Multipath and Interference Resilient ToA Estimation

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Challenges and Opportunities

Time-of-arrival (ToA) estimation is vital for over-the-air (OTA) **time synchronization**, **wireless time transfer** and **positioning**

Future systems face two challenges:

- **Interference**: dense D-MIMO networks will have to contend with strong mutual interference and be resilient to jamming
- **Multipath propagation**: multipath-induced bias severely impacts positioning accuracy, especially indoors and in dense urban environments

Adaptive Spatial Filtering as a Solution

Multi-antenna receivers can tackle both challenges simultaneously

We propose an algorithm based on spatial filtering with desirable properties:

- **Statistically principled**: based on generalized likelihood ratio test
- **Amenable to real-time execution** with gradient-based optimization
- **Capable of ToA super-resolution**
- **No prior knowledge about the channel required**

We devise a GLRT-based score, $\mathcal{L}(\ell, \tau')$, for detecting a **rank-1 signal affected by low-rank structured interference**, considering an **unknown frequency-selective channel**, **unknown noise variance** and an **M-antenna receiver**:

$$\mathcal{L}(\ell, \tau') = \frac{\left\|\tilde{\mathbf{P}}(\tau')\,\tilde{\mathbf{Y}}_\ell\,\tilde{\mathbf{s}}_\mathrm{S}^*(\tau')\right\|^2}{\left\|\tilde{\mathbf{P}}(\tau')\tilde{\mathbf{Y}}_\ell\mathbf{T}(\tau')\right\|_\mathrm{F}^2},$$

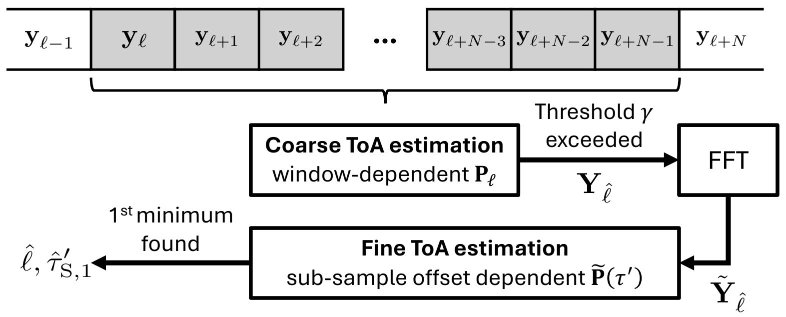
where

- $\tilde{\mathbf{Y}}_\ell$: DFT of received signal window starting at sample ℓ
- $\tilde{\mathbf{P}}(\tau')$: Orthogonal $(M-I)$-rank projector (spatial filter)
- $\tilde{\mathbf{s}}_\mathrm{S}(\tau')$: DFT of a known synchronization signal, shifted by τ'
- $\mathbf{T}(\tau')$: Right projector onto $\mathrm{null}(\tilde{\mathbf{s}}_\mathrm{S}(\tau'))$

We then formulate ToA estimation as

$$\left(\hat{\ell},\, \hat{\tau}'_{\mathrm{S},1}\right) = \underset{\ell\in\mathbb{N}_0,\, \tau'\in[-T_s/2, T_s/2]}{\overset{\text{lex}}{\arg\min}} \;(\ell,\, \tau') \quad \text{s.t.} \quad \mathcal{L}(\ell, \tau') \geq \gamma,\, \frac{\partial\mathcal{L}(\ell,\tau')}{\partial \tau'} = 0$$

and partition the problem in two stages to make it tractable:



Stage 1: Coarse ToA Estimation (Time Domain)

Determines the **first sample index** ℓ for which the (unshifted) known synchronization signal $\mathbf{s}_\mathrm{S}$ is likely to be present

$$\hat{\ell} = \underset{\ell\geq 0}{\arg\min}\ \ell \quad \text{s.t.} \quad \frac{\|\mathbf{P}_\ell\,\mathbf{Y}_\ell\,\mathbf{s}_\mathrm{S}^*\|^2}{\|\mathbf{P}_\ell\mathbf{Y}_\ell\mathbf{T}\|_\mathrm{F}^2} > \gamma'$$

- $\mathbf{P}_\ell$ fitted in the time-domain for every distinct window $\mathbf{Y}_\ell$ with a rank-I_C approximation of the interference and multipath subspace

Stage 2: Fine ToA Estimation (Frequency Domain)

Determines **sub-sample offset** $\tau'_{\mathrm{S},1}$ **of the first multipath component** in signal window output by the coarse ToA stage

$$\hat{\tau}'_{\mathrm{S},1} = \underset{\tau'\in[-T_s/2, T_s/2]}{\arg\min}\ \tau' \quad \text{s.t.} \quad \frac{\partial\mathcal{L}(\hat{\ell}, \tau')}{\partial\tau'} = 0$$

1. Splits interval for τ' is into J sub-intervals with a single minimum
2. Finds the first derivative sign change
3. Refines delay estimate with Golden-section search

- $\tilde{\mathbf{P}}(\tau')$ fitted in the frequency-domain with a rank-I_F approximation of the interference and multipath subspace ($I_F > I_C$)

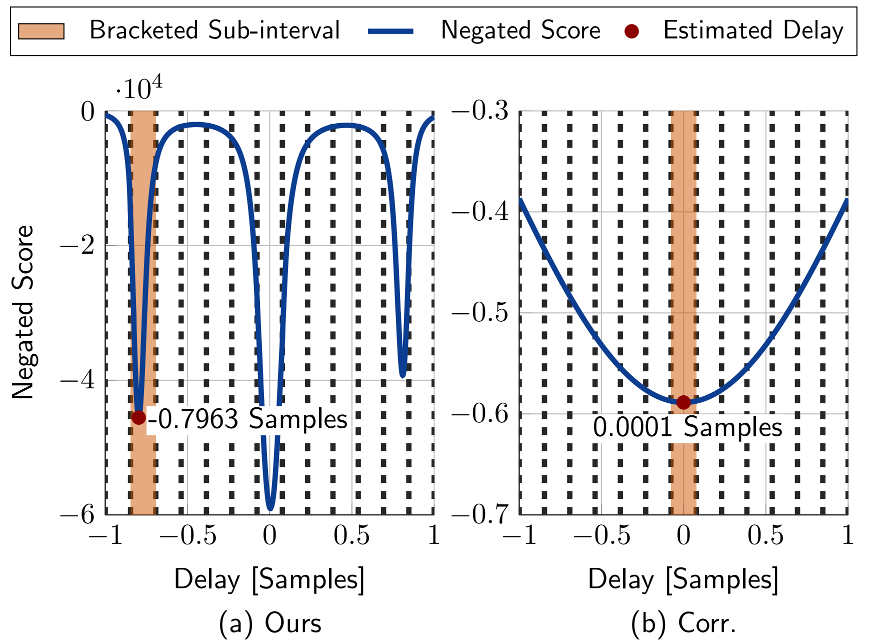


Figure: Fine ToA estimation example with three equally strong MPCs separated by 45° in azimuth and elevation, SNR $= 30$dB, and $I_F = 16$ nulled components

Our approach:

- **Enables fast ToA estimation** (< 10 ms on a general-purpose computer)
- **Overcomes the Rayleigh resolution limit**

Simulation and Results

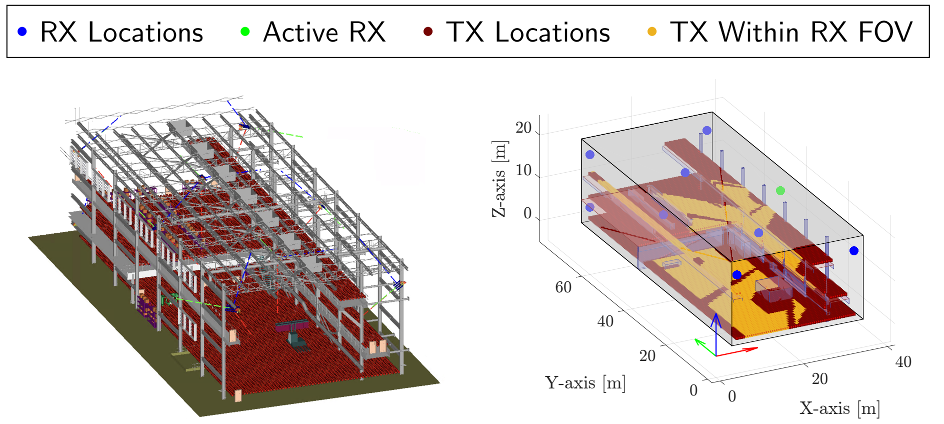


Figure: Indoor factory environment simulated in Wireless InSite to obtain ray-traced channel impulse responses

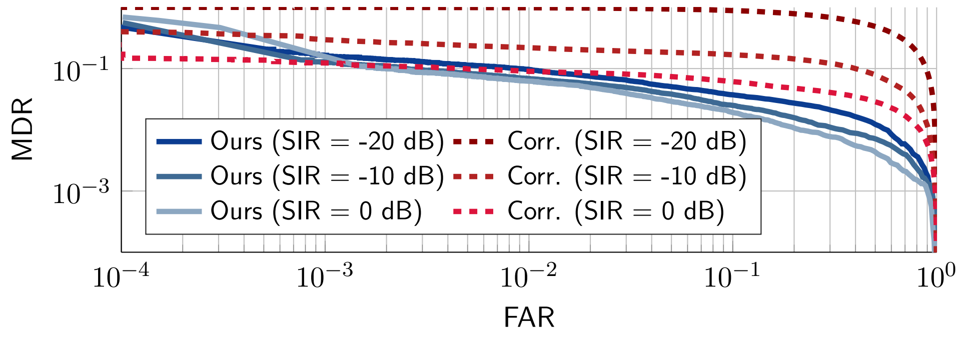


Figure: ROC coarse ToA estimation: SIR$= -20$dB, SNR$= 30$dB, $I_C = 4$

- **Coarse ToA estimation**: outperforms traditional correlation-based detectors; achieves consistently high probability of detection for a wide range of interference power levels
- **Fine ToA estimation**: outperforms correlation and the subspace-based Joint Angle and Delay Estimation (JADE) method, an extension of ESPRIT, at low SIRs; has comparable complexity to JADE, but requires no model order estimation; matches JADE accuracy at high SIRs

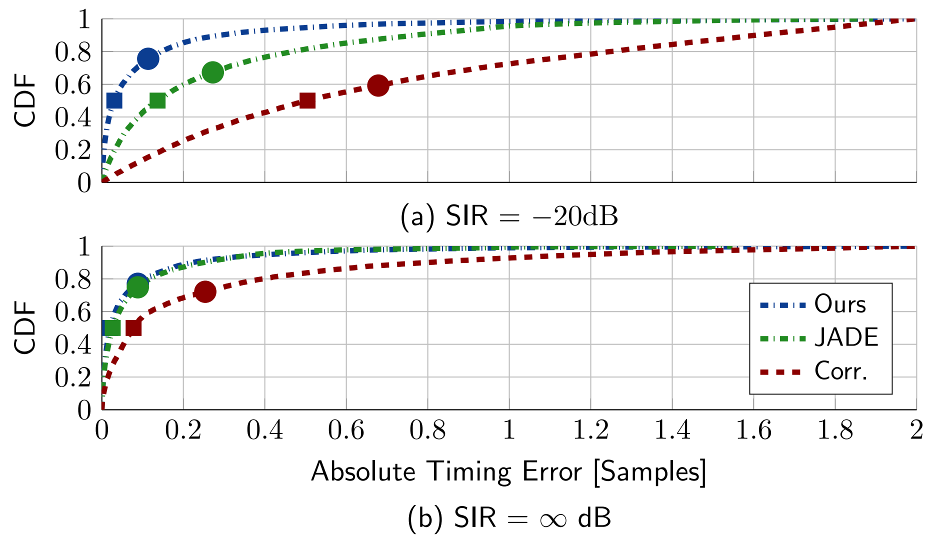


Figure: Absolute timing error CDF for fine ToA estimation: SNR$= 30$dB, $I_F = 16$

This work has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101139155

Funded by the European Union