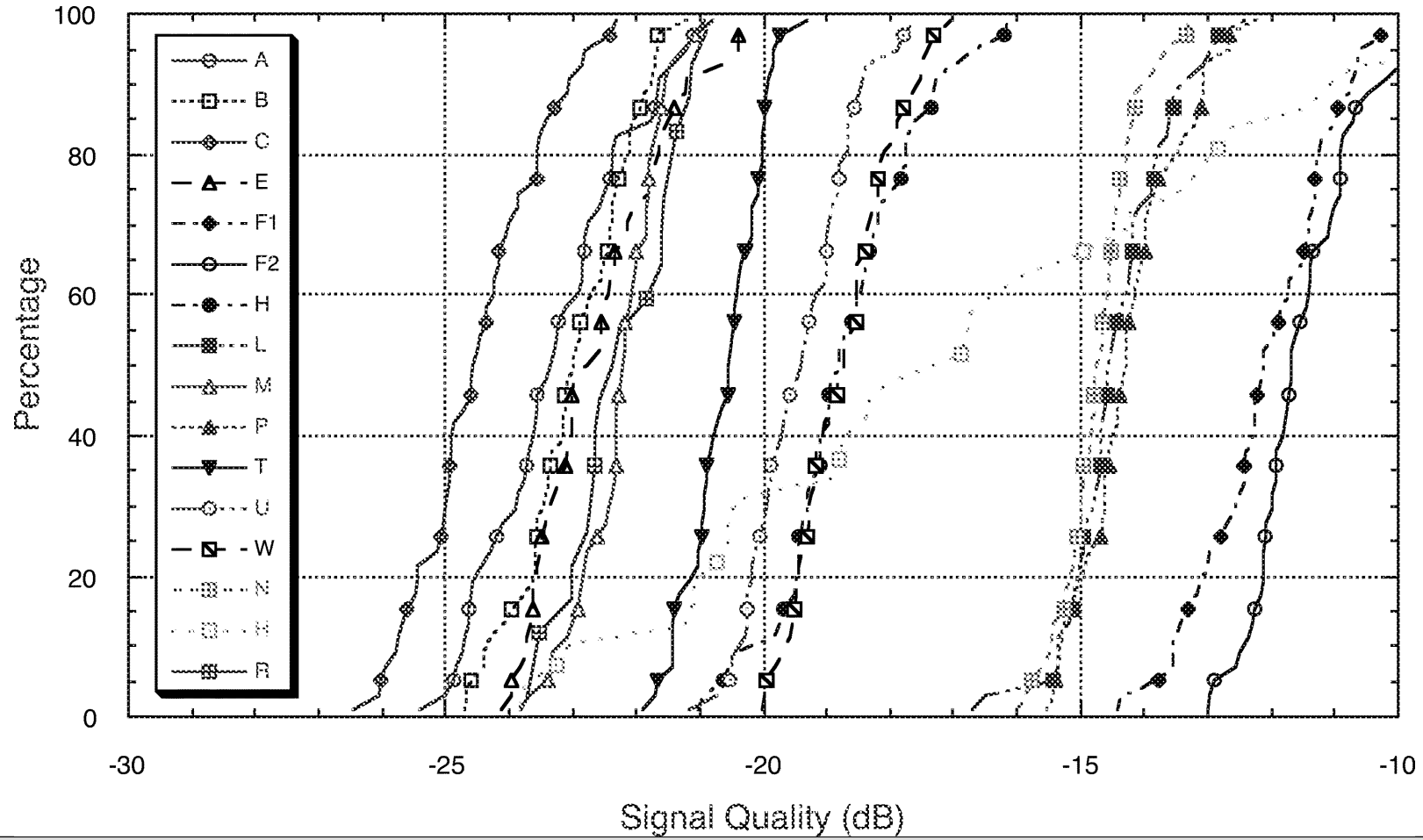
UWB channel characterization - Example

- Example responses to a UWB pulse in different scenarios [Win, Scholtz 02]



UWB channel characterization – Implications (1)

- Empirical CDFs of received energy in different locations



UWB channel characterization – Implications (2)

- Empirical CDFs: Received energy varies by at most 5dB within one location
- → Considerably less than usual NB fading margin
- → Potential for channel-robust communication with UWB signals at low power levels

- Resolution of the multipath diversity combats the effects of small-scale fading
- Needed: Receiver structures exploiting this potential
- *Energy* in multipath components has to be *captured*

UWB Receivers – Rake receiver

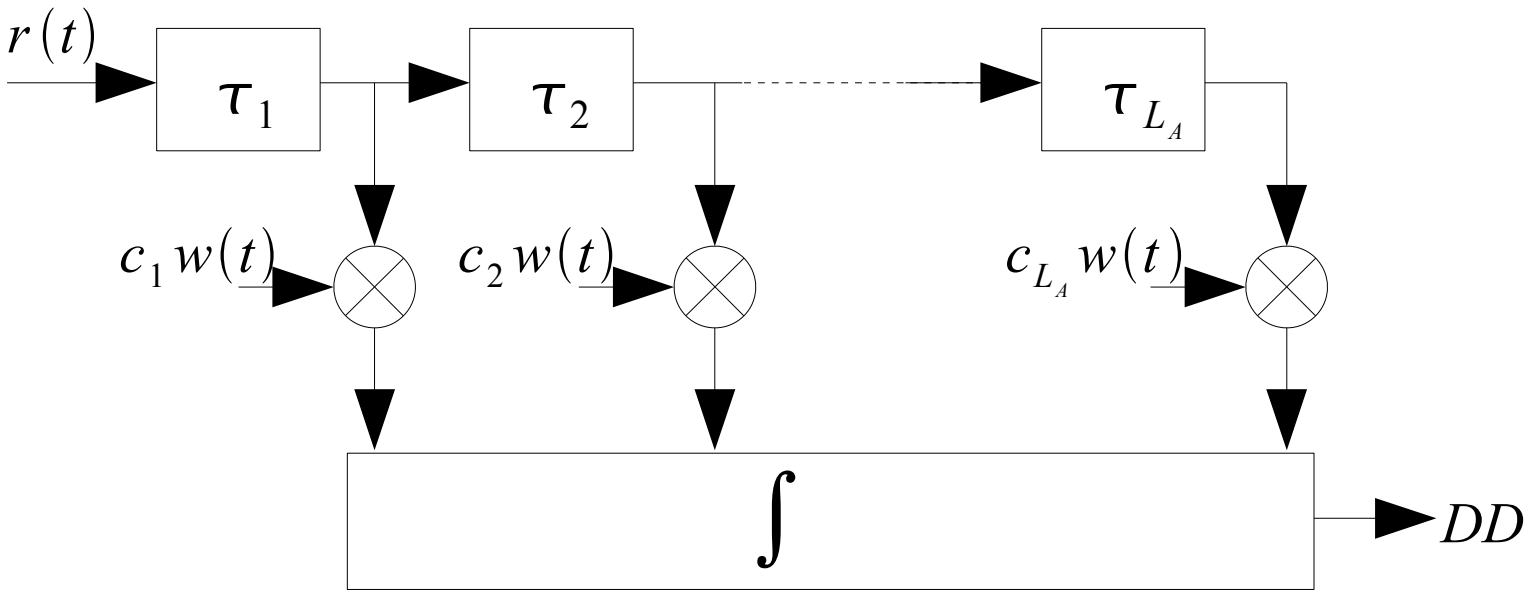
- Received signal: Sum of scaled and delayed pulse copies:

$$r(t) = \sum_{l=1}^{L_A} \tilde{a}_l w(t - \tau_l)$$

L_A ... Number of *resolvable* MPCs

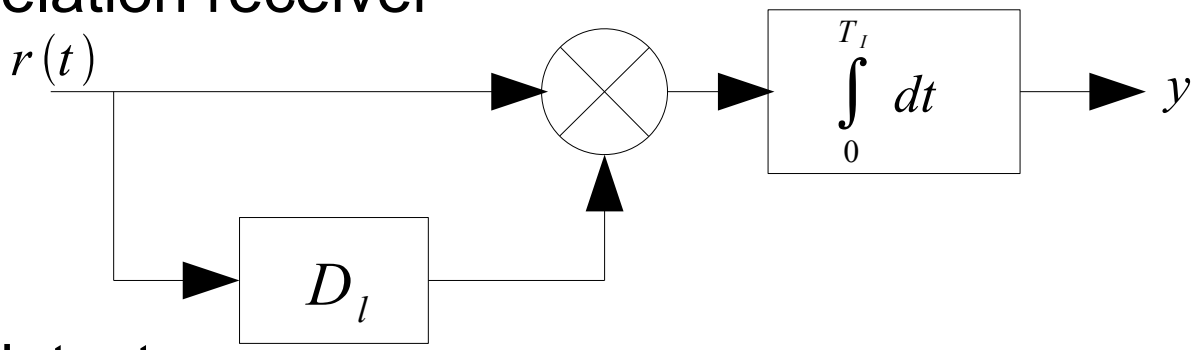
- Ideal receiver cross-correlates with L_A template signals

→ *Rakes* up multipath energy, exploits multipath diversity

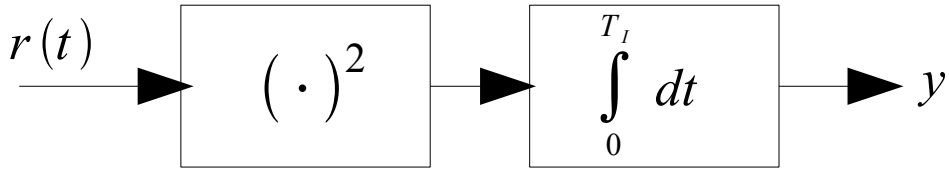


UWB Receivers – Noncoherent Receivers

- Autocorrelation receiver



- Energy detector



- Aim: Exploit multipath diversity without channel estimation
- Signal energy is captured during integration interval
- But also noise energy
- AcR with transmitted reference: Also template is noisy

UWB receiver types - Overview

- Coherent receivers: Rake receiver, types:
  - Ideal: All-Rake (ARake), selects *all resolvable* (L_A) MPCs, unlimited resources, instant adaptability
  - Realizable: Selective Rake (SRake): Selects the L_S *strongest* MPCs
  - Partial Rake (PRake): Selects the L_P *first* MPCs

Complexity <<

- Further reduction of complexity: Noncoherent receivers
  - Autocorrelation receiver
  - Energy detector
  - Noncoherent addition of multipath components

- → How much energy capture is sacrificed by reducing the receiver complexity?

Energy Capture of an optimized Rake

- Energy capture as a function of the number of correlators (rake fingers)
- Fixed number of fingers, delays and tap coefficients minimize:

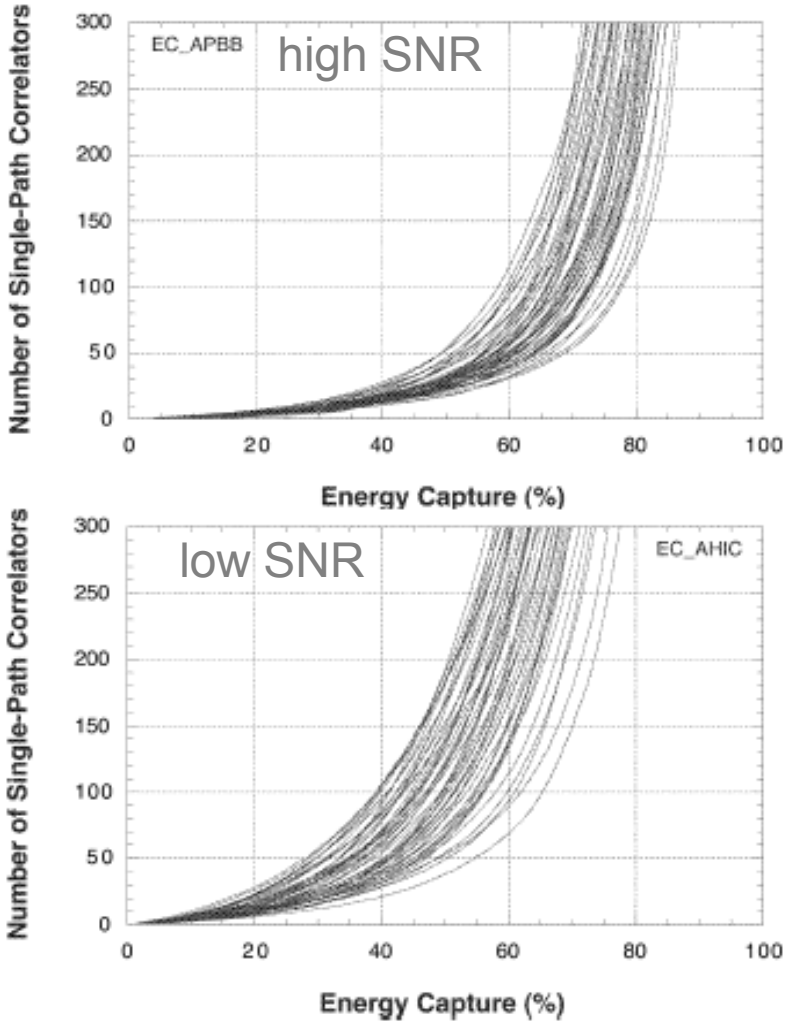
$$E(L)=\int_0^T \left|r(t)-\sum_{l=1}^{L} c_l w(t-\tau_l)\right|^2 dt$$

- Minimum error: $E_{min}(L)$

  Energy capture defined as:

$$EC(L) = 1 - \frac{E_{min}(L)}{E_{tot}}$$

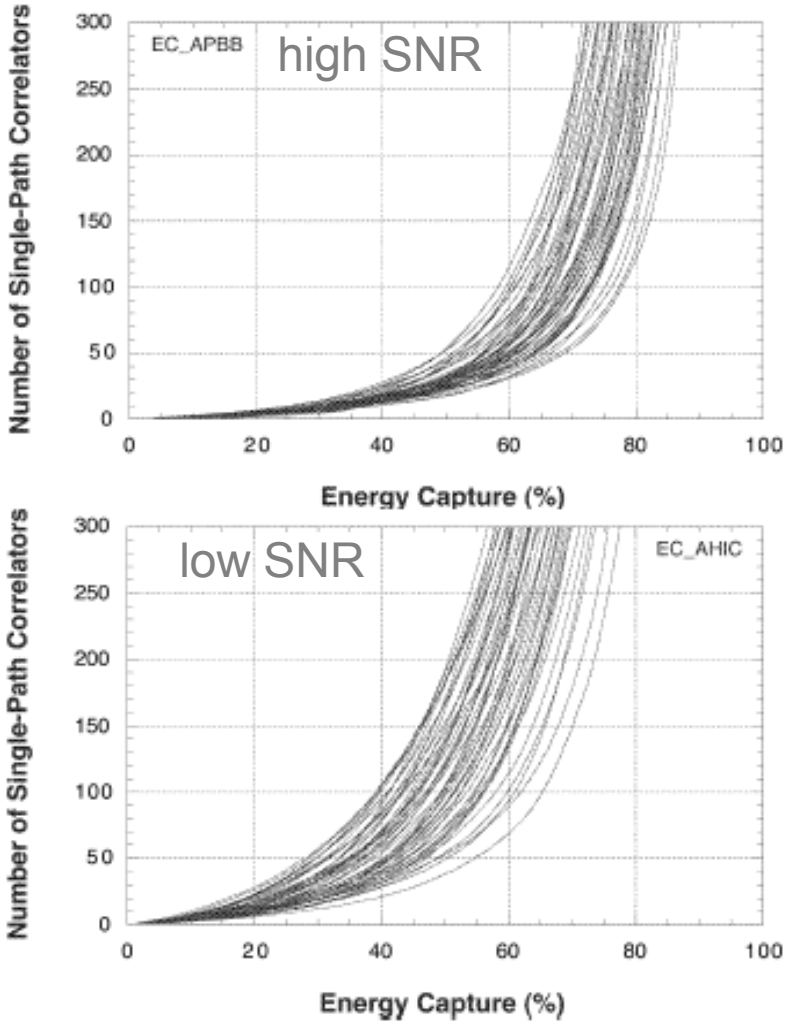
- E_{tot}: Total energy in MPCs



[Win, Scholtz 02]

Energy Capture of an optimized Rake

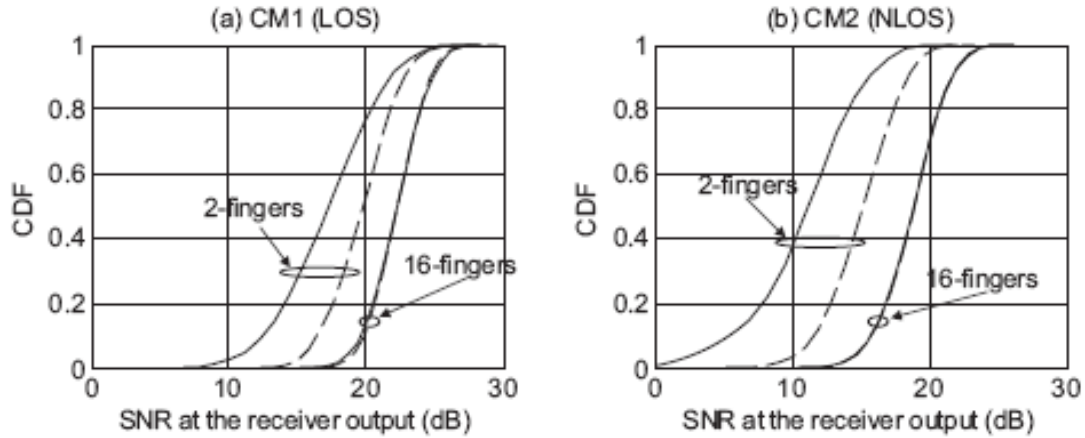
- Rapid increase of EC until L is about 50
- Increasing L above 50 → EC gain becomes gradual
- “Working point” for rake receivers in region where EC(L) is rapidly increasing
- Lower SNR: Less signal energy can be captured



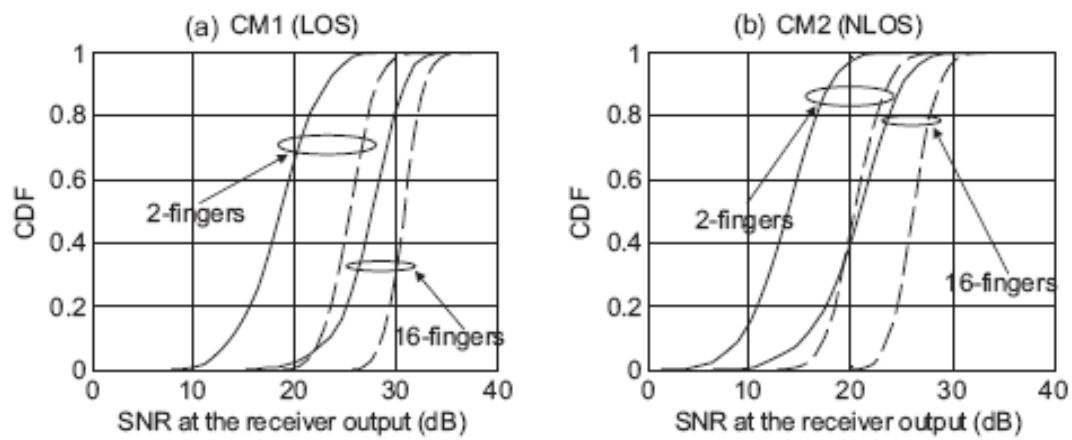
[Win, Scholtz 02]

Energy Capture of SRake and PRake

- CDF of SNR at Rx output
- For 2 and 16 fingers, SRake (solid) and PRake (dashed)
- PRake blindly uses first 2 or 16 MPCs
- At low BW, PRake with 16 fingers captures the same amount of energy as SRake (much of the support of the CIR is covered)
- At high BW, PRake lags behind, effective CIR is much more sparse → PRake can not exploit diversity gain well
- Many delay bins might be empty or carry little energy



BW = 0.5 GHz (3.1 – 3.6 GHz)

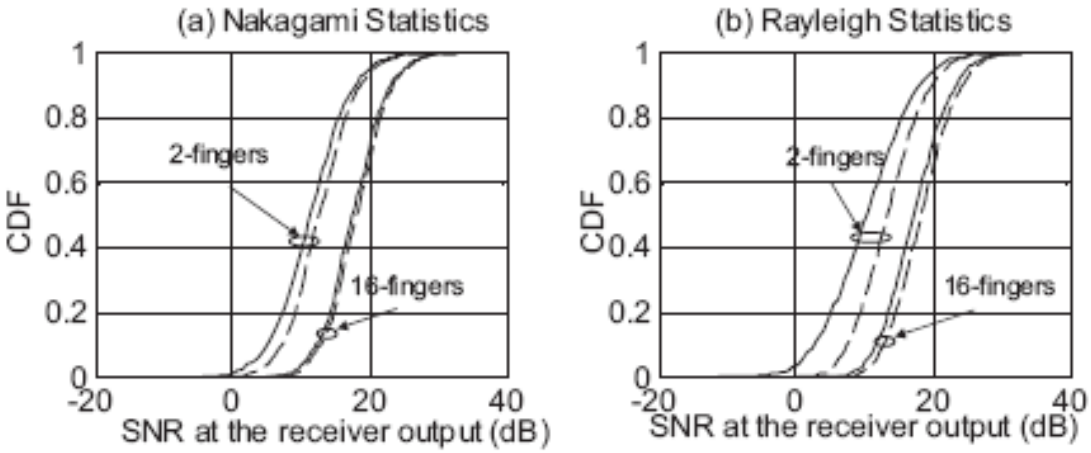


BW = 7.5 GHz (3.1 – 10.6 GHz)

[Cassioli et al 07]

EC of SRake and PRake – Fading statistics

- CDF of SNR at Rx output for Rayleigh and Nakagami fading
- Rayleigh fading allows for higher variations of instantaneous amplitudes → higher fading depth
- Increases performance gap between SRake and PRake
- Smaller instantaneous amplitude variations for Nakagami fading

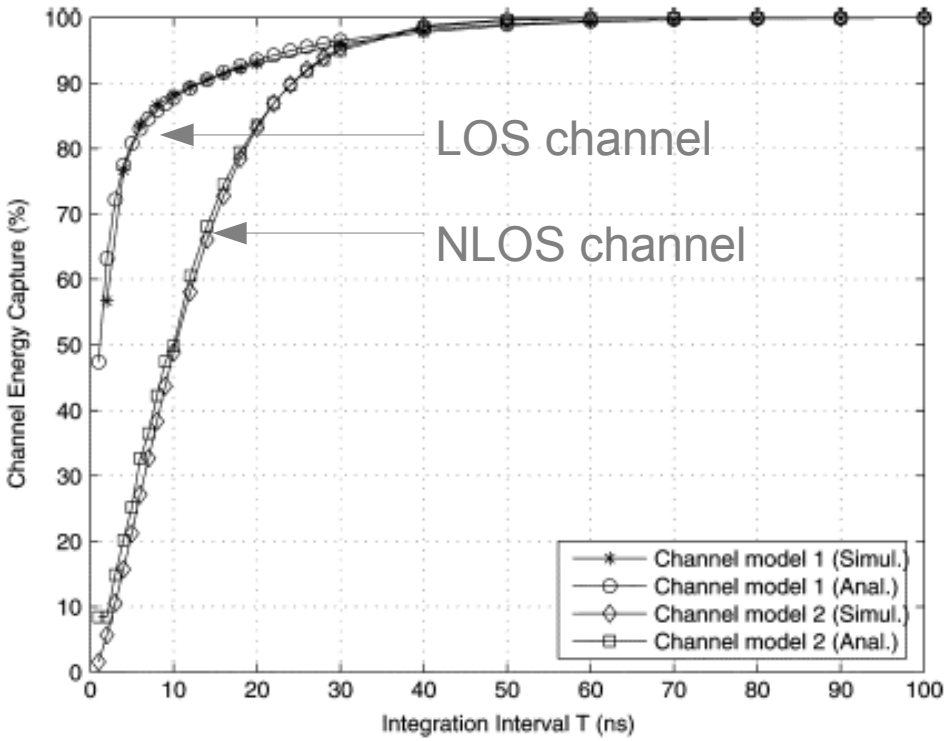


BW = 0.5 GHz (3.1 – 3.6 GHz)

[Cassioli et al 07]

Energy capture of an autocorrelation receiver

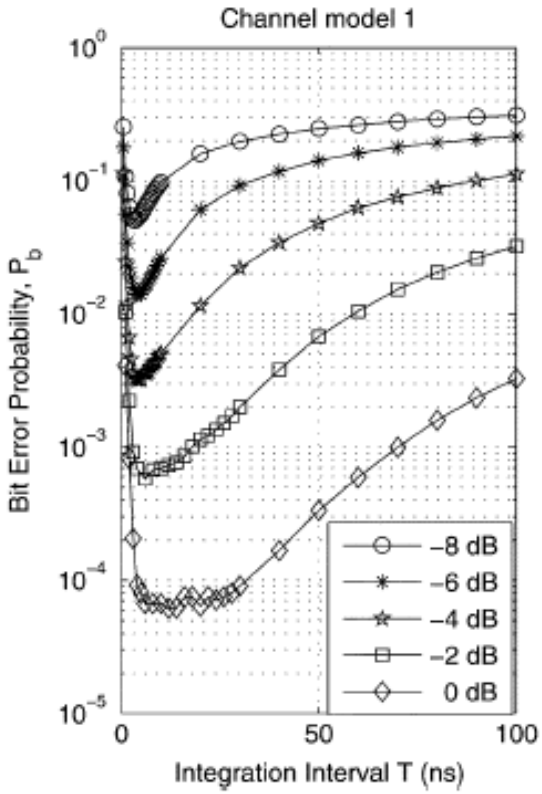
- Transmitted-reference system with AcR at ~ 1 GHz bandwidth
- EC as a function of integration interval T_I
- $EC(T_I)$ increases rapidly, ca. 87% of the energy captured within 10ns (LOS) or ca. 23ns (NLOS)
- But: Also noise energy accumulated within T_I
- → BER-performance of receiver over T_I needed for optimization



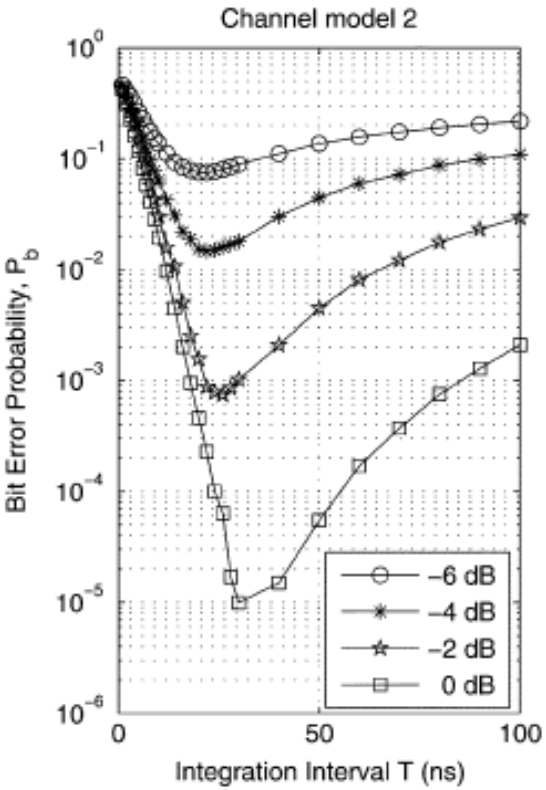
[Na, Saquib 07]

Energy capture of an autocorrelation receiver

- Transmitted-reference system with AcR at ~1GHz bandwidth
- 10 Mb/s data rate
- BER as a function of integration interval T_I
- Optimal T_I depends on noise level and channel
- Comparison with prev. slide: 80-89% of energy capture for channel 1 (LOS), 84-96% for channel 2 (NLOS)
- However, no common, “good” choice for T_I



LOS

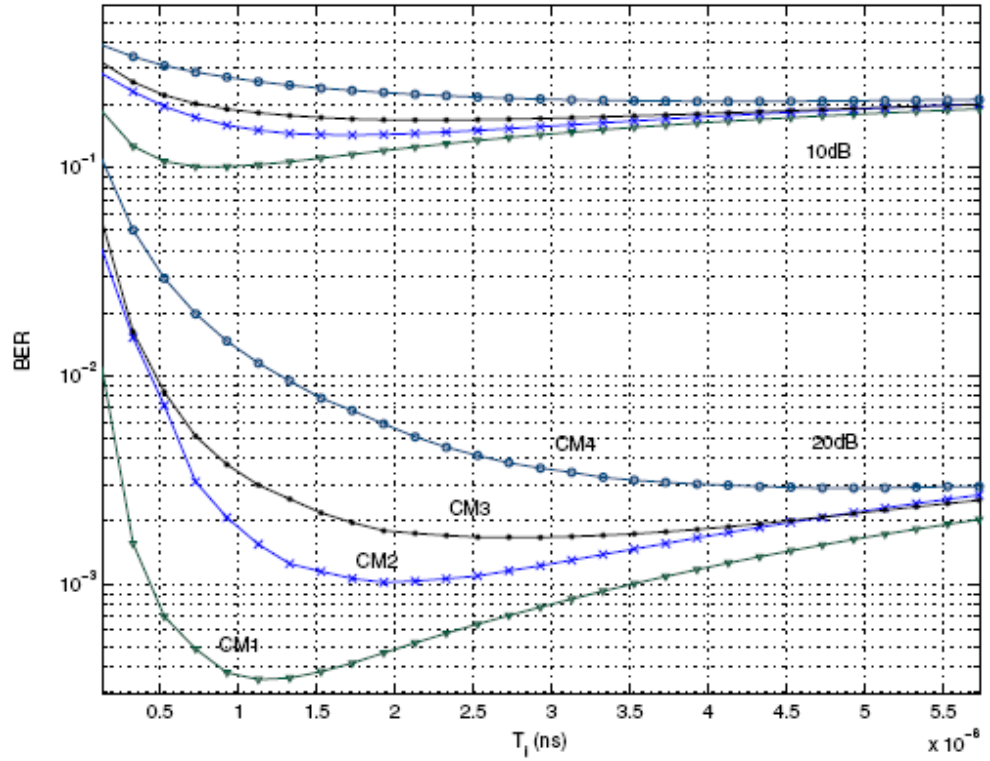


NLOS

[Na, Saquib 07]

Energy capture of an energy detector

- ED receiver, BW=2GHz
- Simulation results for IEEE channel models
- In general: Longer channel → longer T_I and less pronounced BER-minima
- For longer channels, energy is more spread in time

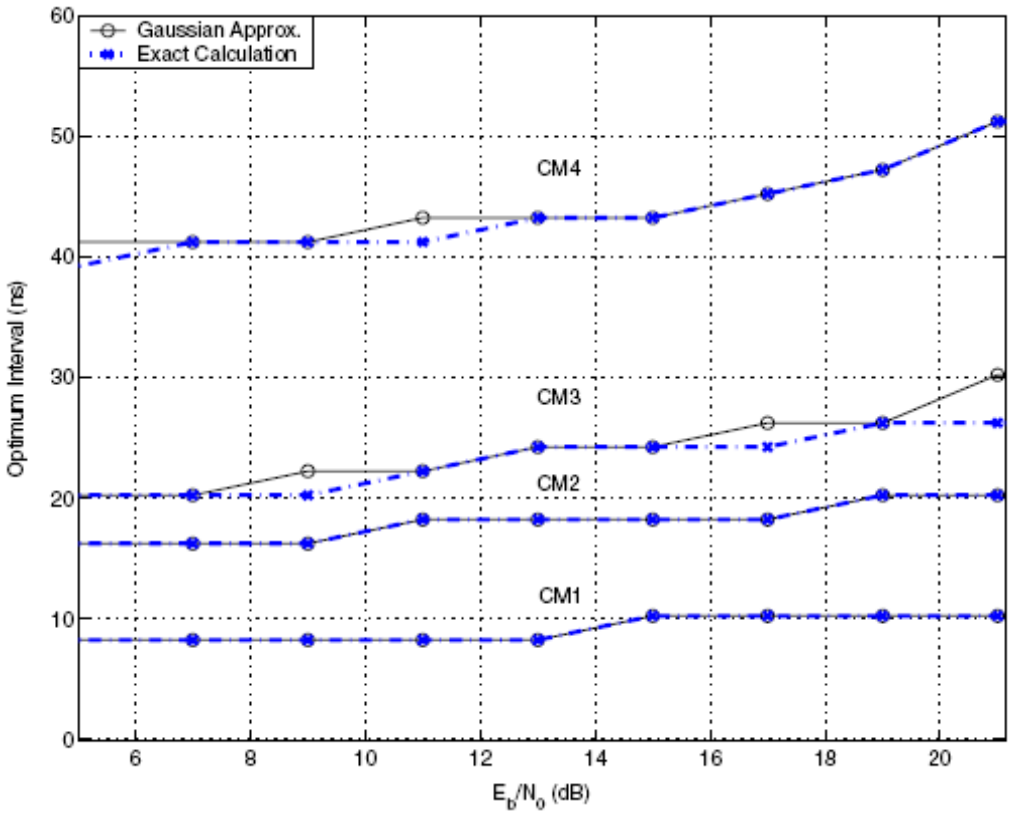


BER(TI) for different SNR and IEEE channel models CM1-CM4

[Sahin et al 05]

Energy capture of an energy detector

- ED receiver, BW=2GHz
- Simulation results for IEEE channel models
- Another view of the optimal integration interval
- Lower noise level → Higher integration interval possible
- Pays off more for longer channels



Optimal T_I over SNR for IEEE channel models CM1-CM4

[Sahin et al 05]

Integration interval optimization for NC-UWB

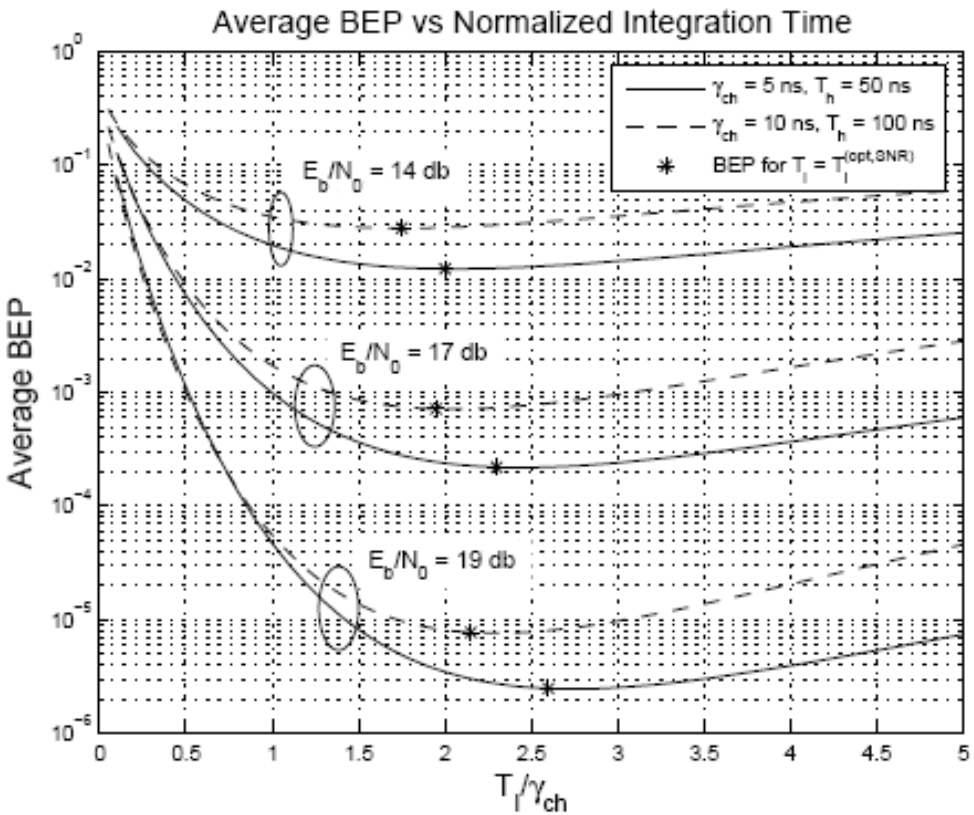
- Important parameter for noncoherent receivers, big impact on performance
- No straightforward solution
- Receivers with adaptive T_I (and synchronization) are proposed
- Often done by simulations over different channel models
- Analytic solutions exist, but often using simplifications:
  - Dense channel (Systems at high BW?)
  - Power delay profile of channel monotonically decreasing (NLOS channels?)
  - Not $BER_{opt}(T_I)$, but $SNR_{max}(T_I)$ at Rx output is taken into account

T_I optimization for NC-UWB - Example

- Analytic calculation of T_I maximizing Rx output SNR
- Assumes dense channel and exponential decaying PDP
- Results of maximized output SNR match well with BER curve

$$T_I^{opt,SNR} = \eta_{ch} \ln\left(\frac{E_b}{N_0}\frac{1.1}{\eta_{ch} W} + 4.3\right)$$

- η_{ch} ... channel decay factor

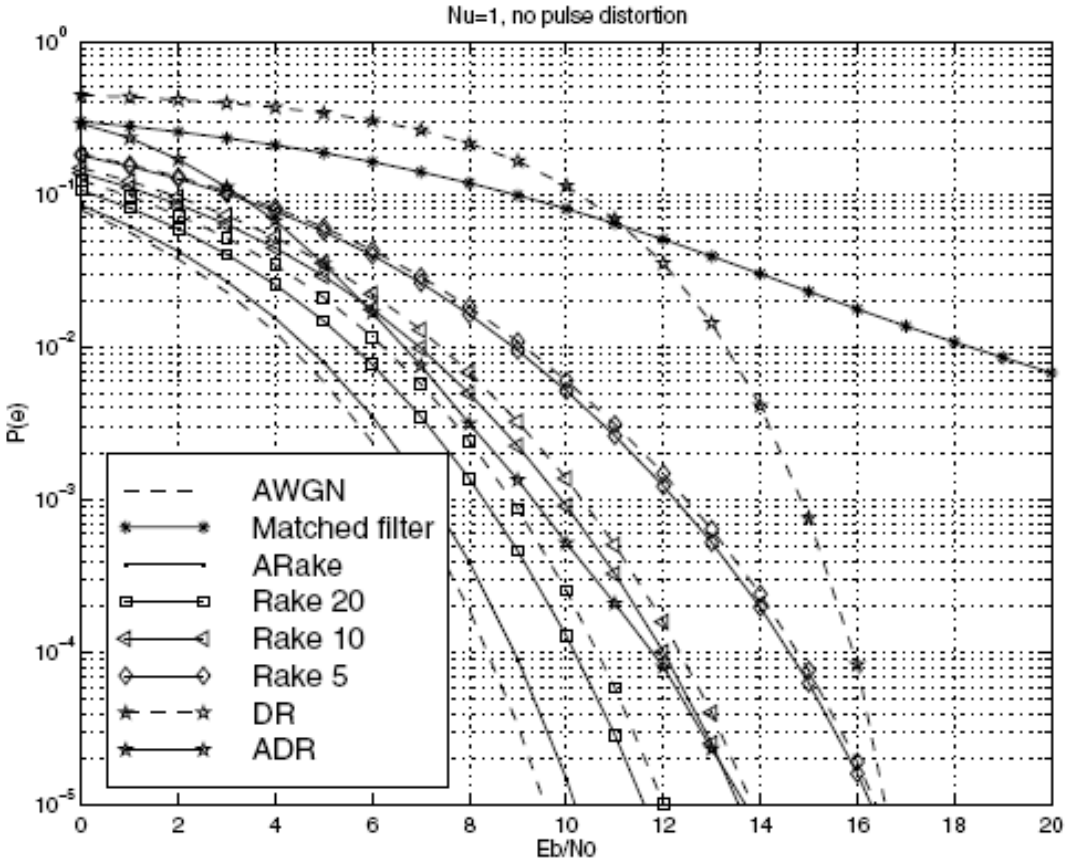


* = Points where SNR at Rx output is maximized

[Pausini 07]

Coherent vs. Noncoherent receivers

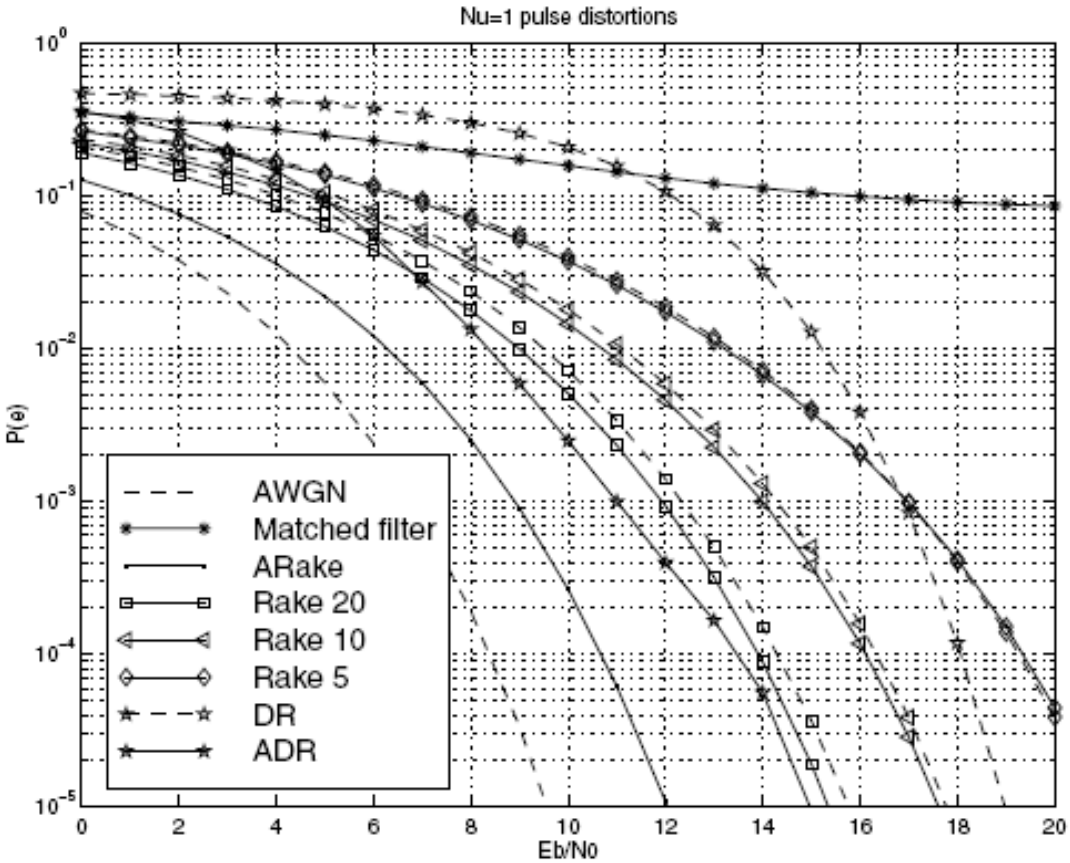
- BER comparison of Rake and Autocorrelation receivers
- Gaussian pulses with duration of 0.7ns are used
- SRake receivers used that know the strongest paths
- Also an AcR with adaptive template update is presented
- → Conventional AcR is around 5dB behind Rake 20 and 2.5dB behind Rake 10 at BER=10^{-5}
- → Adaptive AcR: About same performance as Rake 10



[Durisi, Benedetto 04]

Coherent vs. Noncoherent receivers

- Further comparison including pulse distortion
- Distortion has more influence on Rake receivers
- They do not perform pulse shape estimation
- Adaptive AcR becomes comparable to Rake 20



[Durisi, Benedetto 04]

Conclusion

- UWB signals offer the possibility of combating fading
  - Signal energy dispersed in time
  - Energy of multipath components can be captured → diversity gain
  - Can be done with different levels of complexity
- Reducing complexity leads to less captured energy
  - Not only number of Rake fingers, also their selection is important
  - Noncoherent systems can capture energy, but do not distinguish between signal and noise energy
- Complexity needed depends on channel
  - Optimization is a difficult problem
  - Adaptive solutions may help (especially for noncoherent systems)

References

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- [Win, Scholtz 98]: Moe Z. Win, Robert A. Scholtz: *On the Energy Capture of Ultrawide Bandwidth Signals in Dense Multipath Environments*
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- [Na, Saquib 07]: Yanxin Na, Mohammad Saquib: *Analysis of the Channel Energy Capture in Ultra-Wideband Transmitted Reference Systems*
- [Pausini 07]: Marco Pausini: *Autocorrelation Receivers for Ultra Wideband Wireless Communications*

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- [Molisch et al 03]: Andreas F. Molisch, Jeffrey R. Foerster, Marcus Prendergrass: *Channel Models for Ultrawideband Personal Area Networks*
- [Sahin et al 05]: Mustafa E. Sahin, Ismail Güvenc, Hüseyin Arslan: *Optimization of Energy Detector Receivers for UWB Systems*
- [Dubouloz et al 05]: Samuel Dubouloz, Benoit Denis, Sebastien de Rivaz, Laurent Ouvry: *Performance Analysis of LDR UWB Non-Coherent Receivers in Multipath Environments*
- [Durisi, Benedetto 04]: Giuseppe Durisi, Sergio Benedetto: *Performance of Coherent and Non-Coherent Receivers for UWB Communications*

Thanks for your attention!