Considerations on Ranging in NGV

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Abstract

Considerations on Ranging in NGV given PAR and use case baseline:

- **Analysis method: Lower Bounds**
- **Observation model: AWGN and line of sight (LOS) free space path loss**
- **5.9 GHz band:**
  - Waveform analysis
  - Time-of-arrival (TOA) vs. round-trip-delay (RTD) ranging
  - Bandwidth and different numerologies
- **60 GHz band:**
  - Comparison between RTD ranging and Radar
  - Dynamic Train-to-Train Propagation Measurements and ranging results

Introduction

PAR [1]:

“this amendment defines procedures for at least one form of positioning in conjunction with V2X communications”

Use Case (UC) baseline document [2]:

- UC5 Vehicular Positioning & Location
- UC8 Train-to-Train
- UC9 Vehicle-to-Train

Lower Bounds Evaluation Methodolgy: Benefits

[3], [4], [5]:

- **Knowledge and understanding about an estimation problem**
  - Effect of nonlinearities
  - Identification of limiting factors
- **Estimator efficiency**
  - Evaluation of suboptimal estimators
- **System parameter optimization**
  - Allocation of signal power
  - Waveform design
  - Placement of road side units

Lower Bounds Evaluation Methodolgy: Non-random Parameter Estimation

- **Classical definition**

estimator parameter vector observation vector

$$\underbrace{\mathrm{E}_{\mathbf{y}|\boldsymbol{\theta}}\left[(\hat{\boldsymbol{\theta}}(\mathbf{y})-\boldsymbol{\theta})(\hat{\boldsymbol{\theta}}(\mathbf{y})-\boldsymbol{\theta})^T\right]}_{\text{MSE Matrix}} \geq \mathbf{B}_C$$

parameter vector given

- **Cramér-Rao Lower Bound (CRLB) for <u>unbiased estimators</u>**

$$\mathrm{Cov}(\hat{\boldsymbol{\theta}}) \geq \mathbf{J}_F^{-1}(\boldsymbol{\theta}) \qquad [\mathbf{J}_F]_{ij} = -\,\mathrm{E}_{\mathbf{y}|\boldsymbol{\theta}}\left[\frac{\partial^2}{\partial\theta_i\partial\theta_j}\underbrace{\ln p(\mathbf{y}|\boldsymbol{\theta})}_{\text{log-likelihood of observation vector}}\right]$$

Fisher Information Matrix

  - Biased CRLB usually dependent on unknown estimator bias
  - Over optimistic for many scenarios

Lower Bounds Evaluation Methodolgy: Random Parameter Estimation

- **Bayesian definition** $\mathbf{MSE} = \mathrm{E}_{\mathbf{y},\boldsymbol{\theta}}\left[(\hat{\boldsymbol{\theta}}(\mathbf{y}) - \boldsymbol{\theta})(\hat{\boldsymbol{\theta}}(\mathbf{y}) - \boldsymbol{\theta})^T\right]$

  random parameter vector

- **Ziv-Zakai Lower Bound (ZZLB) [5]**

$$\mathbf{MSE} \geq \frac{1}{2}\int_0^{+\infty}\left\{\int_{-\infty}^{+\infty}[p(\theta)+p(\theta+h)]P_{min}(\theta,\theta+h)d\theta\right\}hdh$$

- **Properties of the Bayesian bounds (ZZLB, …)**
  - Valid for biased estimators
  - Possible to incorporate prior knowledge of the estimated parameters
  - Applicable also to problems that are singular without prior knowledge

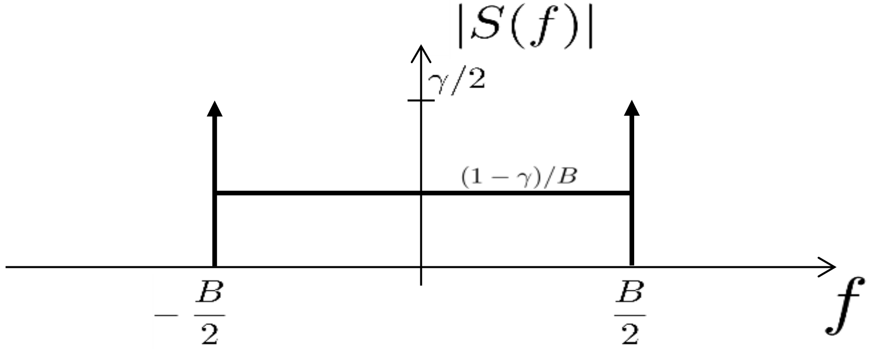
Time-of-Arrival (TOA) Ranging Measurement and Signal Model [6]

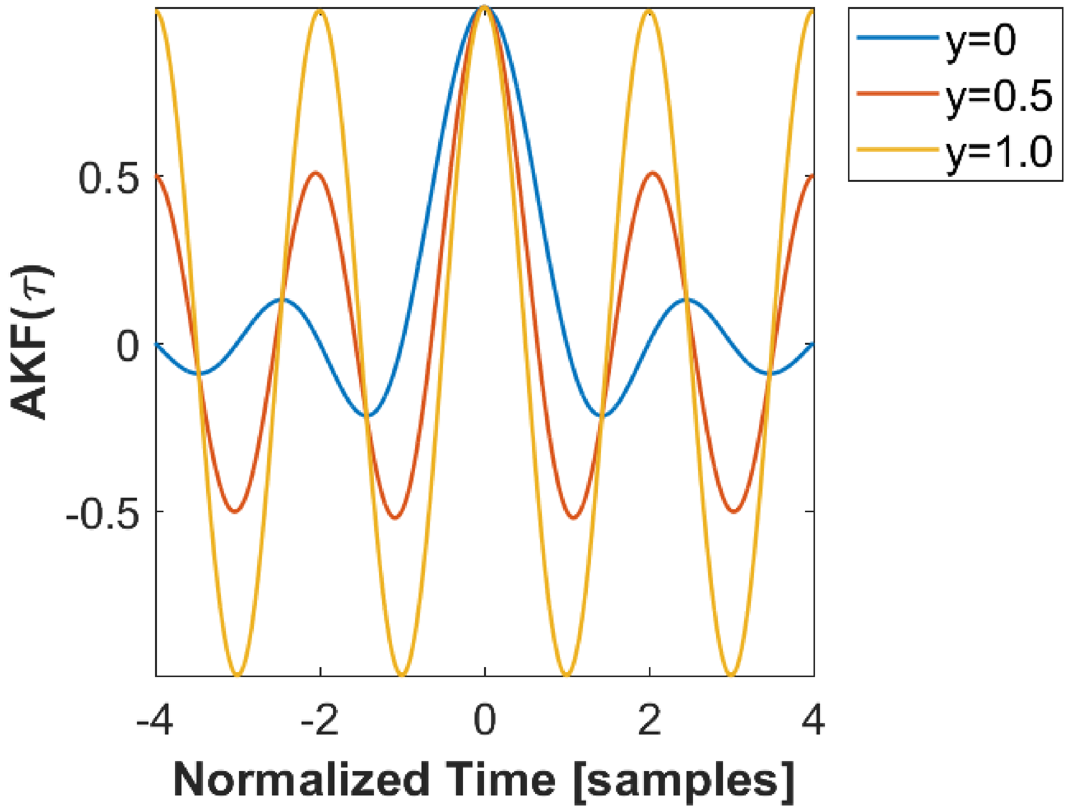
- **Observation model: AWGN**

$$y(t) = s(t-\tau) + n$$

- **Signal model (Dirac-Rectangular)**

$$|S(f)|^2 = \begin{cases} \frac{1-\gamma}{B} + \frac{\gamma}{2}\left[\delta\left(f+\frac{B}{2}\right) + \delta\left(f-\frac{B}{2}\right)\right], & |f| \leq \frac{B}{2} \\ 0, & \text{otherwise} \end{cases}$$



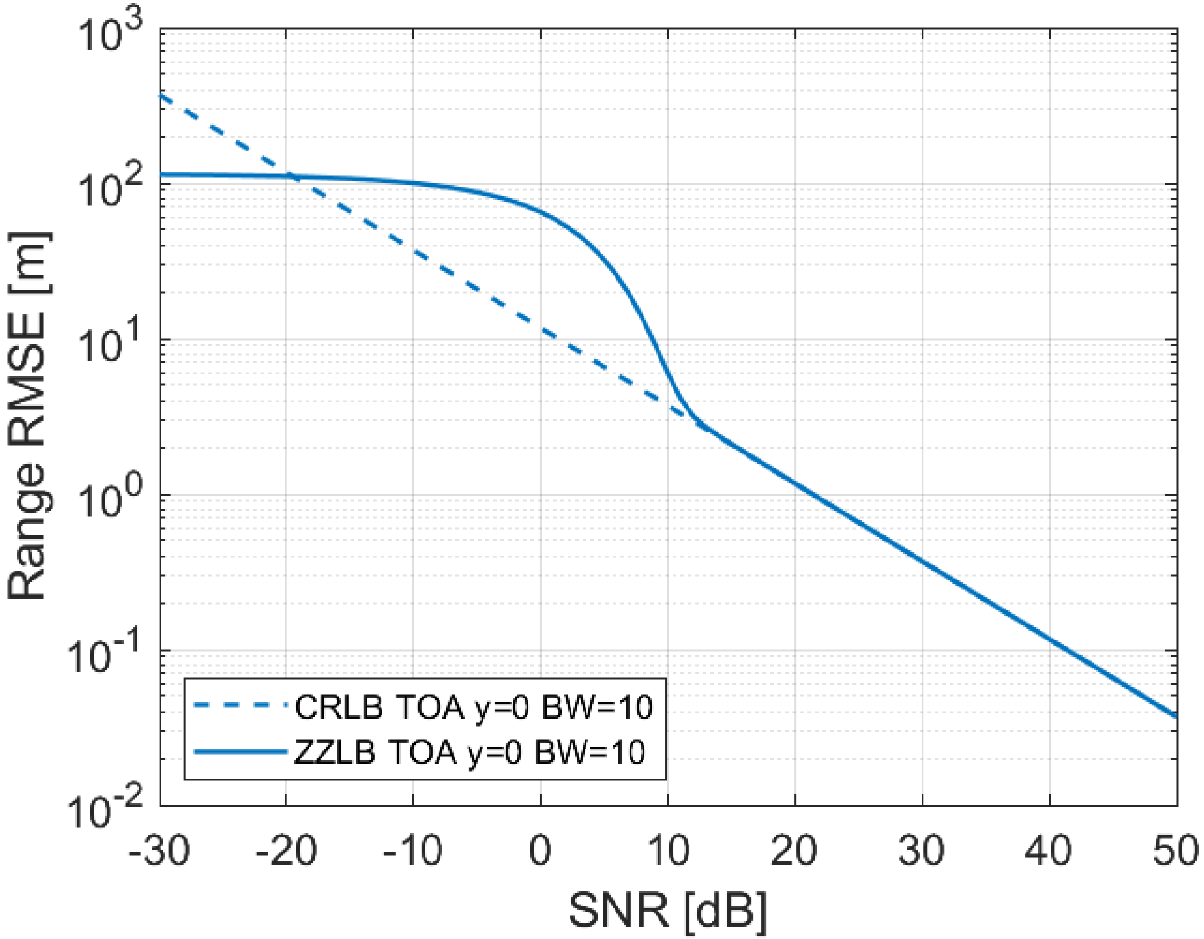


Time-of-Arrival (TOA) Ranging Lower Bounds [6]

Cramér-Rao Lower Bound (CRLB) vs . Ziv-Zakai Lower Bound (ZZLB):

- Same for high SNR
- Rapid increase of ZZLB for medium SNR: Signal ambiguities in observation interval
- Convergence of ZZB to mean of observation interval for low SNR

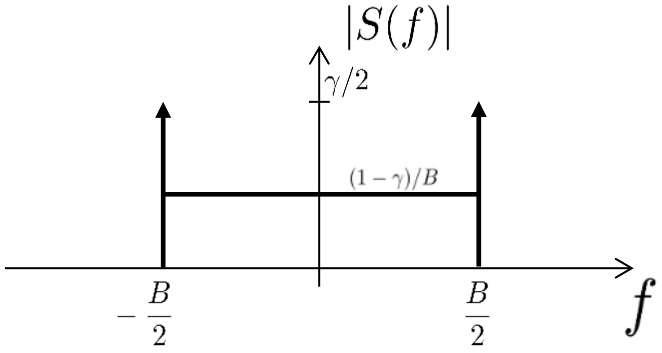
Note, rectangular waveform (γ=0)

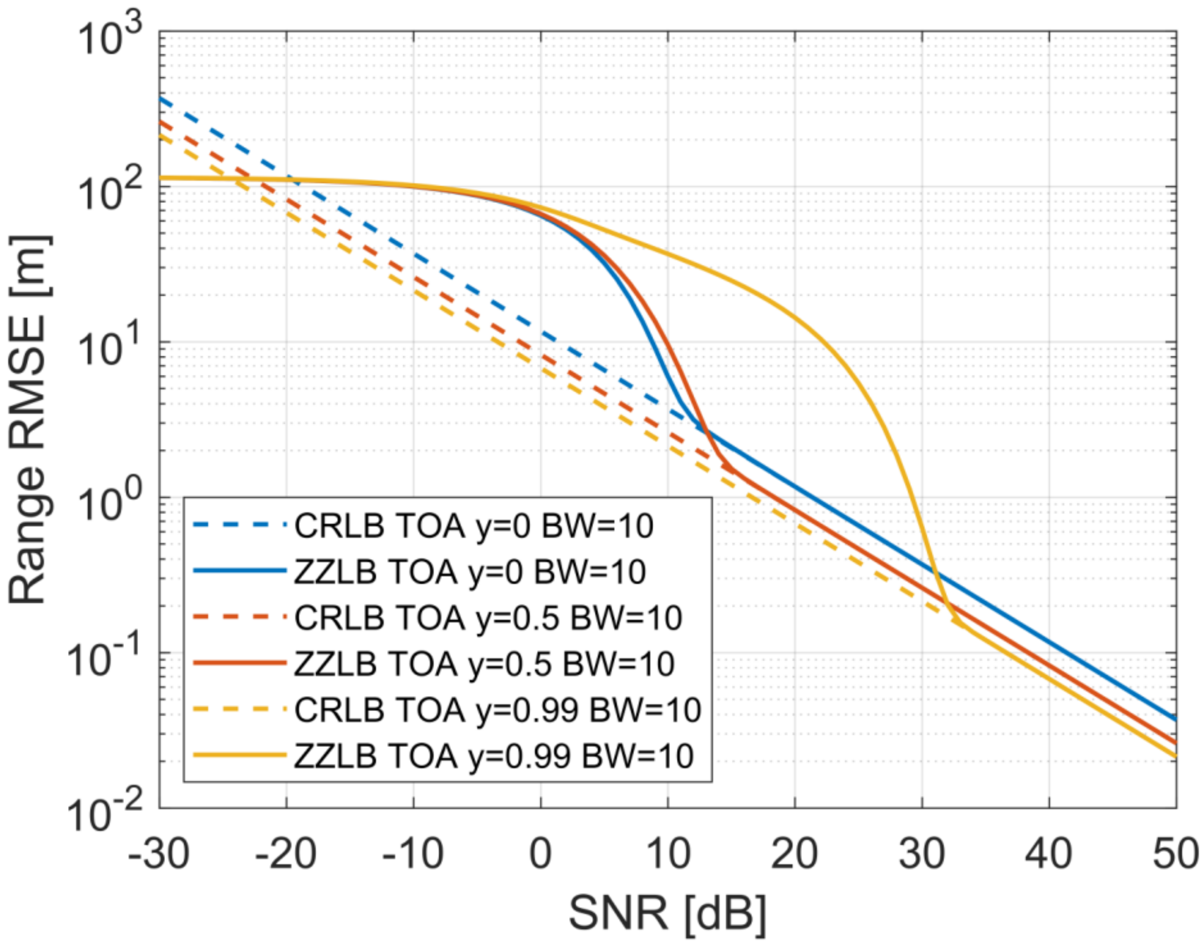


Time-of-Arrival (TOA) Ranging Lower Bounds [6]

Waveform parameter γ:

- γ=0, rectangular highest CRLB, ZZLB converges at lowest SNR
- γ=0.5, 3 dB gain at high SNR, but 2 dB earlier divergence
- γ=0.99, only 0.2 dB additional gain at high SNR, but divergence 20 dB before γ=0





Time-of-Arrival (TOA) Ranging Pathloss Model

Line-of-sight (LOS) free space

$$\mathrm{SNR}(d) = \left(\frac{\lambda}{4\pi d}\right)^2 \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}}}{N_{\mathrm{F}} k_{\mathrm{B}} T_{\mathrm{N}} B_{\mathrm{W}}}$$

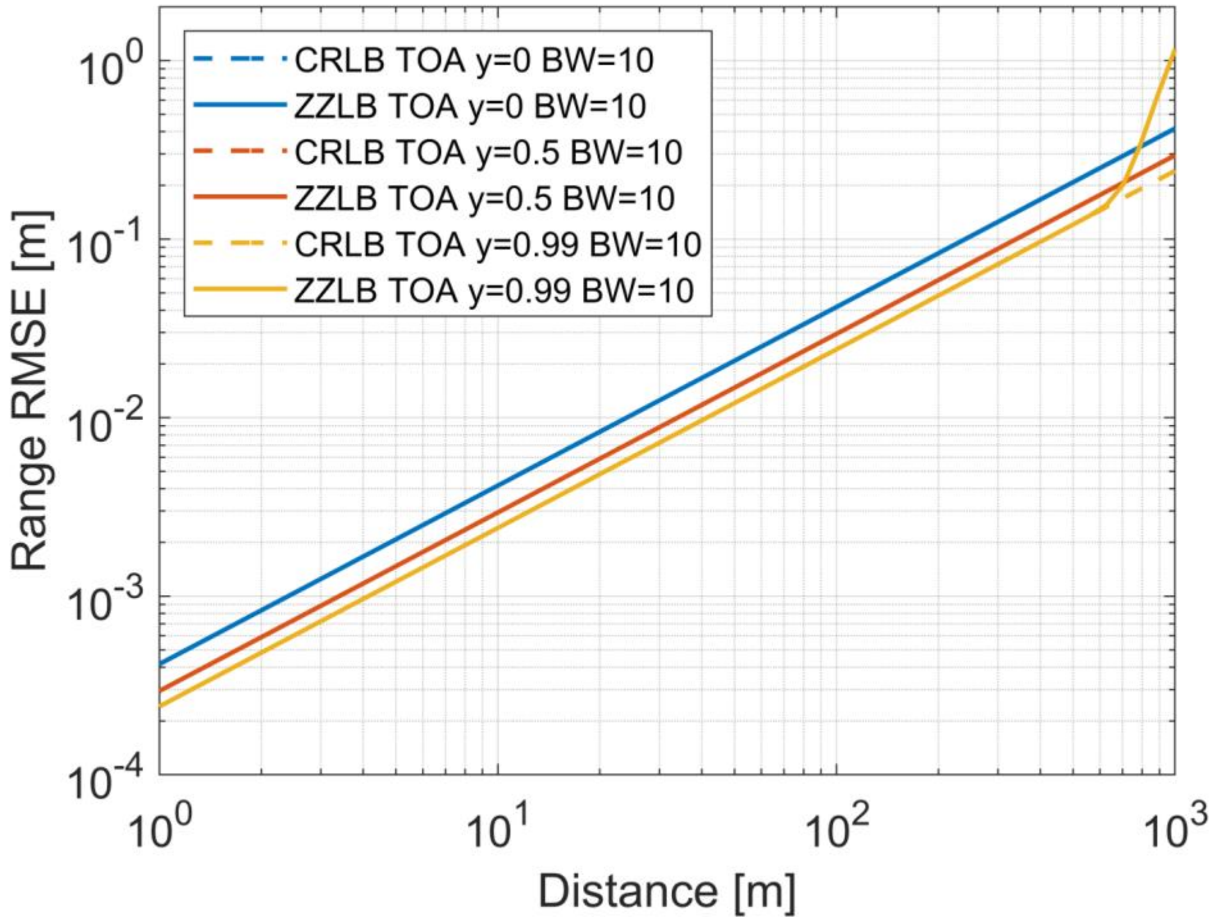
$f_{\mathrm{c}} = 5.9$ GHz, $B_{\mathrm{W}} = 10$ MHz,

$P_{\mathrm{TX}} G_{\mathrm{TX}} = 33$ dBm,

$G_{\mathrm{RX}} = 5$dBi, $N_{\mathrm{F}} = 5$dB,

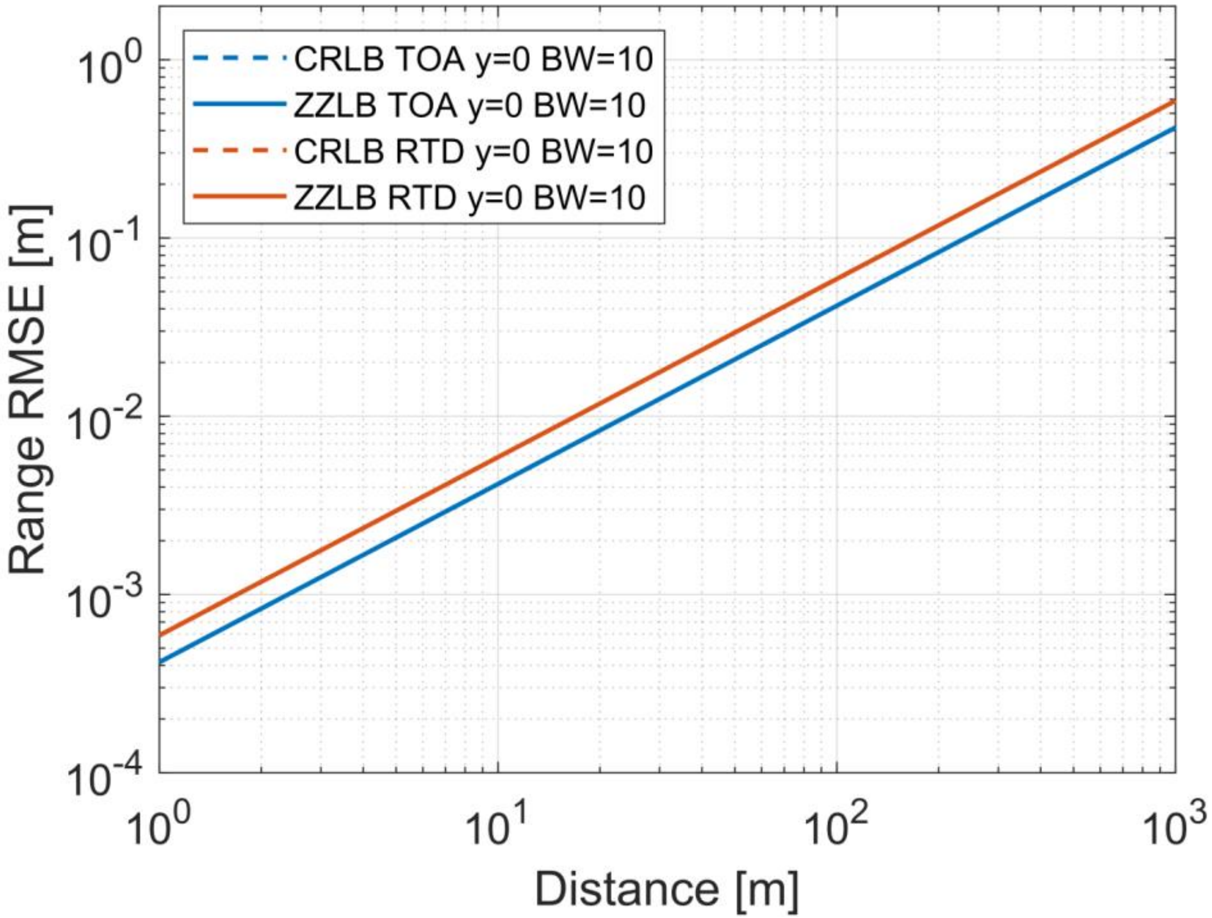
$T_{\mathrm{N}} = 300$K,

k_{B} Boltzmann constant



Time-of-Arrival (TOA) vs. Round-Trip-Delay (RTD) Ranging

- TOA: Synchronized transmitter and receiver
- RTD: No synchronization required, stable oscillators and clocks for duration of message exchange
- RTD model: Two independent TOA measurements

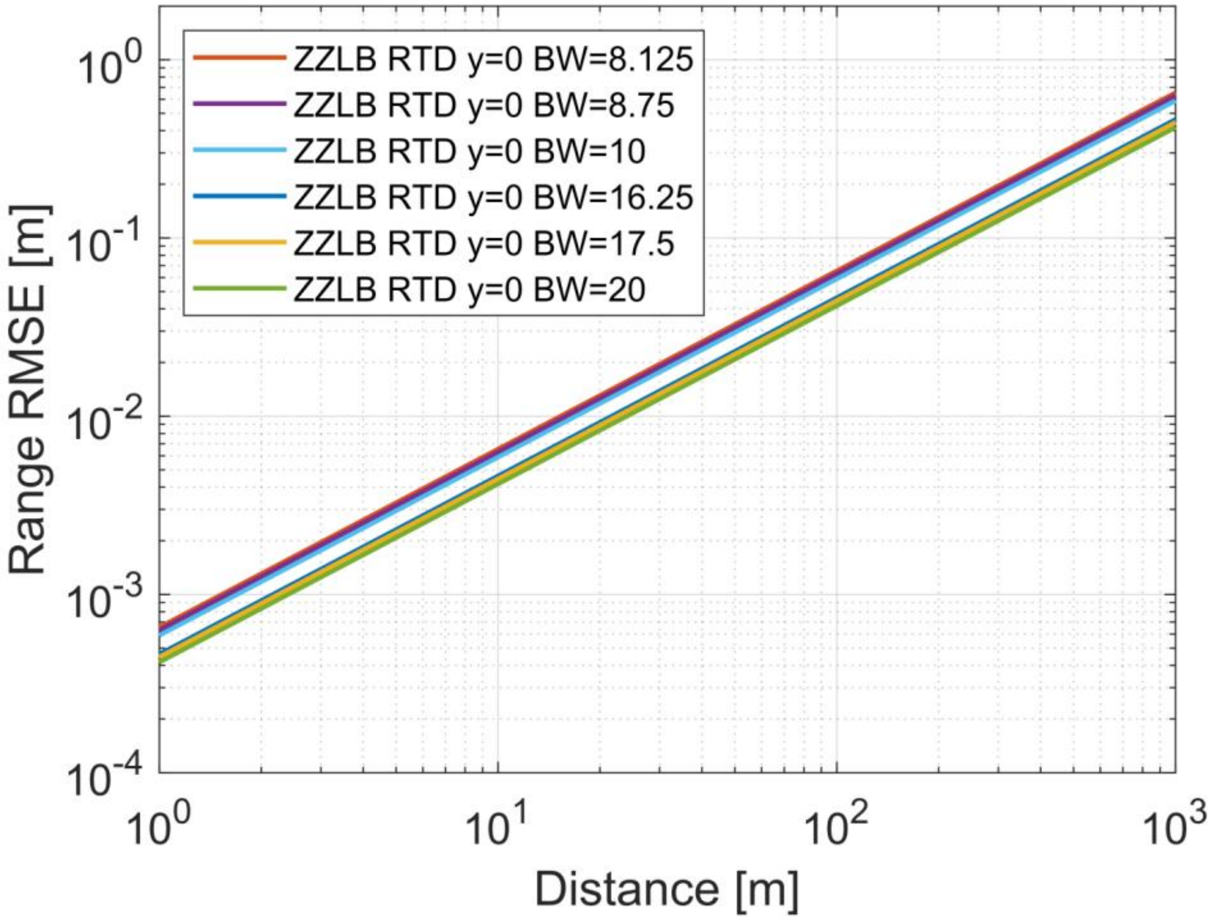


Note, rectangular waveform (γ=0) for remaining slides

Round-Trip-Delay (RTD) Ranging Bandwidth

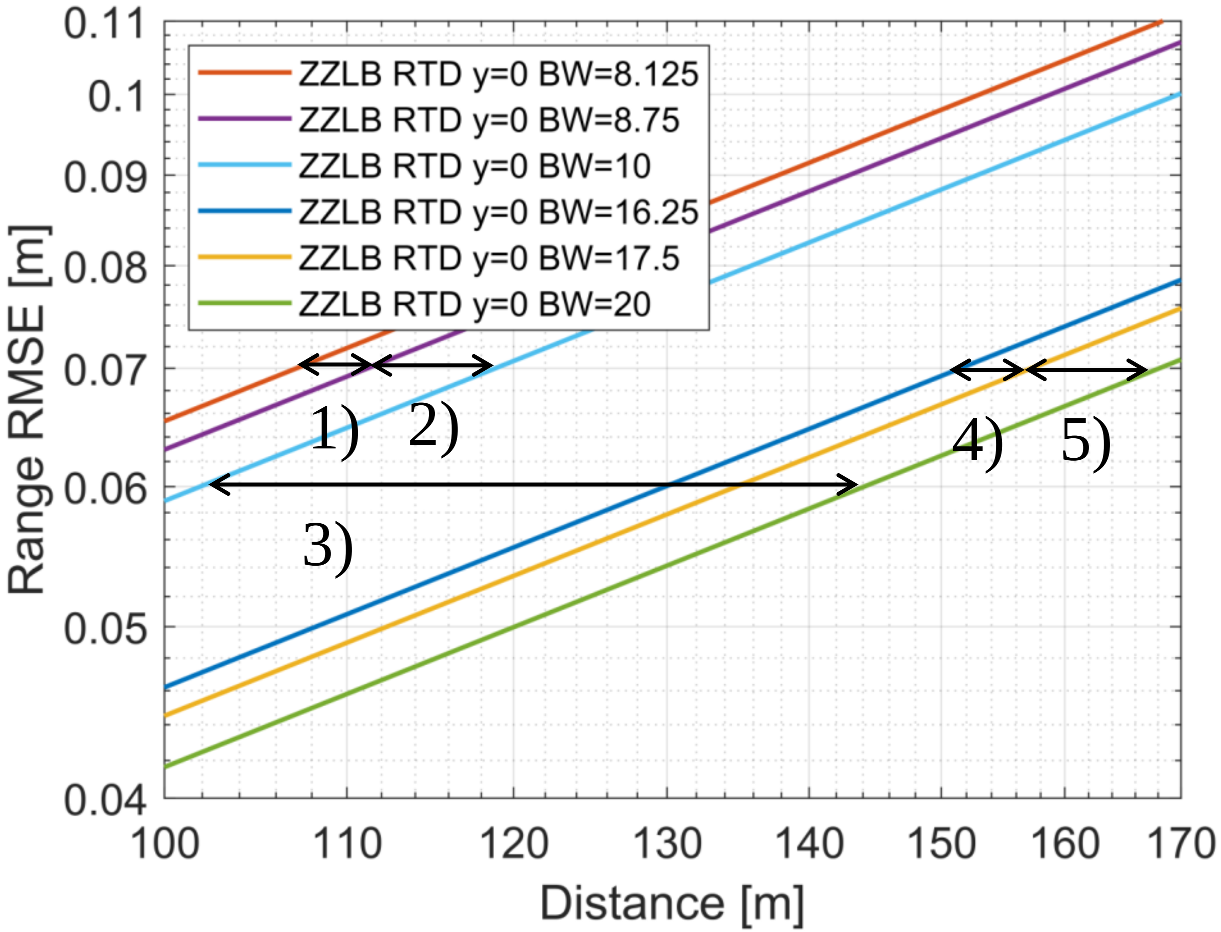
- 8.125 MHz = 52 subcarriers
- 8.75 MHz = 56 subcarriers
- 10 MHz = 64 subcarriers

- 16.25 MHz = 52 subcarriers
- 17.5 MHz = 56 subcarriers
- 20 MHz = 64 subcarriers



Round-Trip-Delay (RTD) Ranging Bandwidth

1) 4% accuracy gain for
   52 ➔ 56 subcarriers 10 MHz
2) 7% accuracy gain for
   56➔64 subcarriers 10 MHz
3) 30% accuracy gain
   10 MHz ➔ 20 MHz
4) 4% accuracy gain for
   52 ➔ 56 subcarriers 20 MHz
5) 7% accuracy gain
   56➔64 subcarriers 20 MHz



Millimeter Wave Round-Trip-Delay (RTD) Ranging and Radar

- Communication, RTD ranging

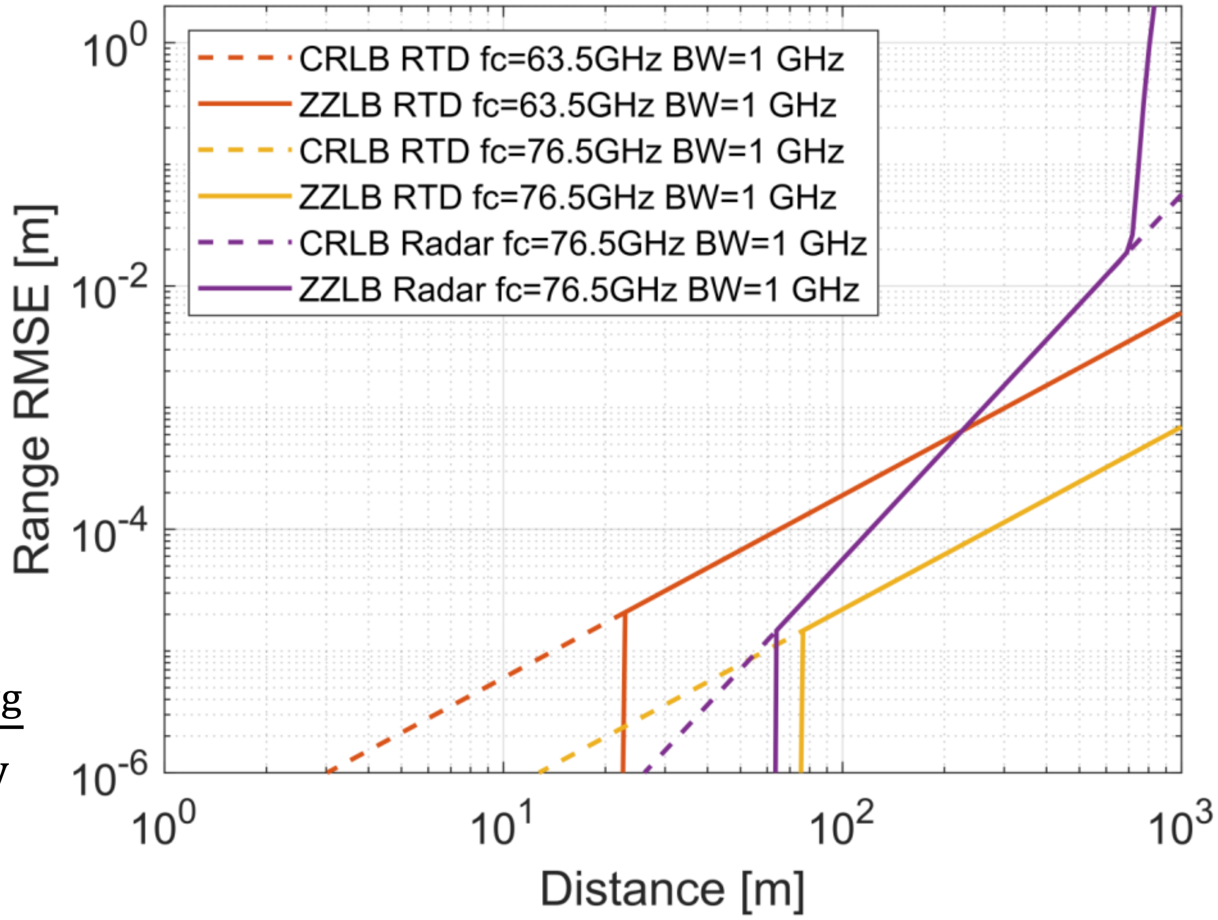
$$\mathrm{SNR}(d) = \left(\frac{\lambda}{4\pi d}\right)^2 \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} N_{\mathrm{Avg}}}{L_{d_0}(d/d_0) N_{\mathrm{F}} k_{\mathrm{B}} T_{\mathrm{N}} B_{\mathrm{W}}}$$

$f_{\mathrm{c}} = 63.5, 76.5$ GHz, $P_{\mathrm{TX}} G_{\mathrm{TX}} = 40$ dBm,
$L_{d_0} = 17.5, 0.2$ dB, $\mathrm{B}_{\mathrm{W}} = 1$ GHz, N_{Avg}=1000,
$d_0 = 2$ km, $G_{\mathrm{RX}} = 23$dBi, $N_{\mathrm{F}} = 5$dB, $T_{\mathrm{N}} = 300$K,

- Radar [7]

$$\mathrm{SNR}(d) = \left(\frac{\lambda}{L_{d_0} d^3/d_0}\right)^2 \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} \sigma_{\mathrm{c}} G_{\mathrm{RX}} N_{\mathrm{Avg}}}{(4\pi)^3 N_{\mathrm{F}} k_{\mathrm{B}} T_{\mathrm{N}} B_{\mathrm{W}}}$$

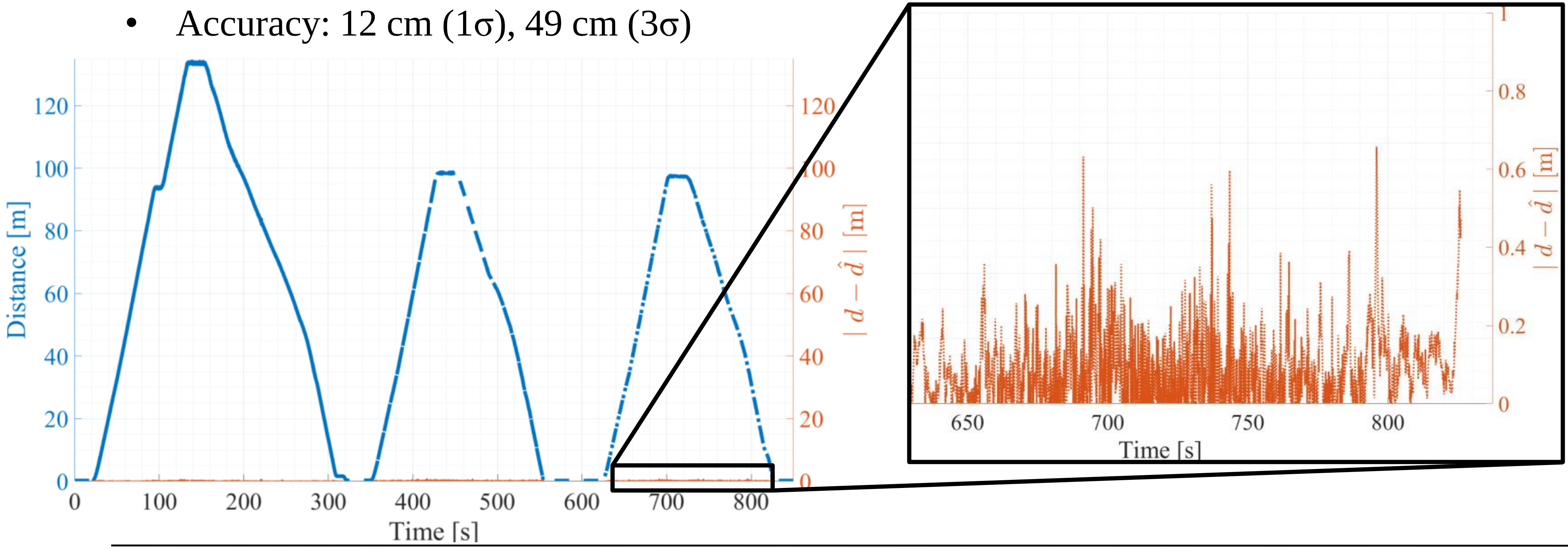
$f_{\mathrm{c}} = 76.5$ GHz, $L_{d_0} = 0.2$ dB, $\sigma_{\mathrm{c}} = 100\ \mathrm{m}^2$,
$P_{\mathrm{TX}} G_{\mathrm{TX}} =$ 50 dBm, k_{B} Boltzmann constant



Dynamic Train-to-Train Propagation Measurements in the Millimeter Wave Band [8]

Dynamic Train-to-Train Propagation Measurements in the Millimeter Wave Band [8]

- $f_c = 60$ GHz, $B_W = 120$ MHz
- Snapshot based distance estimator
- Accuracy: 12 cm (1σ), 49 cm (3σ)



Dynamic Train-to-Train Propagation Measurements in the Millimeter Wave Band [8]

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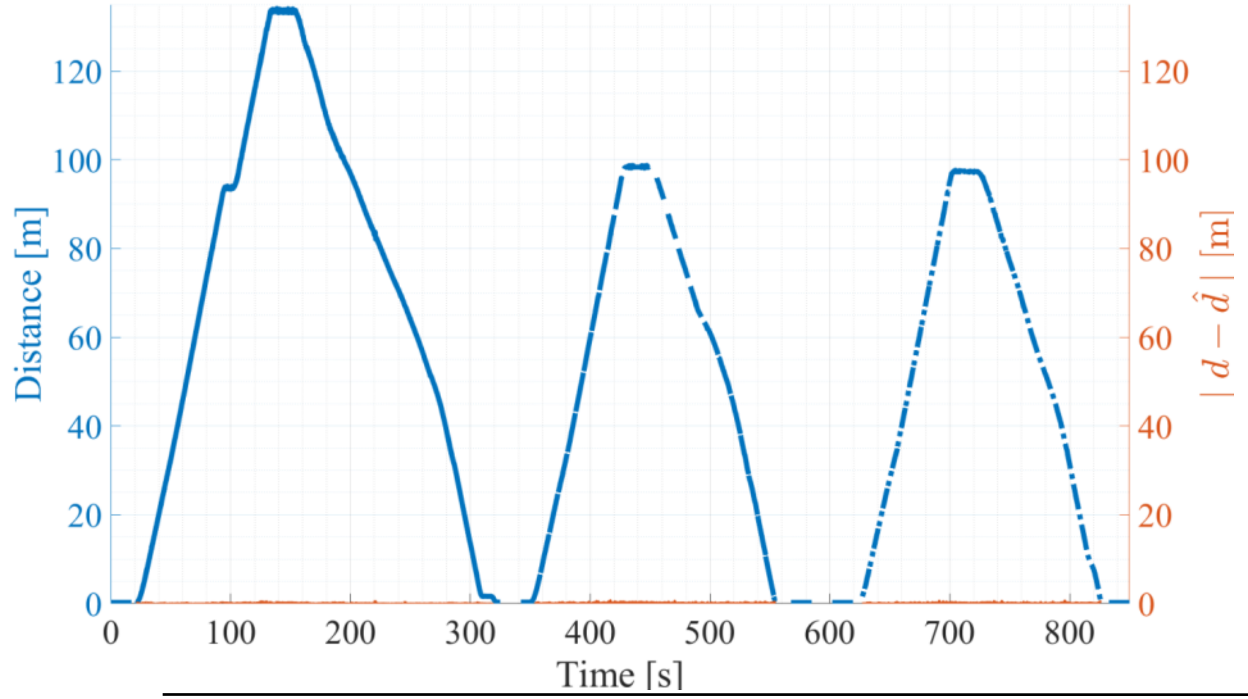
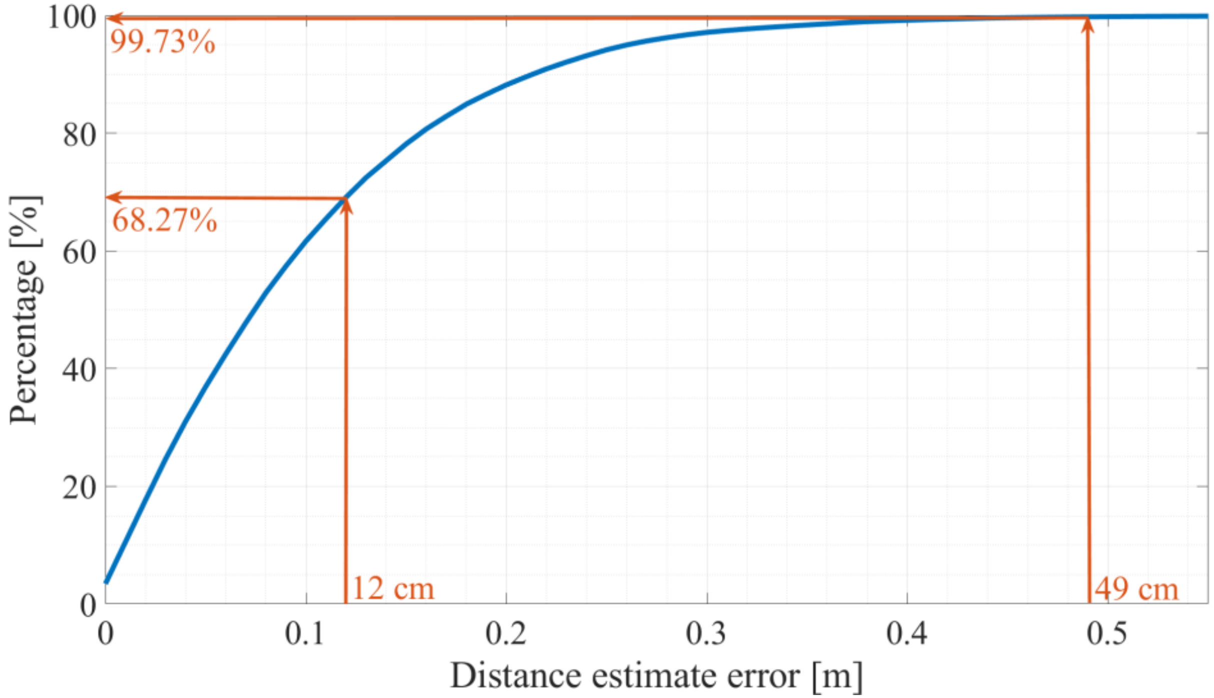




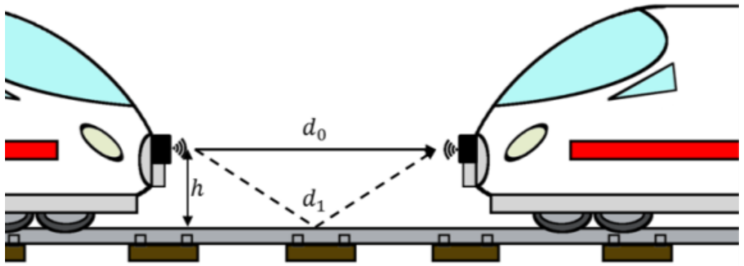
Conclusions

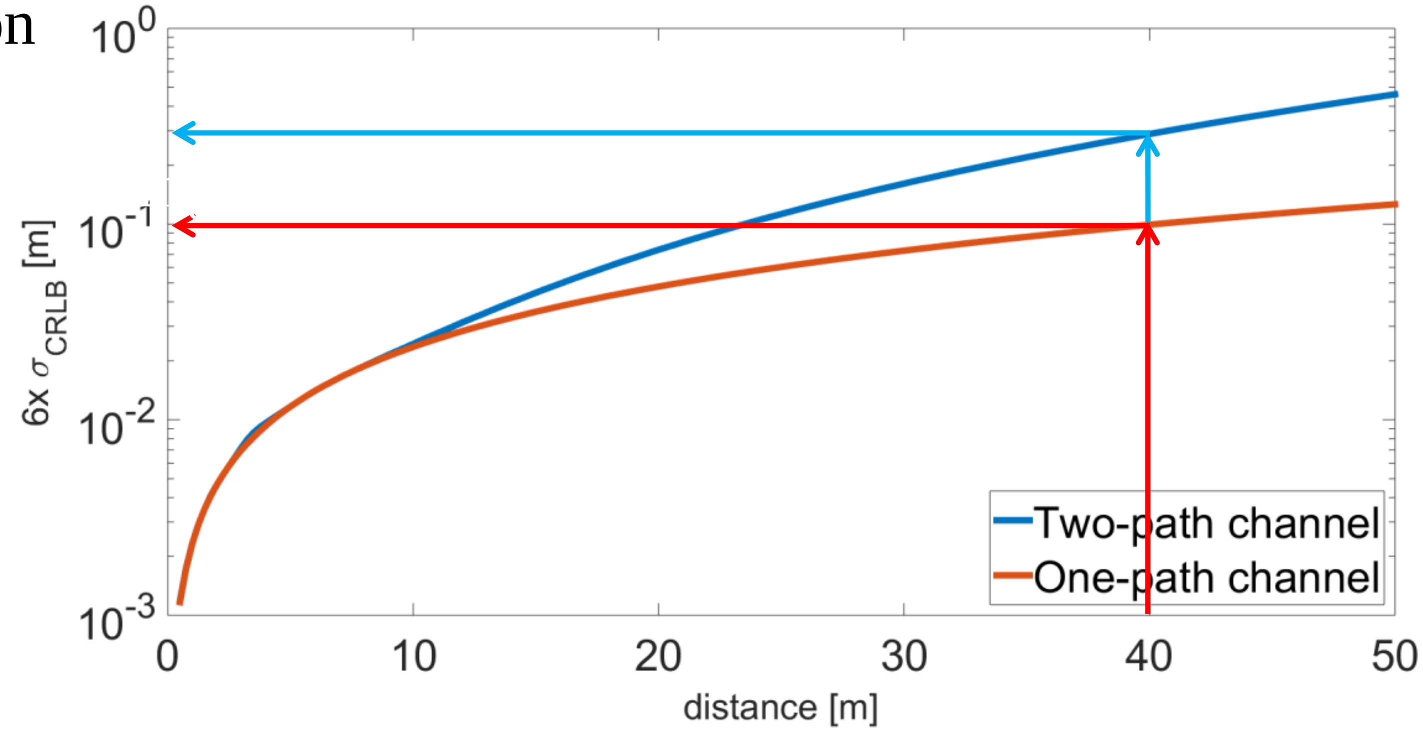
- Bounds
  - Cramér-Rao Lower Bound (CRLB) vs . Ziv-Zakai Lower Bound (ZZLB):
    - CRLB simple, analytic solution vs. ZZLB more complex, numerical solution
    - CRLB and ZZLB same for high SNR
    - CRLB optimistic for low to medium SNR vs. ZZLB tighter at medium to low SNR (accounts for ambiguities)
  - Observation model: Simple model ➔ analytic solution for bounds, but overly optimistic
  - Waveform: Put energy towards band edge, e.g. 50% ➔ 3 dB gain
  - Free Space LoS Pathloss Model @ 5.9 GHz ➔ submeter accuracy
  - RTD 3dB performance loss compared to TOA, no synchronization required
  - Bandwidth comparison: marginal gain for different numerologies, significant gain for 20 MHz vs. 10 MHz
  - Millimeter Wave 63.5 GHz RTD ranging outperforms Radar 76.5 GHz @ distances > 230 m
- Millimeter Wave moving train measurements: 120 MHz BW ➔ 12 cm ranging error @ 1 sigma

Outlook

More realistic observation models

- Multipath, e.g. ground reflection





- Clock and oscillator errors

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[8] Soliman, Mohammad and Unterhuber, Paul and Sand, Stephan and Staudinger, Emanuel and Shamshoom, Jeries and Schindler, Christian and Dekorsy, Armin (2019) *Dynamic Train-to-Train Propagation Measurements in the Millimeter Wave Band - Campaign and First Results*. EuCAP 2019, 31 March - 5 April 2019, Krakow, Poland.

Straw Poll #1

Do you agree to add that 802.11bd in the 5.9 GHz band supports round-trip-delay (RTD) ranging for 10 MHz and 20 MHz bandwidth PPDUs?

Yes/No/Abstain: 17/0/2

Straw Poll #2

Do you agree to add that 802.11bd in the 60 GHz band supports round-trip-time (RTT) ranging for TBD Hz bandwidth PPDUs?

Yes/No/Abstain: