Wideband Channel Tracking for mmWave MIMO System with Hybrid Beamforming Architecture

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Intro: Tracking in mmW MIMO

- **MMW network features massive arrays**
  - Beamforming gain in Tx & Rx to compensate propagation loss
  - Multiplexing gain for throughput boost
  - Reduced interference
  - Vulnerable to beam misalignment

- **Channel state information (CSI) is crucial in mmW MIMO**
  - Channel estimation: training w/o using priori knowledge
    - Widely used in sub-6GHz band
    - High training overhead in mmW
  - Channel tracking: updates CSI w/ priori knowledge
    - Potentially reduce overhead

Fig. BS and UE needs to adaptively change beamformer for reliable communication in mmW MIMO system.
Outlines

- Mobile channel model for algorithm design & evaluation
  - 3GPP narrowband mobile model for above-6GHz band
  - Wideband mmW mobile model

- CSI tracking algorithm design
  - Propagation angle tracking
  - Compressive sensing based narrow-band channel tracking
  - Proposed wideband channel tracking

- Performance-complexity study on tracking algorithms
  - SINR and achievable rate
  - Training overhead
  - Computational complexity
2D narrow band mmW channel model (L paths)

\[ \mathbf{H} = \sum_{l=1}^{L} \alpha_l \mathbf{a}_R(\phi_l) \mathbf{a}_T^H(\theta_l) \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_R, N_T)</td>
<td>Rx/Tx antenna size</td>
</tr>
<tr>
<td>(\phi, \theta)</td>
<td>Angle of arrival (AOA); Angle of departure (AOD)</td>
</tr>
<tr>
<td>(\mathbf{a}_R(\phi)) (\mathbf{a}_T(\theta))</td>
<td>Spatial response of ULA of specific angle;</td>
</tr>
<tr>
<td>(\mathbf{a}_R(\phi) = \begin{bmatrix} e^{j\pi \cdot 0 \cdot \sin(\phi)} &amp; \cdots &amp; e^{j\pi \cdot (N_R-1) \cdot \sin(\phi)} \end{bmatrix}^T)</td>
<td></td>
</tr>
<tr>
<td>(\mathbf{a}_t(\theta) = \begin{bmatrix} e^{j\pi \cdot 0 \cdot \sin(\theta)} &amp; \cdots &amp; e^{j\pi \cdot (N_T-1) \cdot \sin(\theta)} \end{bmatrix}^T)</td>
<td></td>
</tr>
<tr>
<td>(\mathbf{w}_m, \mathbf{v}_m)</td>
<td>Beamformer of (m^{th}) channel probing in Tx and Rx</td>
</tr>
<tr>
<td>(g_m)</td>
<td>Post-Beamforming channel</td>
</tr>
<tr>
<td>(g_m = \mathbf{w}_m^H \mathbf{H} \mathbf{v}_m)</td>
<td></td>
</tr>
</tbody>
</table>
3GPP spatially-consistent UT mobility modelling [G17]

\[ H^{(n)} = \sum_{l=1}^{L} \alpha_l^{(n)} a_R \left( \phi_l^{(n)} \right) a_T^H \left( \theta_l^{(n)} \right), n = 0, 1, \cdots \text{ as time } t_n \]

- Channel variation \( H^{(n)} \) determined by \( \alpha_l^{(n)} \), \( \theta_l^{(n)} \), and \( \phi_l^{(n)} \)
- At \( t_0 \): set BS, UE scatterer location; channel coefficient initialization
- At \( t_n \): update channel coefficient from \( t_{n-1} \)

**Channel Coefficients updates**
\((\Delta t = t_n - t_{n-1})\)

**AOA**
\[ \phi_l^{(n)} = \phi_l^{(n-1)} + \frac{v \Delta t \sin(\beta - \phi_l^{(n)})}{d(n)} \]

**Gain (from delay)**
\[ \alpha_l(t_n) = \exp\left(-\tau_l^{(n)}/\tau_0\right) \]
\[ \tau_l^{(n)} = \tau_l^{(n-1)} - \frac{\cos(\beta) \cos(\phi_l^{(n)}) + \sin(\beta) \sin(\phi_l^{(n)})}{c} v \Delta t \]

Speed: \( v [\cos(\beta) \sin(\beta)]^T \)
Wideband Dynamic Channel Model

- **Modified model for wideband channel**
  - $R$ rays within each of $L$ multipath clusters
    \[
    H^{(n)}(t) = \sum_{l=1}^{L} \sum_{r=1}^{R} \alpha_{l,r}^{(n)} p_c(t - \tau_{l,r}^{(n)}) a_R(\phi_{l,r}^{(n)}) a_T^H(\theta_{l,r}^{(n)})
    \]
  - Pulse shaping function $p_c(t)$ due to band-limited nature in T/Rx
  - UE 2D moving: channel parameters evolve with similar manner
  - UE rotation: AOA of all rays incremented by $\nu_r \cdot \Delta t$
### Wideband Dynamic Channel Model

**Time & freq. domain WB mobile channel**

Discrete Time Domain (delay $d$)

$$H_t^{(n)}[d] = \sum_{l=1}^{L} \sum_{r=1}^{R} \alpha_{l,r}^{(n)} p_c(dT_s - \tau_{l,r}^{(n)}) a_R(\theta_{l,r}^{(n)}) a_T^H(\phi_{l,r}^{(n)})$$

Frequency Domain (subcarrier $k$)

$$H_f^{(n)}[k] = \sum_{d=1}^{D-1} H_t[d] e^{-j \frac{2\pi dk}{K}}$$

**Illustration of mobile channel simulation**

**Top:** Simulated results of delay profile & AOA versus time $t_n$ using proposed model

**Bottom:** Measured results in dense urban environment (at 73 GHz) [WSH+16]

Problem Statement

- **Tracking procedure at** $t_n$
  - BS sends $M$ beacons with
    
    $$
    \mathbf{W}^{(n)} = \begin{bmatrix} \mathbf{w}_1^{(n)} & \cdots & \mathbf{w}_M^{(n)} \end{bmatrix}^T \in \mathbb{C}^{N_T \times M}
    $$
  - UE measures post-BF channel $g_m^{(n)}[k]$ with
    
    $$
    \mathbf{V}^{(n)} = \begin{bmatrix} \mathbf{v}_1^{(n)} & \cdots & \mathbf{v}_M^{(n)} \end{bmatrix} \in \mathbb{C}^{N_R \times M}
    $$

- **Tracking objective**
  - Given probing beamformer $\mathbf{W}^{(n)}$ and $\mathbf{V}^{(n)}$, design tracking algorithm to update channel parameters
Prior-Art: AOA Tracking

- Tracking via angle refinement
  - Probing beams: narrow beams
    \[ w_m^{(n)} = a_T(\hat{\theta}) \]
    \[ v_m^{(n)} = a_R \left( \hat{\phi}^{(n-1)} + (m - 2)\Delta\phi \right) \]
  - Previous CSI*: \( \theta \) and \( \phi^{(n-1)} \)
  - Algorithm: RSS measurement into neighbor angles
    \[ m' = \arg\max_m \sum_k \left| g_m^{(n)}[k] \right|^2 \]
    \[ \hat{\phi}(n) = \hat{\phi}^{(n-1)} + (m' - 2)\Delta\phi \]

- Adopted in IEEE802.11ad (Beam Refinement Protocol) [NCF+14]
  - Low computational complexity: energy measurement & comparison

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* Dominant propagation angle is tracked and subscription \( l \) is omitted; Can be extension to all angles

Compressive narrowband (NB) chan. probing procedure

- Probing beams: quasi-omni beams
  - Fixed over $n$
  - Pseudorandom value $\{\pm 1 \pm 1j\}$ in elements of $W$ and $V$
  - Probe all angles in a compressed manner
- Previous CSI: $\hat{\theta}_l, \hat{\phi}_l^{(n-1)}$ and $\hat{\alpha}_l^{(n-1)}$
- Measured post-BF channel $g^{(n)} = [g_1^{(n)}, \cdots, g_M^{(n)}]^T$

$$g^{(n)} = V^H H^{(n)} W + \boxed{z^{(n)}}$$

$$= V^H \sum_{l=1}^{L} \alpha_l^{(n)} a_R (\phi_l^{(n)}) a_T (\theta_l) W + z^{(n)}$$

- $\theta_l$ is assumed to be known and constant; Such constant (Tx gain) is absorbed in $\alpha_l$
- Adapted from [MRM16]

Parameter updating algorithm for NB channel

- Alternative update estimated path gain $\alpha_l^{(n)}$ and AOA $\phi_l^{(n)}$ based on $g^{(n)}$

\[
\hat{\alpha}_l^{(n)} = \arg \min_{\alpha_l} \left\| g^{(n)} - V^H \sum_{l=1}^L \alpha_l a_R(\phi_l^{(n-1)}) \right\|^2
\]

\[
\hat{\phi}_l^{(n)} = \arg \min_{\phi_l} \left\| g^{(n)} - V^H \sum_{l=1}^L \hat{\alpha}_l^{(n)} a_R(\phi_l) \right\|^2
\]

- Each step can be approximately solved by LS
- Moderate complexity: pseudo-inverse of a $M \times N_t$ matrix
WB Channel Tracking Procedure

- **Proposed wideband (WB) channel probing procedure**
  - Probing beams: $L$ narrow beams for each of the cluster
    
    \[
    a_T(\bar{\theta}_l) \text{ and } a_R(\bar{\phi}_l^{(n-1)}), \ l \leq L,
    \]
    where $\bar{\theta}_l$ and $\bar{\phi}_l^{(n-1)}$ are mean estimated angle of AOD/AOD within cluster $l$

  - Previous CSI*: $\theta_{l,r}$, $\phi_{l,r}^{(n-1)}$, $\tau_{l,r}^{(n-1)}$, and $\alpha_{l,r}^{(n-1)}$

  - Measured effective channel (1st probing beam for example)

\[
g_1^{(n)}[k] = g(k, \alpha_{1,r_1}^{(n)}, \tau_{1,r_1}^{(n)}, \phi_{1,r_1}^{(n)}, \theta_{1,r_1}) = \sum_{r_1=1}^{R} \left[ \alpha_{1,r_1}^{(n)} \exp \left( -j \frac{2\pi k \tau_{1,r_1}^{(n)}}{KT_s} \right) \frac{1 - e^{j\pi N_t \Phi_{1,r_1}^{(n)}}}{1 - e^{j\pi \Phi_{1,r_1}^{(n)}}} \frac{1 - e^{j\pi N_t \Theta_{1,r_1}}}{1 - e^{j\pi \Theta_{1,r_1}}} \right] + \sum_{l=2}^{L} I_j^{(n)}[k] + \tilde{z}[k]
\]

where $\Theta_{1,r_1} \triangleq \sin(\theta_{1,r_1}) - \sin(\bar{\theta}_1)$, $\Phi_{1,r_1}^{(n)} \triangleq \sin(\phi_{1,r_1}^{(n)}) - \sin(\bar{\phi}_1)$

From other multipath cluster & AWGN; Treated as effective noise
WB Channel Tracking Algorithm

Channel coefficients update algorithm

**Gain Refinement:** solve for $\hat{a}^{(n)} = [\hat{a}_{1,1}^{(n)}, \cdots, \hat{a}_{1,R}^{(n)}]^T$

$$\hat{a}^{(n)} = \arg\min_a \left\| \Lambda_\alpha^{(n-1)} a - g_1^{(n)} \right\|^2,$$

where $g_1^{(n)} = [g_1^{(n)}[1], \cdots, g_1^{(n)}[K]]^T$ and $\{\Lambda_\alpha^{(n-1)}\}_{k,r} = \partial g(k, \alpha, \phi, \theta)/\partial \alpha_{1,r}$ is matrix with other coeff. at $t_{n-1}$.

**Delay Refinement:** update delay coeff. $\hat{t}^{(n)} = [\hat{\tau}_{1,1}^{(n)}, \cdots, \hat{\tau}_{1,R}^{(n)}]^T$ via

$$\Delta \hat{t}^{(n)} = \arg\min_{\Delta t} \left\| \hat{h}^{(n-1)} + \Lambda_\tau^{(n-1)} \Delta t - g_1^{(n)} \right\|^2,$$

$$\hat{t}^{(n)} = \hat{t}^{(n-1)} + \Delta \hat{t}^{(n)}.$$

where $\{\Lambda_\tau^{(n-1)}\}_{k,r} = \partial g(k, \alpha, \tau, \phi)/\partial \tau_{1,r}$ and $\hat{h}^{(n-1)}$ is the post-BF channel w/ estimated channel coeff at $t_{n-1}$

**Angle Refinement:** updates AOA coeff. $\hat{\phi}^{[n]} = [\phi_{1,1}^{[n]}, \cdots, \phi_{1,R}^{[n]}]$ via

$$\Delta \hat{\phi}^{[n]} = \arg\min_{\Delta \phi} \left\| \hat{h}^{[n-1]} + \Lambda_\phi^{[n-1]} \Delta \phi - g_1^{(n)} \right\|^2,$$

$$\hat{\phi}^{[n]} = \hat{\phi}^{[n-1]} + \Delta \hat{\phi}^{[n]}.$$

where $\{\Lambda_\phi^{(n-1)}\}_{k,r} = \partial g(k, \alpha, \tau, \phi)/\partial \phi_{1,r}$ with other coeff. at $t_{n-1}$
Channel Parameter Initialization

- Tracking requires channel coeff. estimation at $t_0$
  - Assuming rough angle estimation $\overline{\theta}_1$ and $\overline{\phi}_1$ are reached
  - Use $a_T(\overline{\theta}_1)$ and $a_R(\overline{\phi}_1^{(n-1)})$ for post-BF channel probing $g_1^{(0)}$
  - Orthogonal matching pursuit (OMP) based initialization

### Dictionary

$$\Psi \in \mathbb{C}^{K \times P}$$

$$\{\Psi\}_{k,p} = e^{-j \cdot k \cdot (p \Delta \tau) / KT_b}$$

The $p^{th}$ column contains freq-domain support due to delay $p\Delta\tau$

The post-BF channel probing results $g_1^{(0)}$ consists of up to $R$ supports

**Set of selected index $\mathcal{T}$**

Contains selected $\tau_1, r$ items

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**Algorithm 1** Tracking Initialization

1. Set $g_{\text{res}} = g_1^{(0)}$
2. for $r = 1 : R$
   3. Matching pursuit among delay candidates
      $$k_r = \arg \max_k \| \Psi_k^H g_{\text{res}} \|$$
   4. Update delay coeff. $\mathcal{T} = \mathcal{T} \cup k_r$.
   5. Orthogonalization:
      $$g_{\text{res}} = \frac{(I - \Psi_{\mathcal{T}} \Psi_{\mathcal{T}}^H)g_1^{(0)}}{\| (I - \Psi_{\mathcal{T}} \Psi_{\mathcal{T}}^H)h_1^{(0)} \|}$$
3. end for
4. Compute initial guess of channel parameters
   $$\hat{t}^{[0]} = \Delta \tau [\mathcal{T}_1, \ldots, \mathcal{T}_R]^T, \hat{\phi}^{[0]} = \overline{\phi}1$$
Performance Metrics

- **Metric: spectral efficiency (SE) after beamforming**
  - Scenario of transmission 1 stream
    
    \[
    SE = \frac{1}{K} \sum_{k=0}^{K-1} \log (1 + w_{data}[k]H_{f}[k]v_{data}[k])
    \]
  - SVD based beamforming \( w_{data} \) and \( v_{data} \) as primary eigenvector of MIMO channel
  - As SE upper bound for actual hybrid architecture
  - BF w/ NB CSI: same BF for all sub-carriers
  - BF w/ WB CSI: unique BF for each sub-carrier

<table>
<thead>
<tr>
<th>Beamformer for SE Evaluation</th>
<th>Approach</th>
<th>( w_{data}[k] ) and ( v_{data}[k] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle Tracking</td>
<td>( a_t(\theta), a_r(\phi) ) from ( \hat{\theta}, \hat{\phi} ) (same all sub-carriers)</td>
<td></td>
</tr>
<tr>
<td>NB Channel Tracking</td>
<td>Eigenvectors of ( \hat{H} ) (same for all sub-carriers)</td>
<td></td>
</tr>
<tr>
<td>WB Channel Tracking</td>
<td>Eigenvectors of ( \hat{H}_f[k] ) (for ( k^{th} ) sub-carriers)</td>
<td></td>
</tr>
<tr>
<td>Ideal CSI (Instantaneous)</td>
<td>Eigenvectors of ( H_f[k] ) (for ( k^{th} ) sub-carriers)</td>
<td></td>
</tr>
<tr>
<td>Ideal CSI (only at ( t_0 ))</td>
<td>Eigenvectors of ( H_f[k] ) (for ( k^{th} ) sub-carriers) at ( t_0 )</td>
<td></td>
</tr>
</tbody>
</table>
Simulation: SE v.s. Time

![Graph showing spectral efficiency over time with CSI from tracking](image)

**Simulation Settings**

<table>
<thead>
<tr>
<th>T/Rx Array</th>
<th>ULA w/ $N_T = N_R = 16$</th>
</tr>
</thead>
</table>
| **MIMO Channel** | - $L = 2$ NLOS multipath clusters  
- $R = 20$ rays in each; Scatterer location normalized for 
- Initial intra-cluster RMS delay spread $\sim 15$ ns  
- Initial intra-cluster RMS AOA spread $\sim 7.5$ deg 
  Gain normalized for 0dB per-BF SNR |
| **Mobility** | 10m/s 2D moving  
50 deg/s rotation |
| **T/Rx** | - 1Ghz band w/ $\kappa=512$ subcarrier  
- Transmit $N_s = 1$ data stream |

*Fig. spectral efficiency over time with CSI from tracking;*
## Training Overhead

### Overhead

<table>
<thead>
<tr>
<th></th>
<th>Re-estimation (w/o Tracking)</th>
<th>Prop. Angle Tracking</th>
<th>NB Channel Tracking</th>
<th>WB Channel Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interval btw Channel Est.</strong></td>
<td>100 ms</td>
<td>500 ms*</td>
<td>500 ms</td>
<td>500 ms</td>
</tr>
<tr>
<td><strong>Channel Est. Frame Num.</strong></td>
<td>256**</td>
<td>256</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td><strong>Interval btw Tracking</strong></td>
<td>-</td>
<td>10 ms</td>
<td>10 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td><strong>Tracking Frame Num.</strong></td>
<td>-</td>
<td>6</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td><strong>Overhead</strong>*</td>
<td>3.84%</td>
<td>1.67%</td>
<td>2.23%</td>
<td>1.52%</td>
</tr>
</tbody>
</table>

* Multipath scatterers may significantly change after moving beyond coherence distance, which is assumed to be 10m (1 s w/ 10m/s speed)

** Advanced channel estimation approach may significantly reduces required channel estimation frames

*** A frame length is assumed to be 15μs; Results are conservative since additional higher layer overheads are not considered
Conclusions & Future Works

- We have proposed a wideband mmWave mobile channel model
  - Facilitate tracking algorithm evaluating

- We have proposed a wideband channel tracking algorithm
  - Improved performance over narrowband tracking approach by using lower training overhead

- Future works
  - Study the impact of probing beamformer in tracking performance
  - Study the overhead & capacity trade-off in channel tracking
Thanks for your attention!
References

- [M17] 5GPPP, “mmMAGIC project D2.2 Measurement Results and Final mmMAGIC Channel Models,” May. 2017 [online available] https://5g-mmmagic.eu/results/#deliverables