Harnessing NLOS components for Position and orientation Estimation in 5G Millimeter Wave MIMO

Statistical Signal Processing EE602A

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Objective:

To prove that in 5G millimeter wave MIMO system, NLOS components always provide position and orientation information that consequently increase position and orientation estimation accuracy through Fisher Information Matrix.

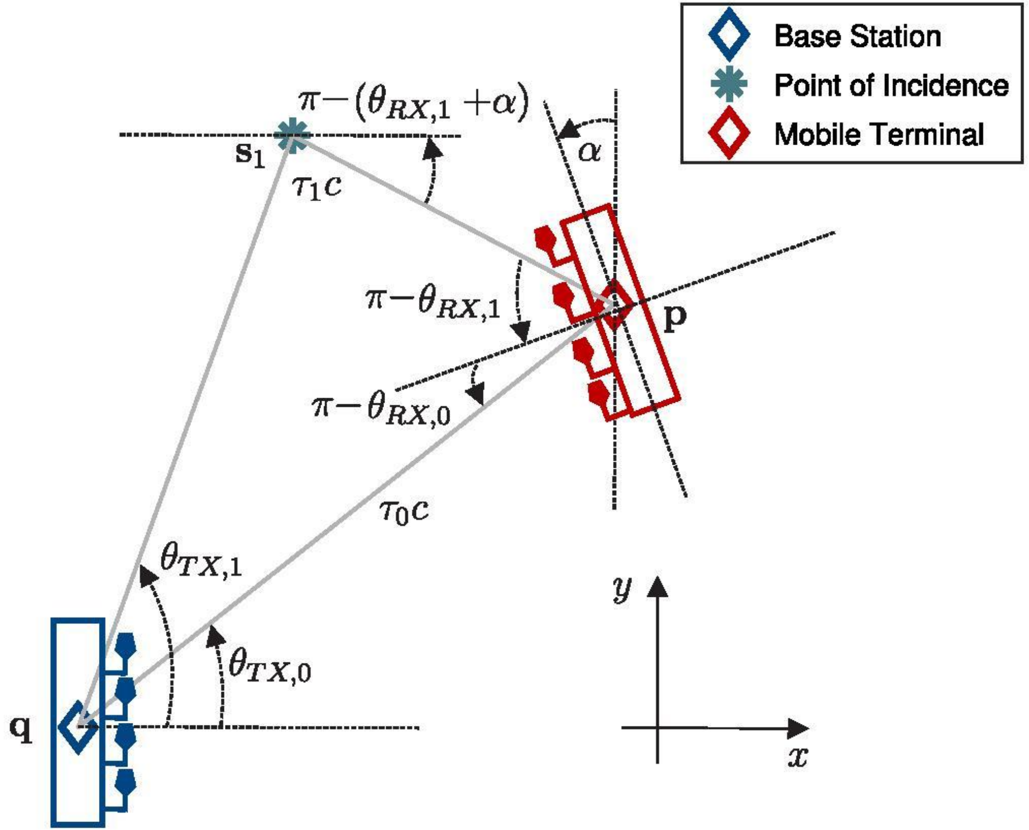
Methodology:

- By considering given geometry we deduce our model.
- Define an estimation problem and state the FIM of channel parameters and then simplify it.
- Derive FIM(EFIM) of position and orientation to analyse the impact of LOS and NLOS paths.
- Calculate net LOS and NLOS information gain and loss from EFIM

Definitions

1. **Non-line of sight** (**NLOS**) refers to the path of propagation of a radio frequency (RF) that is obscured (partially or completely) by obstacles, thus making it difficult for the radio signal to pass through.
2. **Millimeter waves**, also known as extremely high frequency (EHF), is a band of radio frequencies that is well suited for **5G** networks which transmit on frequencies between 30 GHz and 300 GHz
3. **MIMO** (multiple input, multiple output) is an antenna technology for wireless communications in which multiple antennas are used at both the transmitter and the receiver.
4. **PEB**: Position Error Bound and **OEB**: Orientation Error Bound
5. **Fisher Information Matrix(FIM)**: is a way of measuring the amount of information that an observable random variable X carries about an unknown parameter θ of a distribution that models X.

Geometry of System Model



The base station and mobile terminal are equipped with an array of N_{TX} transmit antennas and N_{RX} receive antennas, respectively.

The array of the base station has arbitrary but known geometry. We denote the orientation of the base station array by φ.

The centroids of the base station and mobile terminal arrays are located at the positions **q** = $[qx, qy]^T$ and **p** = $[px, py]^T$, respectively. We assume that the array geometry of the mobile terminal is known while the orientation α of the array is unknown.

Paper Contribution

1. EFIM can be written as the sum of rank one matrices, where each NLOS component contributes a distinct rank one matrix to the EFIM
2. Contribution from each NLOS component increases the position and orientation information content in the EFIM, and thus reduces the PEB and OEB
3. NLOS components provide significant position and orientation information if and only if angle of-arrival (AOA), angle-of-departure (AOD), and time-of arrival (TOA) can be estimated accurately

Channel Model

NLOS components are assumed to originate from single-bounce scattering or reflection only.

Scatterers are objects that are much smaller than the wavelength of the signal, while reflectors are objects with a specific reflection point that are much larger than the wavelength of the signal. We denote the reflecting point and the location of the scatterer by the point of incidence $s_k = [s_{x,k}, s_{y,k}]^T$.

Each path is associated with three distinct channel parameters, namely AOA, AOD, and TOA, where AOA, AOD, and TOA of the kth path are denoted by θRX,k, θTX,k, and τk, respectively. The channel impulse response is given by

$$\mathbf{H}(t) = \sum_{k=0}^{K-1} \underbrace{\sqrt{N_{\mathrm{RX}} N_{\mathrm{TX}}} h_k \mathbf{a}_{\mathrm{RX},k}(\theta_{\mathrm{RX},k}) \mathbf{a}_{\mathrm{TX},k}^H(\theta_{\mathrm{TX},k})}_{\mathbf{H}_k} \times \delta(t - \tau_k),$$

where $h_k = h_{R,k} + jh_{I,k}$ is the complex path gain while $a_{TX,k}(\theta_{TX,k})$ and $a_{RX,k}(\theta_{RX,k})$ denote the unit-norm array response vectors of the kth path at the transmitter and receiver, respectively. No angular spreads are considered.

Receiver Model

The noisy observed signal at the receiver is given by

$$\mathbf{r}(t) \triangleq \sum_{k=0}^{K-1} \sqrt{E_s}\mathbf{H}_k\mathbf{F}\mathbf{s}(t-\tau_k) + \mathbf{n}(t), \quad t \in [0, N_s T_s],$$

where $n(t)=[n_1(t), n_2(t),...,n_{NRX}(t)]^T$ is zero-mean additive white Gaussian noise (AWGN) with power spectral density (PSD) N_0.

It can be regarded as the receiver architecture which results in the lowest PEB and OEB.

System-Level Aspects

In this paper, localization is considered in the downlink. Localization can be performed during the initial access or the in-service phase.In this phase, no additional information regarding the location of the mobile terminal or the scatterers or reflectors is necessary to perform positioning. Only the multipath components of the reflectors or scatterers which are illuminated by these beams are received by the mobile terminal. From these components, the positions of the respective reflectors or scatterers can be estimated and stored in a map.

FIM of The Channel Parameters

Our required FIM can be written as

$$\mathbf{J}_{\boldsymbol{\eta}} \triangleq \begin{bmatrix} \mathbf{J}_{\boldsymbol{\theta}_{\mathrm{RX}}\boldsymbol{\theta}_{\mathrm{RX}}} & \mathbf{J}_{\boldsymbol{\theta}_{\mathrm{RX}}\boldsymbol{\theta}_{\mathrm{TX}}} & \cdots & \mathbf{J}_{\boldsymbol{\theta}_{\mathrm{RX}}\mathbf{h}_{\mathrm{I}}} \\ \mathbf{J}^{\mathrm{T}}_{\boldsymbol{\theta}_{\mathrm{RX}}\boldsymbol{\theta}_{\mathrm{TX}}} & \ddots & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \mathbf{J}^{\mathrm{T}}_{\boldsymbol{\theta}_{\mathrm{RX}}\mathbf{h}_{\mathrm{I}}} & \cdots & \cdots & \mathbf{J}_{\mathbf{h}_{\mathrm{I}}\mathbf{h}_{\mathrm{I}}} \end{bmatrix},$$

Where $[\mathbf{J}_{\boldsymbol{\eta}}]_{u,v} \triangleq \dfrac{1}{N_0}\displaystyle\int_0^{N_s T_s} \mathbb{E}_{\mathrm{a}}\left[\Re\left\{\frac{\partial \boldsymbol{\mu}^{\mathrm{H}}_{\boldsymbol{\eta}}(t)}{\partial[\boldsymbol{\eta}]_u}\frac{\partial \boldsymbol{\mu}_{\boldsymbol{\eta}}(t)}{\partial[\boldsymbol{\eta}]_v}\right\}\right] dt.$ and $\boldsymbol{\mu}_{\boldsymbol{\eta}}(t) = \displaystyle\sum_{k=0}^{K-1}\sqrt{E_s}\mathbf{H}_k\mathbf{F}\mathbf{s}(t-\tau_k).$

By definition, we can define CRLB, $\mathbb{E}\left[(\boldsymbol{\eta}-\hat{\boldsymbol{\eta}})(\boldsymbol{\eta}-\hat{\boldsymbol{\eta}})^{\mathrm{T}}\right] \succeq \mathbf{J}^{-1}_{\boldsymbol{\eta}},$ where $\boldsymbol{\eta} \triangleq [\boldsymbol{\theta}^{\mathrm{T}}_{\mathrm{RX}}, \boldsymbol{\theta}^{\mathrm{T}}_{\mathrm{TX}}, \boldsymbol{\tau}^{\mathrm{T}}, \mathbf{h}^{\mathrm{T}}_{\mathrm{R}}, \mathbf{h}^{\mathrm{T}}_{\mathrm{I}}]^{\mathrm{T}},$

And ^n is estimation of n. After simplifying, the FIM via results of other papers, we finally arrive at:-

$$\tilde{\mathbf{J}}_{\boldsymbol{\eta}} \triangleq \begin{bmatrix} \tilde{\mathbf{J}}_{\boldsymbol{\theta}_{\mathrm{RX}}\boldsymbol{\theta}_{\mathrm{RX}}} & \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} \\ \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}_{\boldsymbol{\theta}_{\mathrm{TX}}\boldsymbol{\theta}_{\mathrm{TX}}} & \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}_{\boldsymbol{\theta}_{\mathrm{TX}}\mathbf{h}_{\mathrm{R}}} & \tilde{\mathbf{J}}_{\boldsymbol{\theta}_{\mathrm{TX}}\mathbf{h}_{\mathrm{I}}} \\ \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}_{\boldsymbol{\tau}\boldsymbol{\tau}} & \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} \\ \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}^{\mathrm{T}}_{\boldsymbol{\theta}_{\mathrm{TX}}\mathbf{h}_{\mathrm{R}}} & \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}_{\mathbf{h}_{\mathrm{R}}\mathbf{h}_{\mathrm{R}}} & \mathbf{0}_{\mathrm{K}} \\ \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}^{\mathrm{T}}_{\boldsymbol{\theta}_{\mathrm{TX}}\mathbf{h}_{\mathrm{I}}} & \mathbf{0}_{\mathrm{K}} & \mathbf{0}_{\mathrm{K}} & \tilde{\mathbf{J}}_{\mathbf{h}_{\mathrm{I}}\mathbf{h}_{\mathrm{I}}} \end{bmatrix}.$$

Derivation of FIM of the Position related Parameters(EFIM)

$$\tilde{\boldsymbol{\eta}}_k \triangleq [\tau_k, \theta_{\mathrm{TX},k}, h_{\mathrm{R,k}}, h_{\mathrm{I,k}}, \theta_{\mathrm{RX},k}]^{\mathrm{T}}$$

Rearranging Parameters for easier formatting for future calculation by multiplying the permutation matrix

$$\mathbf{J}_{\tilde{\boldsymbol{\eta}}} \triangleq \mathbf{P}_{\pi}\tilde{\mathbf{J}}_{\boldsymbol{\eta}},$$

$$\mathbf{J}_{\xi_1}^{\mathrm{e}} \triangleq \mathbf{J}_{\xi_1\xi_1} - \mathbf{J}_{\xi_1\xi_2}\mathbf{J}_{\xi_2\xi_2}^{-1}\mathbf{J}_{\xi_1\xi_2}^{\mathrm{T}}.$$

$$\mathbf{J}_{\tilde{\eta}_k} \triangleq \begin{bmatrix} \sigma_{\tau_k}^{-2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \underbrace{\begin{bmatrix} \tilde{\sigma}_{\theta_{\mathrm{TX},k}}^{-2} & b_{\mathrm{R},k} & b_{\mathrm{I},k} \\ b_{\mathrm{R},k} & \sigma_{\mathrm{h_{R,k}}}^{-2} & 0 \\ b_{\mathrm{I},k} & 0 & \sigma_{\mathrm{h_{I,k}}}^{-2} \end{bmatrix}}_{\mathbf{J}_{\theta_{\mathrm{TX},k}\mathbf{h}_k}} & \mathbf{0} \\ 0 & \mathbf{0} & \sigma_{\theta_{\mathrm{RX},k}}^{-2} \end{bmatrix},$$

Then we transform above matrix to position, orientation and points of incidence domain

$$\mathbf{J}_{\breve{\boldsymbol{\eta}}} \triangleq \mathbf{T}\mathbf{J}_{\bar{\boldsymbol{\eta}}}\mathbf{T}^{\mathrm{T}},$$

where $\mathbf{T} \triangleq \frac{\partial \bar{\boldsymbol{\eta}}^{\mathrm{T}}}{\partial \breve{\boldsymbol{\eta}}}$.

After solving the parameters we break our EFIM in three parts as follows:-

$$\begin{aligned} \mathbf{J}_{\bar{\eta}_{\mathbf{p},\alpha}}^{\mathrm{e}} = & \underbrace{\mathbf{A}\mathbf{J}_{\bar{\eta}_{\mathrm{LOS}}}\mathbf{A}^{\mathrm{T}}}_{\triangleq \tilde{\mathbf{A}}^{(\mathrm{G})}\text{ - LOS info gain}} + \underbrace{\mathbf{B}\mathbf{J}_{\bar{\eta}_{\mathrm{NLOS}}}\mathbf{B}^{\mathrm{T}}}_{\triangleq \tilde{\mathbf{B}}^{(\mathrm{G})}\text{ - NLOS info gain}} \\ & - \underbrace{\mathbf{B}\mathbf{J}_{\bar{\eta}_{\mathrm{NLOS}}}\mathbf{D}^{\mathrm{T}}(\mathbf{D}\mathbf{J}_{\bar{\eta}_{\mathrm{NLOS}}}\mathbf{D}^{\mathrm{T}})^{-1}\mathbf{D}\mathbf{J}_{\bar{\eta}_{\mathrm{NLOS}}}\mathbf{B}^{\mathrm{T}}}_{\triangleq \tilde{\mathbf{B}}^{(\mathrm{L})}\text{ - NLOS info loss}}. \end{aligned}$$

Net NLOS Gain

After subtracting NLOS loss term from NLOS gain term we get matrix B(N) who we define as $\tilde{\mathbf{B}}^{(N)} \triangleq \sum_{k=1}^{K-1} \mathbf{\Psi}_{\mathbf{s}_k}$ where

$$\begin{aligned}\mathbf{\Psi}_{\mathbf{s}_k} \triangleq\ & \epsilon_{\mathbf{s}_k} \mathbf{\Upsilon}_{0,0}(\theta_{\mathrm{TX},0}, 0, 0) \\ & + \beta_{\mathbf{s}_k} \mathbf{\Upsilon}_{1,1}(\theta_{\mathrm{RX},k}, \pi/2, \|\mathbf{p}-\mathbf{q}\|) + \gamma_{\mathbf{s}_k} \mathbf{B}_k^{(\mathrm{L})}.\end{aligned}$$

As above net net information matrix is rank one, the only non-zero eigenvalue of this matrix is given by

$$\lambda_{\mathbf{s}_k} \triangleq \frac{2 + \|\mathbf{p}-\mathbf{s}_k\|^2 (1+\cos(\Delta\theta_k))}{(1-\cos(\Delta\theta_k))c^2\sigma^2_{\tau_k} + (1+\cos(\Delta\theta_k))(\|\mathbf{p}-\mathbf{s}_k\|^2 \sigma^2_{\theta_{\mathrm{RX},k}} + \|\mathbf{q}-\mathbf{s}_k\|^2 \sigma^2_{\theta_{\mathrm{TX},k}})}$$

Thus every NLOS component is additive and, thus, contributes to the EFIM which, in turn, reduces the position and orientation error bound. Hence NLOS components can be harnessed to increase the position and orientation estimation accuracy in 5G mm-wave MIMO systems.

Corollary and interpretations of results

EFIM can be written as sum of outer-products of the eigenvectors:-

$$\mathbf{J}^{\mathrm{e}}_{\breve{\boldsymbol{\eta}}_{\mathbf{p},\alpha}} = \sum_{j \in R,D,A} \lambda^{(\mathrm{G})}_{j,0} \mathbf{v}^{(\mathrm{G})}_{j,0} \left(\mathbf{v}^{(\mathrm{G})}_{j,0}\right)^{\mathrm{T}} + \sum_{k=1}^{K-1} \lambda_{\mathbf{s}_k} \mathbf{v}_{\mathbf{s}_k} \mathbf{v}^{\mathrm{T}}_{\mathbf{s}_k}.$$

So even without the information of LOS path we can estimate the position with atleast three NLOS components.

PEB is defined as

$$\mathrm{PEB} = \sqrt{\mathrm{tr}\left\{\left[\left(\mathbf{J}^{\mathrm{e}}_{\breve{\boldsymbol{\eta}}_{\mathbf{p},\alpha}}\right)^{-1}\right]_{1:2,1:2}\right\}}.$$

Discussions and Implications

1. Useful for designing position and orientation estimators
2. NLOS path provides position and orientation information, and hence every NLOS path reduces the PEB. (all NLOS paths should be considered)
3. Paths with insignificant net NLOS information gain could be neglected by an estimator without considerable losses in terms of accuracy
4. A NLOS path, whose point of incidence is far away from the mobile terminal, contains mainly orientation information and only marginal position information
5. In the absence of the LOS path, at least three NLOS paths lead to a full rank EFIM.

Numerical Examples

Example 1:

Geometry has significant impact on NLOS gain. Illumination of plane has significant impact on NLOS gain. Points of incidence of NLOS paths should be illuminated with narrow beams. Narrower beams result in better PEB reduction.

The two figures map each other.

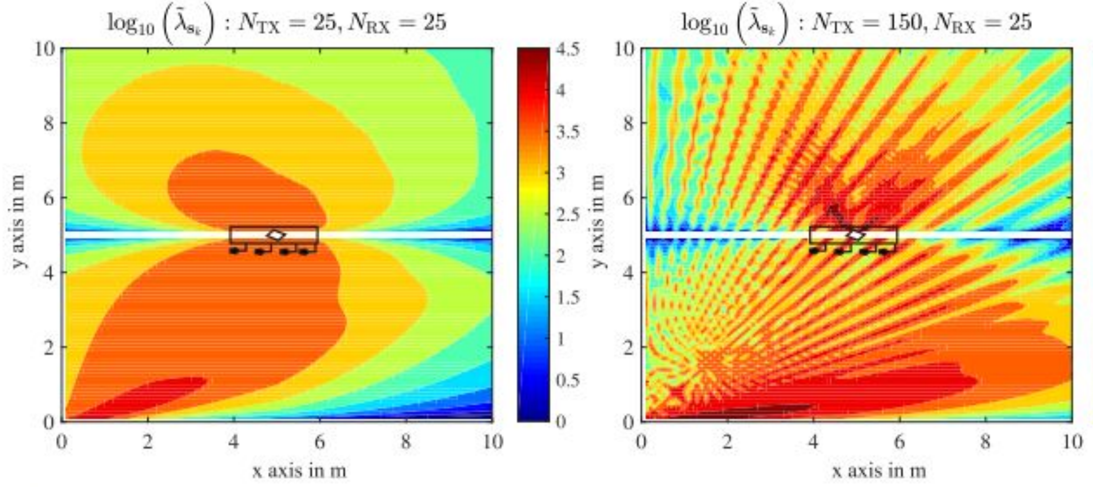
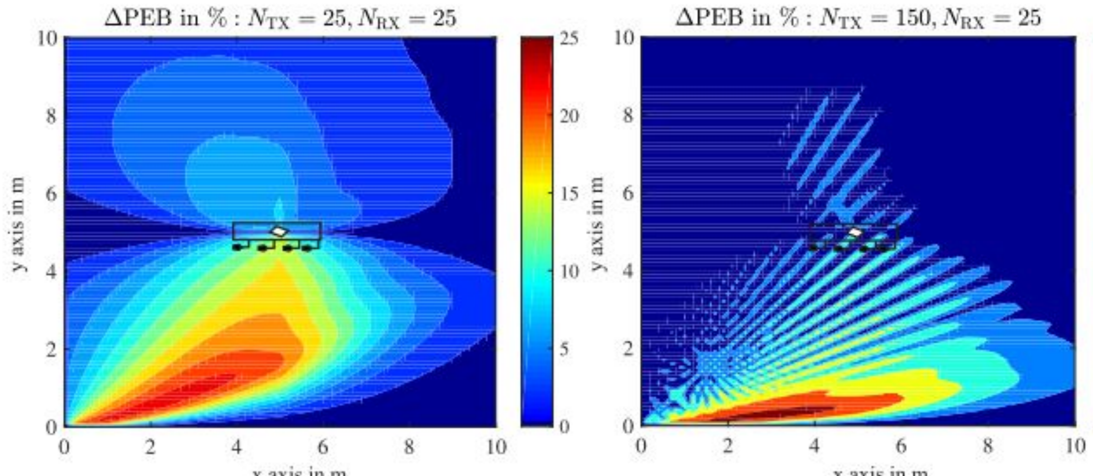
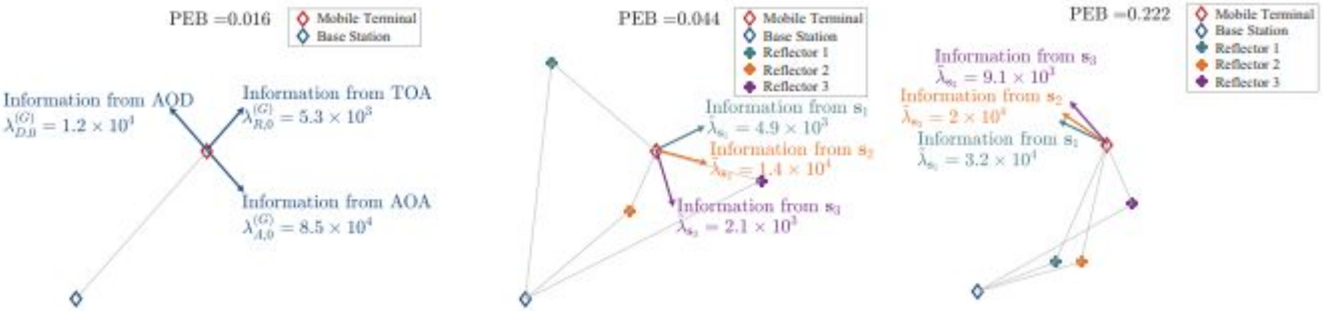


Fig. 2. *Net position information gain* - Narrower beamwidth caused by more transmit antennas (right) allows for larger net position information compared to wider beamwidth (left).



Numerical Example



Example 2: Even in absence of LOS path, the PEB is just slightly impaired with three NLOS paths.When reflectors are densely-spaced in AOD-domain, PEB is significantly higher.

Thank You