Coordinated Beam Discovery, Association, and Mobility Management in Ultra-Dense Millimeter-Wave Network

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Challenges in mmW networks

1. **Latency and overhead of initial access**
- Beamforming gain is required during initial access to establish the link between BS and UE.
- The overhead cost of beam scanning during initial access reduces the throughput of the link.

2. **User association and resource allocation with hybrid architecture**
- To reduce hardware cost, hybrid architecture with fewer RF chains than the number of antennas will be used at BS and UE.
- Due to blockages, an RF chain at BS may not be reachable by all the RF chains at BS.
- Association of RF chains at the BS to RF chains at UE is required instead of association between BSs and UEs.

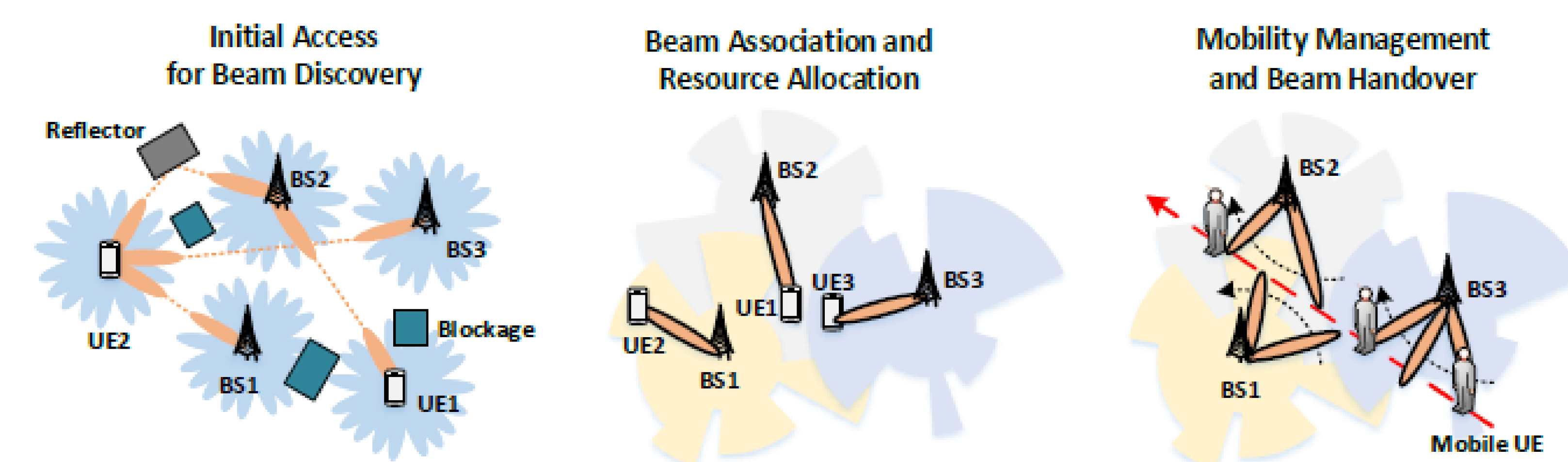
3. **Frequent handovers in mobile ultra-dense networks**
- Small movement of UE can render the link inactive due to narrow beams.
- Dense deployment of BSs is required to provide good coverage under high propagation loss in mmW band.
- Frequent handovers under UE mobility can impede seamless data transfer in ultra-dense networks.

Proposed Approach

1. Initial access for fast beam discovery
- Low latency beam-discovery, CSI acquisition, and beamforming with practical hardware modeling in hybrid architecture [1,2].

2. Beam association and resource allocation (BA/RA)
- Joint association of UE beams with BS beams along with beam-width optimization
- BA/RA taking into account CSI acquisition errors.

3. Mobility management and beam handover
- Wideband channel tracking to maintain connectivity within cell [3].
- Joint link update and BA/RA to minimize number of handovers.



Initial Access for Fast Beam Discovery [1]

System Model:

Post combining received signal at UE

$$y[n] = \sum_{m=1}^{M} \underbrace{\mathbf{v}_m^H \mathbf{H} \mathbf{w}_m}_{g_m} s_m[n] e^{j(2\pi \Delta f T_s n + \Psi[n])} + u[n]$$

Known design parameters — **Parameters to be estimated**

M	Num. of beam pattern pairs (training frames)
$\boldsymbol{v_m}/\boldsymbol{w_m}$	Tx/ Rx Beamformers in slot m
$s[n]$	Pilots
Δf	Initial freq. offset
T_s	Sampling interval
$\psi[n]$	Phase noise
$u[n]$	Post combining AWGN

Objective:
- Estimate synchronization parameters: Δf.
- Estimate CSI: $\boldsymbol{H}$

Proposed Algorithm:

Initial BF training:
- Synchronization: design Extended Kalman Filter based on (1,2) for Δf estimation

Status updating equation

$$\underbrace{\begin{bmatrix} \angle y[n] \\ \Delta f \end{bmatrix}}_{\mathbf{x}_n} = \underbrace{\begin{bmatrix} 1 & 2\pi T_s \\ 0 & 1 \end{bmatrix}}_{\mathbf{F}} \underbrace{\begin{bmatrix} \angle y[n-1] \\ \Delta f \end{bmatrix}}_{\mathbf{x}_{n-1}} + \underbrace{\begin{bmatrix} \Delta\Psi[n] \\ 0 \end{bmatrix}}_{\mathbf{w}_n} \cdot \quad (1)$$

Observation equation

Estimated from adjacent samples

Observation error

$$\mathbf{z}_n = \left[\frac{\Re(y[n])}{|y[n]|} \quad \frac{\Im(y[n])}{|y[n]|} \quad \Delta\hat{f} \right]^T = \underbrace{\left[\cos(\{\mathbf{x}_n\}_1) \quad \sin(\{\mathbf{x}_n\}_1) \quad \{\mathbf{x}_n\}_2 \right]^T}_{h(\mathbf{x}_n)} + \mathbf{v}_n \quad (2)$$

CSI Estimation:
- Estimate effective channel g_m from phase compensated $y[n]$;
- Formulate compressive sensing problem

$$\underbrace{\mathbf{g}}_{\mathbf{g}\in\mathbb{C}^M} = \underbrace{(\mathbf{W}^T \mathbf{A}_t^*) \otimes (\mathbf{V}^T \mathbf{A}_r)}_{\Lambda} \underbrace{\mathbf{h}}_{\mathbf{h}\in\mathbb{C}^{N_r N_t}} \quad (3)$$

Notations in (3)

$$\{\mathbf{A}_r\}_k = \mathbf{a}_r\left(\frac{-\pi}{2} + \frac{(k-1)\pi}{N_r - 1}\right), \{\mathbf{A}_t\}_k = \mathbf{a}_t\left(\frac{-\pi}{2} + \frac{(k-1)\pi}{N_t - 1}\right)$$

$$\mathbf{W} = [\mathbf{w}_1, \cdots, \mathbf{w}_M], \mathbf{V} = [\mathbf{v}_1, \cdots, \mathbf{v}_M]$$

$$\mathbf{g} = [g_1, g_2, \cdots, g_M]^T,$$

$\mathbf{h}$: sparse vector to be solved; contains spatial support of $\mathbf{H}$

- Estimate $\boldsymbol{H}$ from g_m using orthogonal matching pursuit.

Results

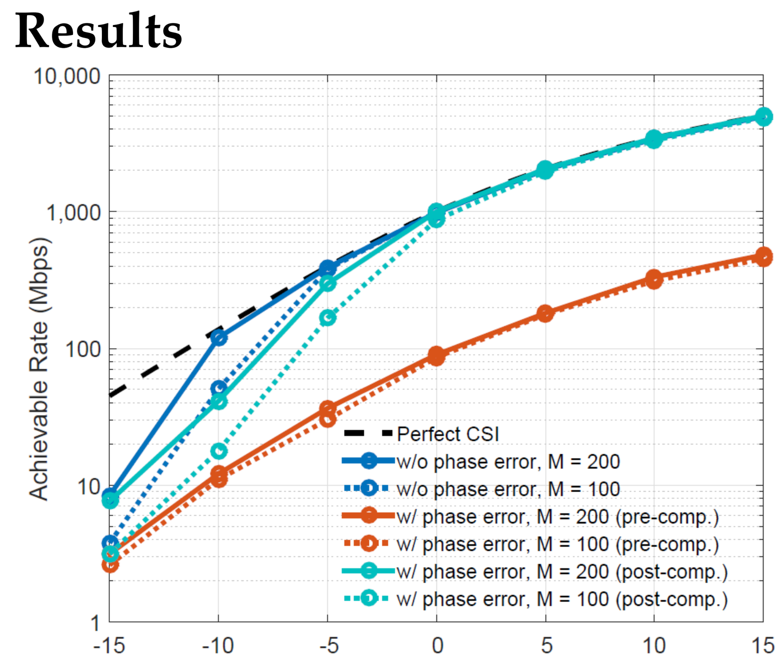


Fig. 1: Achievable rate vs SNR

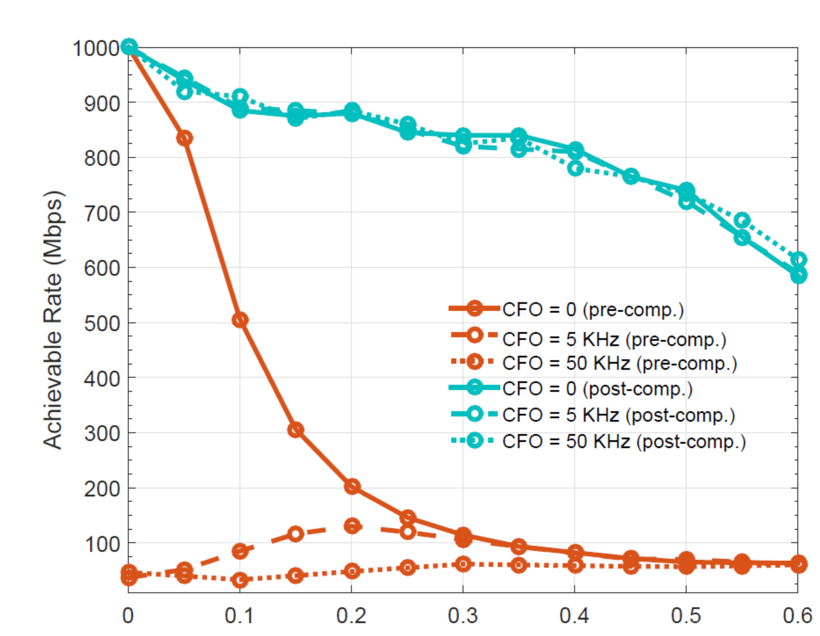


Fig. 2: Achievable rate vs RMS phase noise

Observations:
- The proposed initial BF training performance is nearly the same as compressive channel sounding with perfect synchronization (Fig. 1)
- The proposed algorithm achieves 10x more spectral efficiency than regular compressive channel sounding (Fig. 2)
- The proposed algorithm requires order of magnitude less training time than initial access with beam sweeping

(Training symbols used: in proposed alg.: M = {100,200}; in beam sweeping: 2048)

Mobility Management: Wideband Channel Tracking [3]

System Model:

Post combinining rx signal at UE on subcarrier k at time instant n:

$$y^{(n)}[k] = \boldsymbol{V}^{\boldsymbol{H}}[k]\boldsymbol{H}^{(n)}[k]\boldsymbol{W}[k]\boldsymbol{s}[k] + \boldsymbol{V}^{\boldsymbol{H}}[k]\boldsymbol{u}[k]$$

$\boldsymbol{V}[k]$	Received combining matrix at subcarrier k
$\mathbf{W}[k]$	Precoding matrix at subcarrier k
$s[k]$	Pilots
$\mathbf{u}[k]$	AWGN vector
$\boldsymbol{H}^{(n)}[k]$	Downlink MIMO channel matrix at subcarrier k

Objective:
- Track CSI $\boldsymbol{H}^{(n)}[k]$ at instant t_n given initial estimate $\boldsymbol{H}^{(0)}[k]$ at t_0.

Approach:
- $\boldsymbol{H}^{(n)}[k]$ is modeled as:

 # clusters — **# rays** — **Delay**

$$\mathbf{H}^{(n)}[k] = \sum_{l=1}^{L} \sum_{r_l=1}^{R} \alpha_{l,r_l}^{(n)} \exp\left(\frac{-j2\pi k \tau_{l,r_l}^{(n)}}{K T_s}\right) \mathbf{a}_r\left(\phi_{l,r_l}^{(n)}\right) \mathbf{a}_t^H\left(\theta_{l,r_l}^{(n)}\right)$$

Complex gain — **AoA at UE** — **AoD at BS (assumed to be const. during tracking)**

Step 1: initialization at $n = 0$
- Estimate $\boldsymbol{H}^{(0)}[k]$ using widebaband channel estimation.
- Extract $\alpha_{l,r_l}^{(0)}, \tau_{l,r_l}^{(0)}, \phi_{l,r_l}^{(0)}, \theta_{l,r_l}^{(0)}$ from $\boldsymbol{H}^{(0)}[k]$ using Orthogonal Matching Pursuit.

Step 2: tracking at $n > 0$
- Estimate $\tau_{l,r_l}^{(n)}, \phi_{l,r_l}^{(n)}$ using gradient descent, assuming α, θ to be constants. Estimate $\boldsymbol{H}^{(n)}[k]$ from $\{\alpha, \tau, \phi, \theta\}$.

Results:

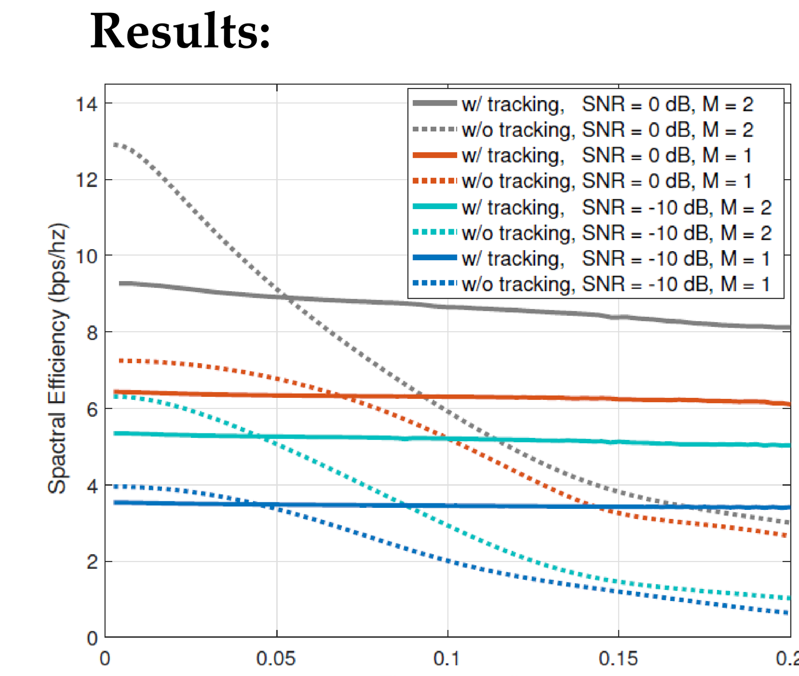


Fig. 3: Spectral efficiency vs time for number of RF chains $M = 1$ and $M = 2$.
Spectral efficiency is computed using estimated $\boldsymbol{H}^{(n)}[k]$.

Observations:
The spectral efficiency using the proposed tracking algorithm remains above 90% of initial efficiency after 200ms.

References to on-going works

[1] H. Yan and D. Cabric, "Compressive Sensing Based Initial Beamforming Training for Massive MIMO Millimeter-Wave Systems", in IEEE GlobalSIP 2016.
[2] H. Yan and D. Cabric, "Digital Predistortion for Hybrid Precoding Architecture in Millimeter-wave Massive MIMO Systems," in IEEE ICASSP 2017.
[3] H. Yan, S. Chaudhari and D. Cabric, "Wideband Channel Tracking for mmWave MIMO System with Hybrid Beamforming Architecture", submitted to IEEE CAMSAP 2017.

Future work
- Interleaved beam discovery and data transfer using multiple RF chains to increase throughput
- Beam association and resource allocation taking into account CSI estimation errors.
- Development of link update procedure under UE mobility to reduce the number of handovers while maintaining certain data rate at UE.