Ranging with Ultrawide Band

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Overview

Introduction
- Ranging (TW-TOA)
- Propagation Channel
- Noise

Generalized Maximum Likelihood Estimation

Non-Coherent Receiver Types

Estimators for Non-Coherent Receivers
- MES
- W-MESS
- TC
- MES-SB

Other Estimators

Summary

Ranging

Determining the distance between two devices by

- measuring phase delay (carrier wave)
- transmitting time stamps (synchronized clocks)
- measuring (round-trip) propagation time of a pulse

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High temporal resolution needed!

Impulse radio UWB uses pulses with a duration in the order of a few ns – high ranging capabilities.

TW-TOA

One-way ranging schemes require synch'd clocks – hard to realize for low-power handhelds.

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- Device 1 transmits a pulse at τ_{start} and starts a timer
- As soon as Device 2 detects the pulse, it waits for a certain time $T_M/2$

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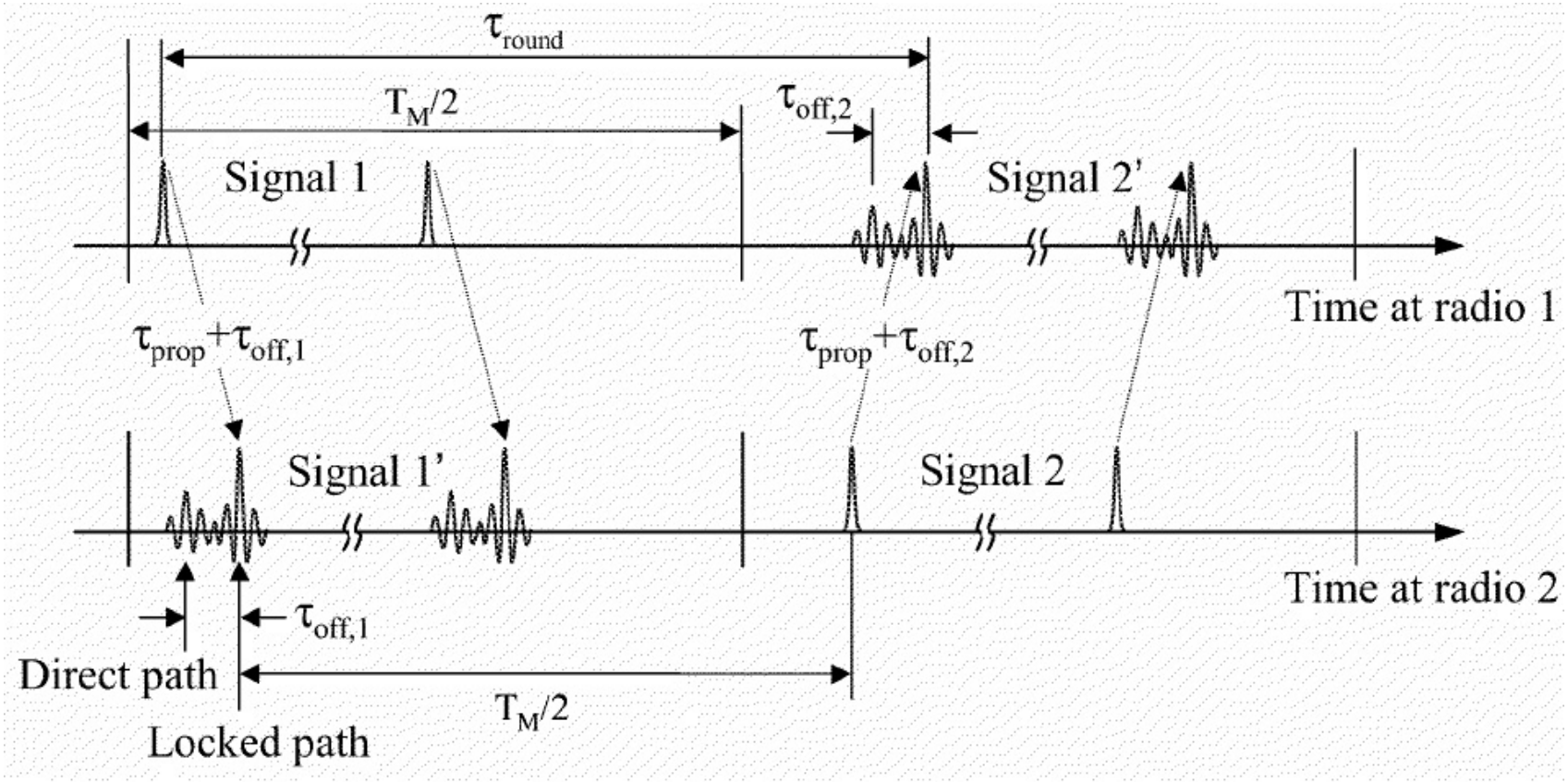
- Device 2 transmits a pulse
- As soon as Device 1 detects the pulse at τ_{TOA} it stops the timer

TW-TOA (cont'd)



Taken from [1]

TW-TOA (cont'd)

From round-trip time τ_{round}

$$\tau_{round} = \tau_{TOA} - \tau_{start} = 2\tau_{prop} + \frac{T_M}{2} \tag{1}$$

we can calculate propagation time of pulse:

$$\tau_{prop} = \frac{\tau_{round} - \frac{T_M}{2}}{2} \tag{2}$$

And finally:

$$d = v_{prop}\tau_{prop} \tag{3}$$

TW-TOA (cont'd)

Sources of Uncertainty

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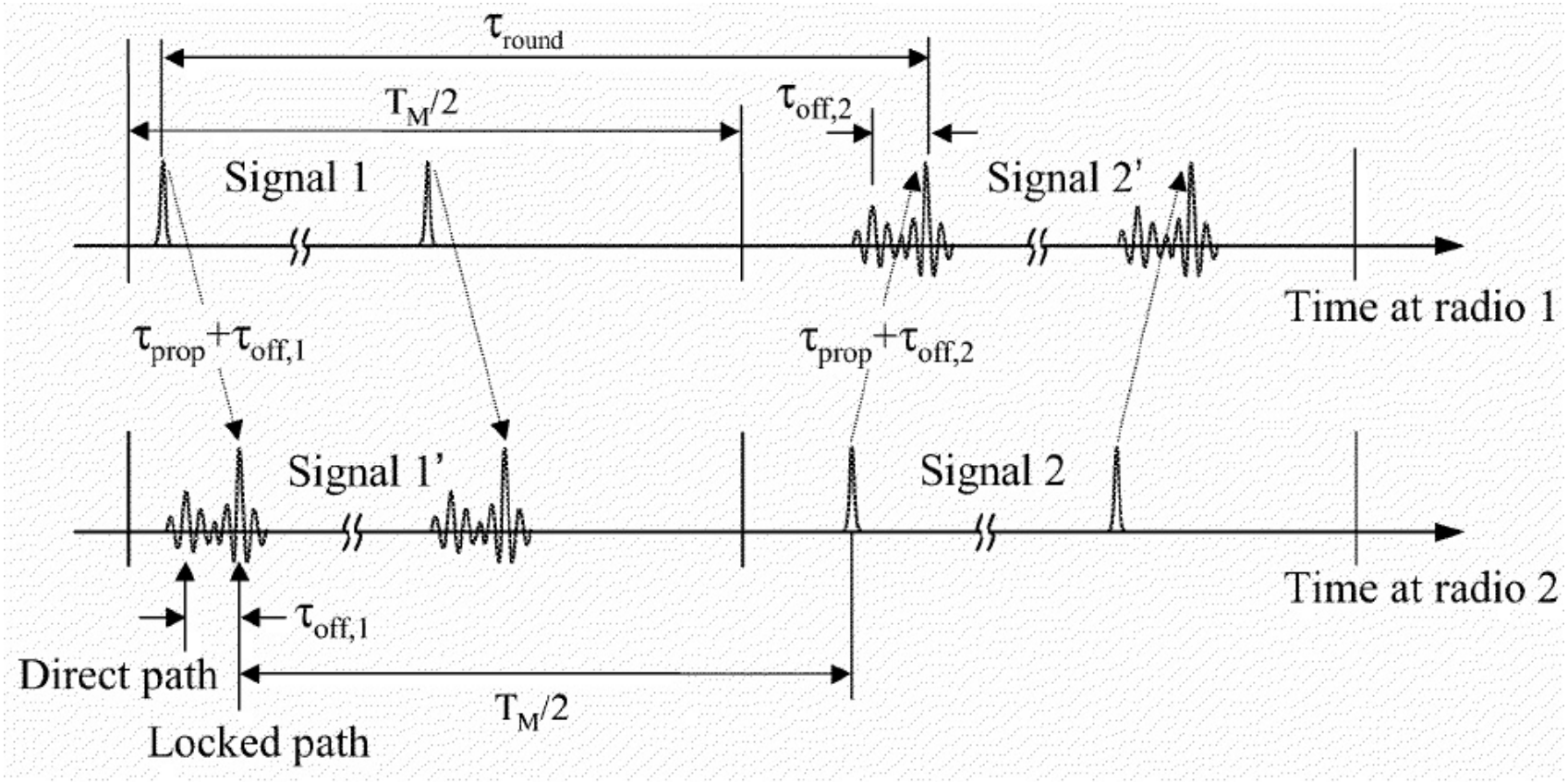
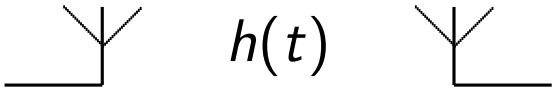
- Propagation speed $v_{prop} \approx c$ has to be known (difficult!)
- Propagation time τ_{prop} has to be known (even more difficult!)
  - *Both* devices have to detect the first pulse of the channel impulse response accurately
  - Otherwise: $\tau_{off,1}, \tau_{off,2}$

TW-TOA (cont'd)



Taken from [1]

Channel Impulse Response (CIR)



$$h(t) = \sum_{l=0}^{\infty} \alpha_l \delta(t - \tau_l)$$

- Sum of weighted δ-pulses representing reflections/multipath components
- Only approximation/doesn't model distortions
- $\tau_0 = \tau_{prop}$
- α_0 is (complex) path gain of first pulse

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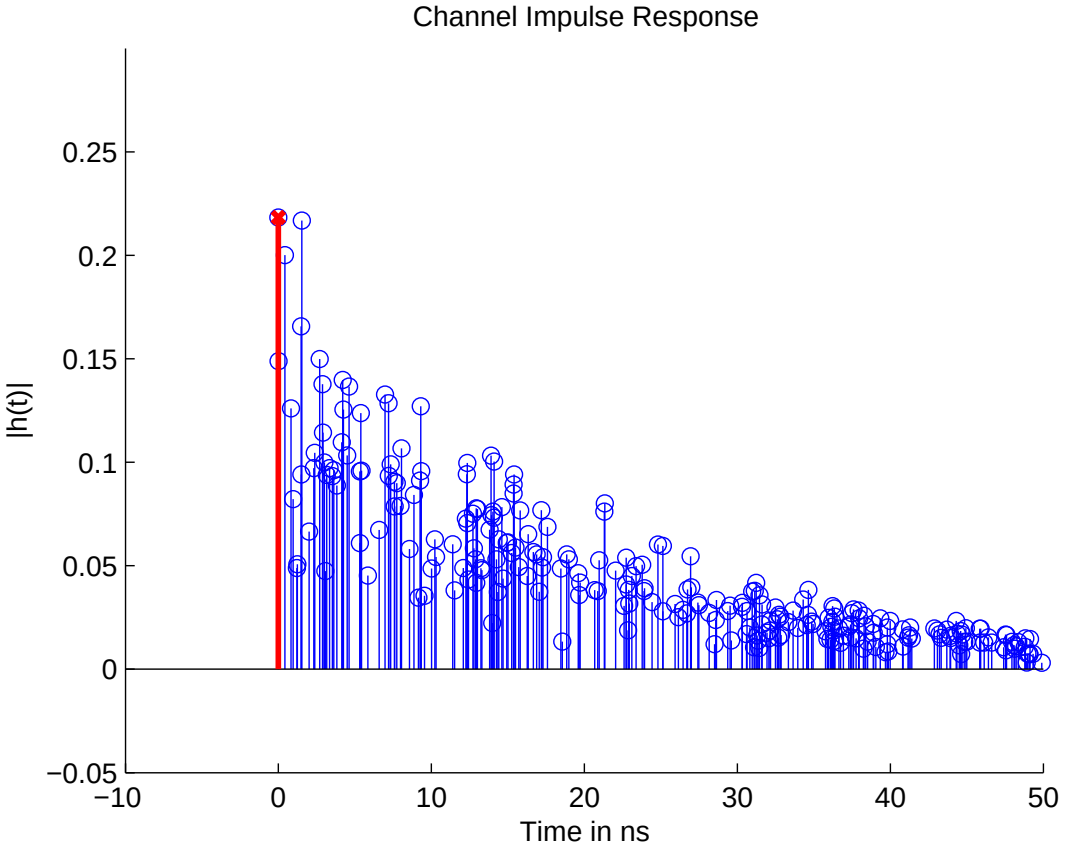

Modelled according to [2]

Ranging (revisited)

Ranging is closely related to determining the time difference between the transmitted pulse and the first path of the CIR – the leading edge, direct path, line-of-sight component, etc.

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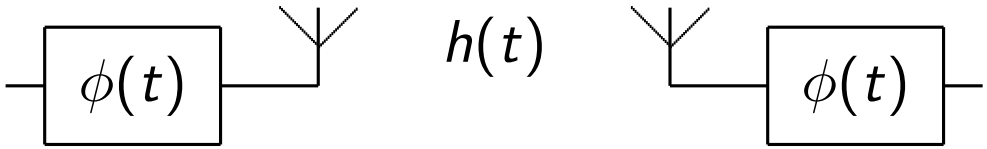
Transmitting (Dirac) δ-pulses would allow infinite accuracy, but requires infinite bandwidth!

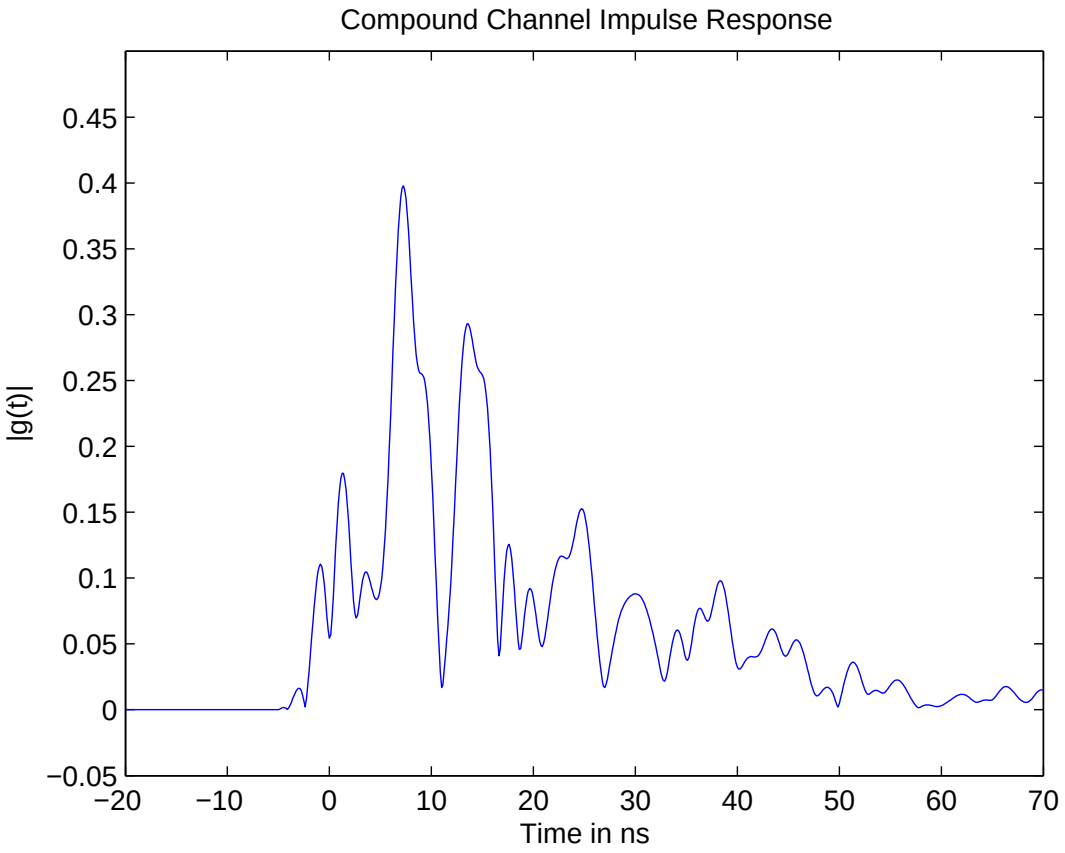
Pulse Shaping – Compound CIR



$$g(t) = \phi(t) * h(t) * \phi(t) = h(t) * \Phi(t) = \sum_{l=0}^{\infty} \alpha_l \Phi(t - \tau_l)$$

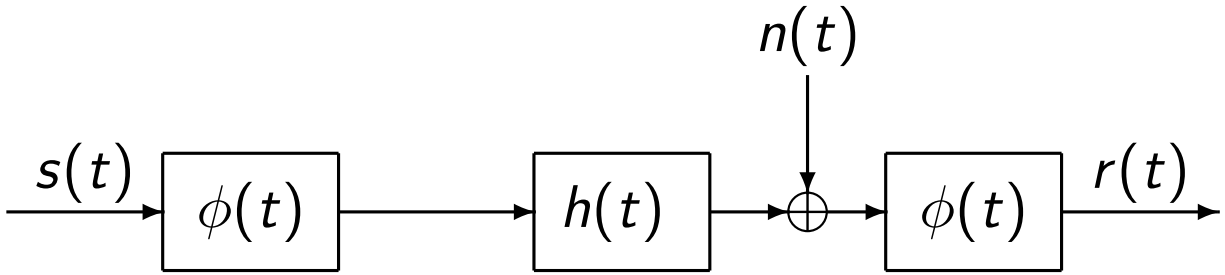
- Pulse shaping distributed over TX (bandlimiting) and RX (noise reduction)
- Information about the CIR is lost because of filtering/bandlimiting/pulse shaping
- $\phi(t)$ is a root-raised cosine (RRC) filtered pulse
- $\Phi(t)$ is a raised cosine (RC) filtered pulse

Compound CIR



Pulse duration $T_p = 2$ ns

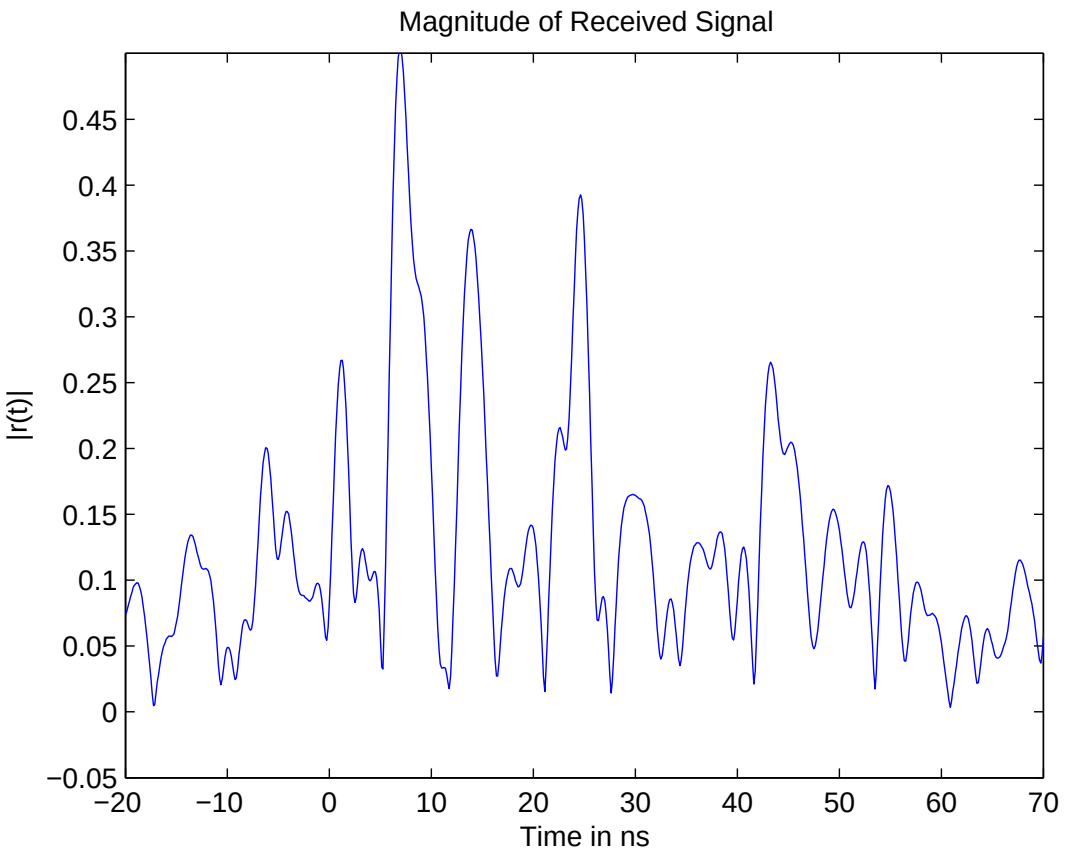
Adding noise



$$r(t) = \phi(t) * h(t) * \phi(t) + n(t) * \phi(t) = g(t) + \tilde{n}(t)$$

- Assumption: Only one single pulse is transmitted ($s(t) = \delta(t)$)
- Channel noise is filtered at receiver (reduced noise power/bandwidth)
- $n(t)$ zero-mean, (complex) Gaussian noise
- $\tilde{n}(t)$ is the filtered version of it

Adding noise (cont'd)



Adding just a little noise: $\frac{E_p}{N_0} = 20$ dB

Adding noise (cont'd)

Where's the leading edge?

- Multipath propagation,
- Bandlimiting/filtering $\rightarrow$ small scale fading, overlaps *and*
- Additive noise

make accurate TOA estimation hard to realize. Leading edge detection algorithms necessary!

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Generalized Maximum Likelihood (GML)

Assuming the received signal is

$$r(t) = \alpha_0 \Phi(t - \tau_{prop}) + \sum_{l=1}^{\infty} \alpha_l \Phi(t - \tau_l) + n(t)$$

- $n(t)$ is white Gaussian noise

GML (cont'd)

According to [1] we can rewrite

$$\hat{\tau}_{prop} = \arg\min_{\tau_{prop}} \left[\min_{\alpha_0, \alpha_l, \tau_l} \left\| r(t) - \alpha_0 \Phi(t - \tau_{prop}) + \sum_{l=1}^{\infty} \alpha_l \Phi(t - \tau_l) \right\|^2 \right]$$

That is, the upper norm is minimum if all (nuisance) parameters are estimated correctly – only noise remains. From the infinite set of parameters, only τ_{prop} is of interest for us.

GML (cont'd)

Realization

- Sample the received signal according to Nyquist (20.5 GHz!)
- Consider only L MPCs preceding and including the peak path
- Limit search region between $-\tau_{limit}$ and τ_{peak}
- Only search for paths stronger than a certain threshold $|\alpha_l| > \zeta$

Parameters $\alpha_0, .., \alpha_L, \tau_{prop}, \tau_1, .., \tau_L$ are estimated iteratively $\rightarrow$ high computational complexity.

GML – Discussion (cont'd)

Although this approach is too complex to pursue, we'll find parts of it in other algos:

- Likelihood-based estimation techniques
- "Search-back" window τ_{limit}
- Stopping threshold ζ

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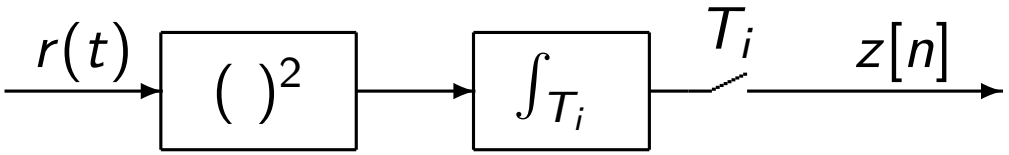
Energy Detector



$$z[n] = \int_{(n-1)T_i}^{nT_i} |r(t)|^2 dt$$

- Noisy template (correlated!) – heavily affected by noise
- Pulse distortions considered
- By far most simplistic approach – widely used in literature
- Well understood analytically

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Maximum Energy Selection (MES)

Assuming the output samples of the receiver are given by $z[n]$, the MES estimate is given as

$$\hat{n}_{TOA} = \arg\max_{n} \{z[n]\}$$

- The strongest path is assumed the leading edge
- Neighboring samples are not taken into consideration

MES – Discussion

Advantages

- Robust for a wide range of SNR
- No channel knowledge required
- Easy to realize

Disadvantages

- Strongest peak $\neq$ leading edge (NLOS)
- By accident, noise may exceed strongest path for very low SNR $\rightarrow$ consider neighboring samples!
- No leading edge detection – big error for high SNR

Weighted Maximum Energy Sum Selection (W-MESS)

Assuming the output samples of the receiver are given by $z[n]$, the W-MESS estimate is given as

$$\hat{n}_{TOA} = \arg\max_{n} \left\{ \sum_{k=0}^{N_e-1} \rho_k z[n+k] \right\}$$

- Incorporates channel knowledge:
- Correlating samples with estimated power delay profile (PDP)
- ρ_k are the mean energies for a particular channel model and T_i
- N_e is the number of noise+signal samples

W-MESS – Discussion

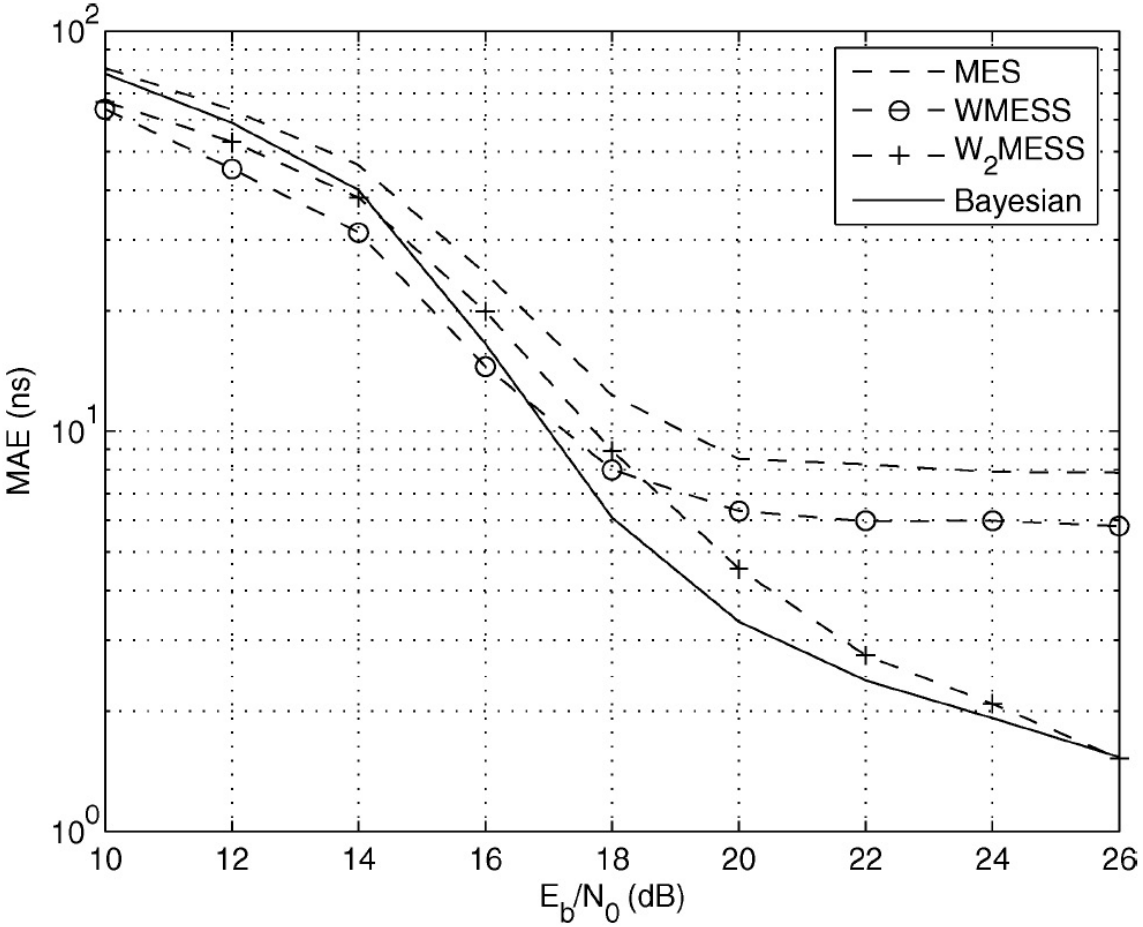
Advantages

- Leading edge detection
- Better results

Disadvantages

- Requires statistical channel knowledge (which model fits? LOS? NLOS?)
- Length of the PDP has to be known approximately
- Harder to realize
- Sub-optimal approach: Use exponential as weight instead of PDP

Comparison of Likelihood-Based Estimators

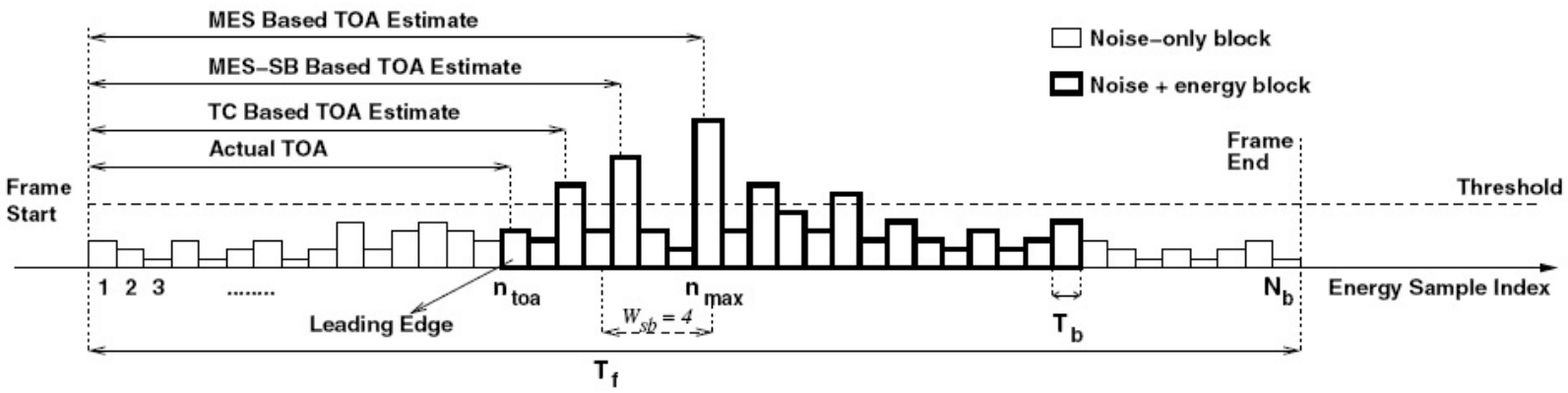


Taken from [3]

Threshold-based Estimation

Requires coarse estimation (e.g. symbol duration)

- Threshold Comparison (TC)
- MES Search-Back (MES-SB)



Taken from [4]

Threshold Comparison (TC)

Assuming the output samples of the receiver are given by $z[n]$, the TC estimate is given as

$$\hat{n}_{TOA} = \min_n \{z[n] > \zeta\}$$

- Compare receiver output samples with a certain threshold ζ
- First sample exceeding ζ is TOA estimate

TC – Discussion

Advantages

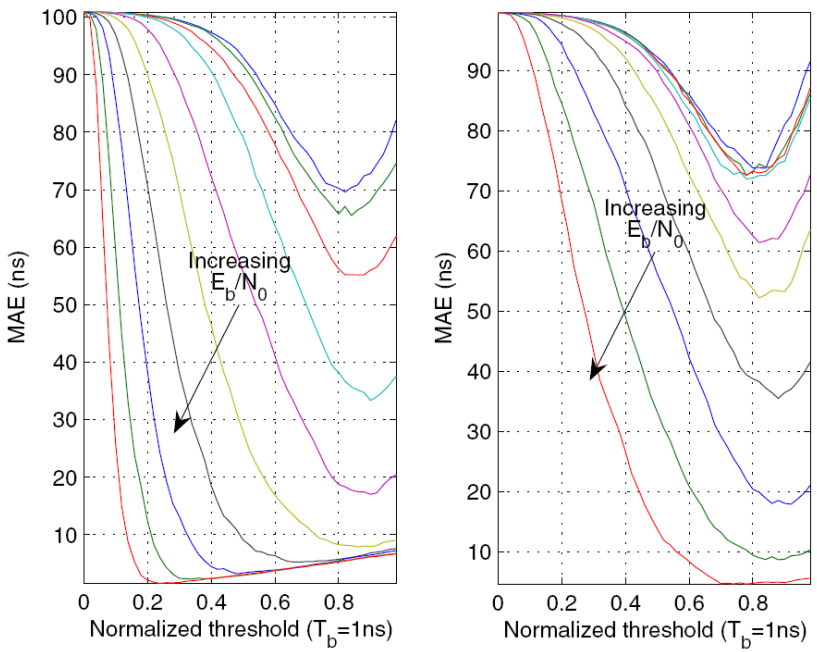
- Leading edge detection
- Easy to realize

Disadvantages

- Noise samples exceeding ζ in low SNR
- Optimum threshold dependent on noise characteristics
- Optimum threshold dependent on channel characteristics

Influence of Threshold Selection

E.g. normalized threshold w.r.t. noise floor and maximum energy block [4]



Optimum (normalized) threshold for CM1 and CM2. Taken from [4]

MES Search-Back (MES-SB)

Assuming the output samples of the receiver are given by $z[n]$, the MES-SB estimate is given as

$$\hat{n}_{TOA} = \min_{n \in \{n_{max} - N_w, n_{max}\}} \{z[n] > \zeta\}$$

- Leading edge is assumed to precede maximum energy block $z[n_{max}]$
- Search N_w preceding samples (search-back window)
- First sample exceeding ζ (within that window) is TOA estimate

MES-SB – Discussion

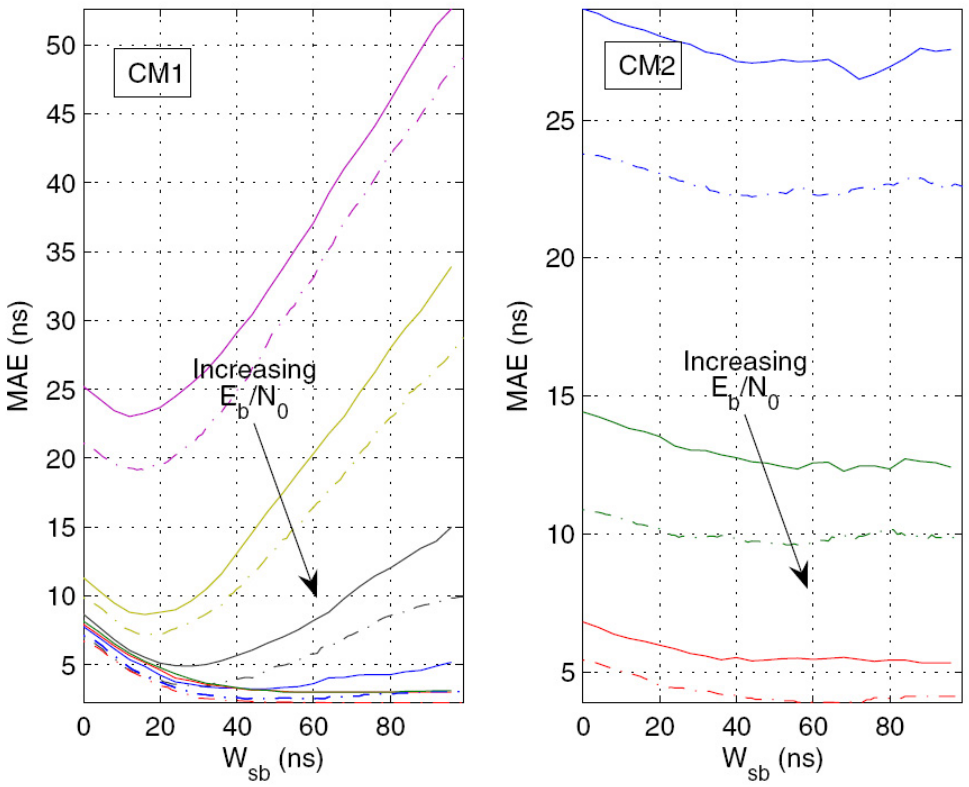
Advantages

- Leading edge detection
- Still easy to realize
- Increased robustness (comparable to MES)

Disadvantages

- Optimum search-back window size dependent on noise and channel characteristics
- Optimum threshold dependent on noise and channel characteristics

Influence of Search-Back Window



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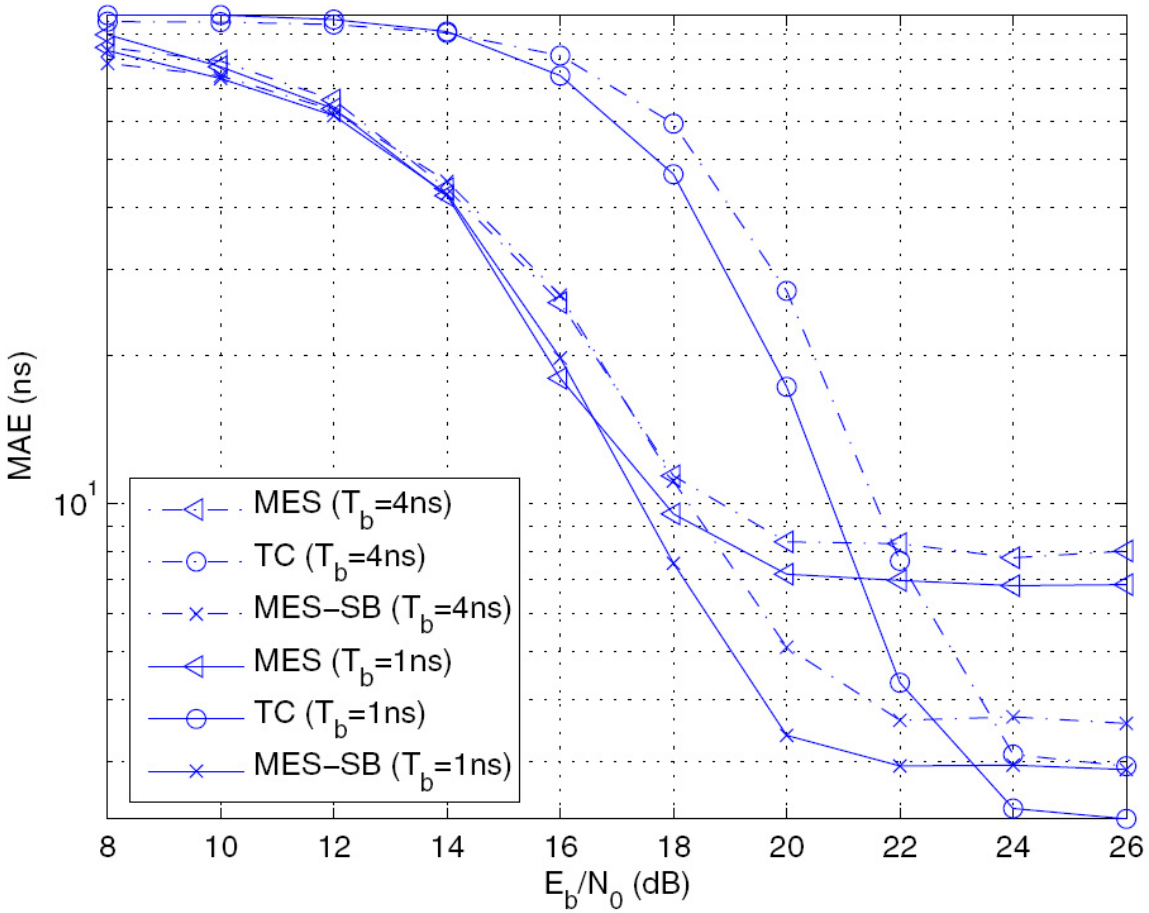

CM1, taken from [4]

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Two-Step Estimation

Estimate TOA in two steps:

- Energy Detection step for coarse estimate, correlation step for refinement
- Multiple integrators in parallel, change uncertainty region after first step
- Determining position of CIR within frame, then position of leading edge within CIR (with least squares)
-

Used by [6, 7, 12]...

Changes in Signal Statistics

Detect leading edge by sudden change in received signal statistics

- Noise+signal samples have a greater variance (more energy)
- Segmented analysis of received signal
- Hypothesis testing

Used by [8]

Multiscale Energy Products

Similar to wavelet analysis:

- Average ED output samples over different filter lengths
- Multiply results
- Suppresses noise, enhances peaks close to the leading edge

Used by [9]

Ranging with multiple symbols

Exploit processing gain (partly)

- Average signal over multiple symbols – noise flattening
- Non-coherent combining loss (noise-cross-noise, noise-cross-signal, noise-squared) – SR advantageous
- IEEE 802.15.4a: Ternary Preamble Sequences with perfect autocorrelation properties
- "Averaging via correlation"

Used by [10, 1, 3, 11]

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Ranging: Capabilities and Problems

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- Multipath Propagation makes matters complicated – energy is preserved, but CIR *spreads* transmitted pulse (MES $\neq$ TOA)
- $\longrightarrow$ Necessity for leading edge detection algorithms

Summary (cont'd)

Reduced Complexity leads to further Problems:

Coherent receivers/Nyquist sampling are contradictory to low-power low-complexity goal

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- Non-coherent design (e.g. ED) makes leading edge detection even more difficult
- Sub-Nyquist sampling/integration reduces ranging accuracy (less temporal resolution)
- Leading edge detection algos have to be designed accordingly

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That's what makes it interesting...

That's it!

Thank you for your attention!

- J.-Y. Lee and R. A. Scholtz, "Ranging in a dense multipath environment using an UWB radio link," *JSAC*, vol. 20, no. 9, pp. 1677–1682, December 2002.
- K. Witrisal and M. Pausini, "Statistical analysis of UWB channel correlation functions," *IEEE Transactions on Vehicular Technology*, March 2008, to appear.
- I. Guvenc, Z. Sahinoglu, and P. V. Orlik, "Toa estimation for IR-UWB systems with different transceiver types," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 4, pp. 1876–1886, April 2006.
- I. Guvenc and Z. Sahinoglu, "Threshold-based TOA estimation for impulse radio UWB systems," in *ICU 2005. IEEE International Conference on Ultra-Wideband.*, 09 2005.

——, "Threshold selection for UWB TOA estimation based in kurtosis analysis," *IEEE Communications Letters*, vol. 9, no. 12, pp. 1025–1027, December 2005.

S. Gezici, Z. Sahinoglu, H. Kobayashi, and H. Poor, "Ultra wideband geolocation," in *Ultrawideband Wireless Communications*. John Wiley & Son, Inc., 2005.

S. Wu, Q. Zhang, and N. Zhang, "A two-step TOA estimation method for IR-UWB ranging systems," in *CNSR*, 2007, pp. 1–7.

C. Mazzucco, U. Spagnolini, and G. Mulas, "A ranging rechnique for UWB indoor channel based on power delay profile analysis," in *VTC*, Los Angeles, September 2004, pp. 2595–2599.

- I. Guvenc and Z. Sahinoglu, "Multiscale energy products for TOA estimation in IR-UWB systems," in *Globecom*, St. Louis, 2005, pp. 209–213.
- "IEEE 802.15.4a (amendment 1: Add alternate PHYs)," August 2007, part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs).
- Z. Sahinoglu and S. Gezici, "Ranging in the IEEE 802.15.4a standard," in *Wireless and Microwave Technology Conference*, December 2006, pp. 1–5.
- L. Stoica and I. Oppermann, "Modelling and simulation of a non-coherent IR UWB transceiver architecture with TOA estimation," in *PIMRC*, 2006