Wideband Channel Tracking for mmWave MIMO System with Hybrid Beamforming Architecture

(Invited Paper)

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***Abstract*—Millimeter-wave (mmWave) systems require a large number of antennas at both base station (BS) and user equipment (UE) for a desirable link budget. Due to time varying channel under UE mobility, up-to-date channel state information (CSI) is important to obtain the beamforming gain. The overhead cost of frequent channel estimation becomes a bottleneck to achieve high throughput. In this paper, we propose the first mmWave frequency selective channel tracking technique for hybrid analog and digital beamforming architecture. During tracking, this technique exploits mmWave channel sparsity and uses only one training symbol to update the CSI. Our simulation study utilizes a dynamic channel simulator that builds on top of recently proposed geometric stochastic approach from mmMAGIC project at 28 GHz. Assuming 10m/s moving speed and 200 deg/s rotation speed at UE, the proposed algorithm maintains the 80% of the spectral efficiency as compared to static environment over a time window of 100 ms. The proposed tracking algorithm reduces the overhead by 3 times as compared to existing channel estimation technique.**

I. INTRODUCTION

Millimeter-wave (mmWave) communication is a promising technology for future 5G cellular networks [1]. Due to the total 10 GHz spectrum approved for mobile systems in the 28, 38, and 72 GHz band [2], 5G networks can support 100 times higher data rate than the 4G networks. As shown in both theory and prototypes, mmWave system requires beamforming with large antenna arrays at both base station (BS) and user equipments (UE) to overcome severe propagation loss [3], [4]. The large number of antennas makes traditional digital beamforming less attractive due to its high cost. The analog-digital hybrid beamforming architectures have become popular since they can potentially achieve optimal spectral efficiency band while maintaining reasonable hardware cost and power consumption [5].

Further, the large number of antennas at BS and UE results in narrow beams. In a mobile environment, however, a small movement of UE results in mis-alignment of beams, which in turn renders the link between the BS and the UE inactive. Therefore, up-to-date channel state information (CSI) is necessary to keep the link active. The overhead cost of frequent channel estimation becomes a bottleneck to achieve high throughput in a wideband channel when the UE is moving.

The overhead of channel estimation can be reduced by tracking temporal variations in the channel. This procedure is often referred to as channel tracking. The narrowband channel tracking problem has been investigated in [6]–[12]. The objective of narrowband tracking is to track the angle-of-arrival (AOA) and angle-of-departure (AOD) of primary propagation paths. Works [6]–[8] assumed Gauss-Markov model for the evolution of AOA and AOD, and designed the tracking algorithm accordingly. Works [9]–[12] designed the tracking algorithm with trajectory-based geometric mmWave channel, which is closer to situation in a mobile network. Currently, no tracking algorithm for wideband frequency selective channel has been reported. On the other hand, wideband channel estimation using compressive sensing are proposed in [13], [14], but channel tracking is not considered.

In this work, we utilize the temporal correlation in mmWave frequency selective channel and design corresponding tracking algorithm for the hybrid architecture. We model the temporal correlation using the approach presented in recent channel models [15], [16]. The proposed channel tracking algorithm is implemented at the UE to track the channel parameters, namely, channel gains, AOAs and delays associated with different scattering clusters.

Notations: Scalars, vectors, matrices are denoted by non-bold, bold lower-case, and bold upper case letters, respectively, e.g. h, $\mathbf{h}$ and $\mathbf{H}$. The element in i-th row and j- column in matrix $\mathbf{H}$ is denoted by $\{\mathbf{H}\}_{i,j}$. Transpose, Hermitian transpose and pseudoinverse are denoted by $(.)^{\mathrm{T}}$, $(.)^{\mathrm{H}}$ and $(.)^{\dagger}$, respectively. The norm of a vector $\mathbf{h}$ is denoted by $||\mathbf{h}||$.

II. SYSTEM MODEL

Consider a single-user downlink system where one mmWave BS with N_t antennas serves an UE with N_r antennas. The BS and the UE use analog-digital hybrid precoding and combining architecture, respectively, with M RF chains. They use OFDM with K subcarriers. At the BS, the M data streams are precoded in the DSP, up-converted to radio frequency (RF), and precoded by RF phase shifters before transmitting the signal. The UE adopts similar operation at the receiver end. The post-combining received signal at the UE on subcarrier k is expressed as

$$\mathbf{y}[k] = \mathbf{W}_{\mathrm{BB}}^{\mathrm{H}}[k]\mathbf{W}_{\mathrm{RF}}^{\mathrm{H}}\mathbf{H}[k]\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]\mathbf{s}[k] + \mathbf{W}_{\mathrm{BB}}^{\mathrm{H}}[k]\mathbf{W}_{\mathrm{RF}}^{\mathrm{H}}\mathbf{v}[k].$$

where $\mathbf{s}[k] \in \mathbb{C}^{M\times 1}$ and $\mathbf{y}[k] \in \mathbb{C}^{M\times 1}$ are the transmitted and received symbols at subcarrier k, $\mathbf{F}_{\mathrm{BB}} \in \mathbb{C}^{M\times M}$ and $\mathbf{F}_{\mathrm{RF}} \in \mathbb{C}^{N_{\mathrm{t}}\times M}$ are the digital and analog precoding matrices, respectively. Similarly, $\mathbf{W}_{\mathrm{BB}} \in \mathbb{C}^{M\times M}$ and $\mathbf{W}_{\mathrm{RF}} \in \mathbb{C}^{N_{\mathrm{r}}\times M}$ are the digital and analog combining matrices, respectively. The $N_{\mathrm{r}} \times N_{\mathrm{t}}$ MIMO channel at subcarrier k is given by $\mathbf{H}[k]$ and the noise vector is $\mathbf{v}[k] \sim \mathcal{CN}(0, \sigma_{\mathrm{n}}^2\mathbf{I})$ with noise power σ_{n}^2.

Since the analog precoding procedure is implemented via phase shifters, each element in the $\mathbf{F}_{\mathrm{RF}}$ and $\mathbf{W}_{\mathrm{RF}}$ has unit amplitude. Note that the analog precoding and combining

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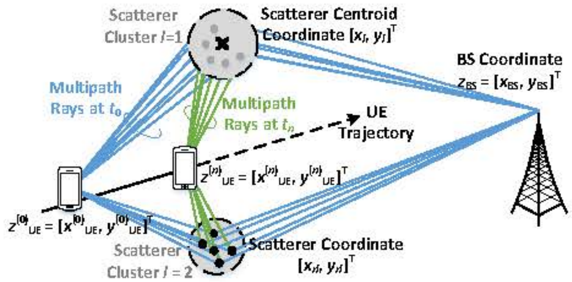

Fig. 1. Illustration of time varying channel model using geometric stochastic approach with $L = 2$ dominant multipath clusters. Coordinate of each scatterer cluster are generated at the beginning of channel realization (t_0) and remain fixed. Variation of channel small scale parameters at t_n follows changed UE location and straightforward geometry.

matrices F_{RF} and $\mathbf{W}_{\mathrm{RF}}$ are identical for all subcarriers [14]. Due to sparse scattering in mmWave band [3], the channel consists of a few dominant multipath clusters. In this work, we use 2D model such that only azimuth angle of propagation is considered. The frequency domain MIMO channel in the k^{th} subcarrier at time t_n is expressed as [17]

$$\mathrm{H}^{(n)}[k] = \sum_{l=1}^{L}\sum_{r_l=1}^{R} \alpha_{l,r_l}^{(n)} \exp\left(\frac{-\jmath 2\pi k \tau_{l,r_l}^{(n)}}{KT_{\mathrm{s}}}\right) \mathrm{a}_{\mathrm{r}}\left(\phi_{l,r_l}^{(n)}\right) \mathrm{a}_{\mathrm{t}}^{\mathrm{H}}\left(\theta_{l,r_l}^{(n)}\right), \tag{1}$$

where L is the number of multipath clusters, R is the number of rays in each cluster. The sampling duration is denoted by T_{s}. The complex gain, propagation delay, AOD, and AOA for each multipath ray are denoted as $\alpha_{l,r_l}^{(n)}$, $\tau_{l,r_l}^{(n)}$, $\theta_{l,r_l}^{(n)}$, and $\phi_{l,r_l}^{(n)}$, respectively at time t_n and $\phi_{l,r_l}, \theta_{l,r_l} \in [-\pi/2, \pi/2], \forall l, r_l$. $\mathrm{a}_{\mathrm{t}}(\theta) \in \mathbb{C}^{N_{\mathrm{t}}}$ and $\mathrm{a}_{\mathrm{r}}(\phi) \in \mathbb{C}^{N_{\mathrm{r}}}$ are the spatial responses of a half-wavelength spaced uniform linear array (ULA) as assumed in both BS and UE. The i^{th} elements are $\{\mathrm{a}_{\mathrm{t}}(\theta)\}_i = e^{\jmath\pi i \sin(\theta)}/\sqrt{N_{\mathrm{t}}}$ and $\{\mathrm{a}_{\mathrm{r}}(\phi)\}_i = e^{\jmath\pi i \sin(\phi)}/\sqrt{N_{\mathrm{r}}}$, respectively.

Our objective is to design an algorithm to track time varying MIMO channel $\mathrm{H}^{(n)}[k]$ at UE. Different from explicit channel estimation which requires excessive beam steering, the proposed technique uses estimation of $\mathrm{H}^{(0)}[k]$ as baseline, e.g., [14], and tracks its time variation with significantly reduced steering overhead.

Time varying wideband channel model: As illustrated in Fig. 1, in each channel realization, the channel evolution follows mobility of the UE. The BS is located at $\mathbf{z}_{\mathrm{BS}} = [x_{\mathrm{BS}}, y_{\mathrm{BS}}]^{\mathrm{T}}$ and the location of UE at time t_n is denoted by $\mathbf{z}_{\mathrm{UE}}^{(n)} = [x_{\mathrm{UE}}^{(n)}, y_{\mathrm{UE}}^{(n)}]^{\mathrm{T}}$. The centroid of the l^{th} scatterers cluster $[x_l, y_l]$ is determined by mean delay of this cluster τ_l (on the ellipse with UE and BS at the two foci at t_0.) There are R scatterers in each cluster and they are located at $\mathbf{z}_{l,r_l} = [x_{r_l}, y_{r_l}]^{\mathrm{T}}$, such that $x_{r_l} \sim \mathcal{N}(x_l, \sigma_l^2)$ and $y_{r_l} \sim \mathcal{N}(y_l, \sigma_l^2)$. As proposed in geometric stochastic channel modeling approach in mmMAGIC project [15], the locations of scatterers are fixed within spatial correlation distance (typically a few meters.) In the tracking time interval of interest, we adopt this assumption to model the time varying channel.

The temporal evolution of the channel $\mathrm{H}^{(n)}[k]$ is modeled implicitly by the variation of small scale parameters (SSP) namely, $\alpha_{l,r_l}^{(n)}, \tau_{l,r_l}^{(n)}, \theta_{l,r_l}^{(n)}, \phi_{l,r_l}^{(n)}$. The complex gains of rays are assumed to have equal power within cluster [16]. Therefore, we drop the subscript r_l for α. The complex gains follow Gauss-Markov model, i.e., $\alpha_{l,r_l}^{(n)} = \rho\alpha_{l,r_l}^{(n-1)} + \zeta_l^{(n)}$, where ρ is the correlation factor and $\zeta_l^{(n)} \sim \mathcal{CN}(0, 1-\rho^2)$. We consider two kinds of motion of the UE: position change and array orientation change. In the former, the location of UE changes as $\mathbf{z}_{\mathrm{UE}}^{(n)} = \mathbf{z}_{\mathrm{UE}}^{(n-1)} + \mathbf{v}\Delta t$ with constant speed $\mathbf{v}$ over time interval of interest and $\Delta t = t_n - t_{n-1}$ is the duration between adjacent time slots. Delays and angles $\tau_{l,r_l}^{(n)}, \phi_{l,r_l}^{(n)}$ evolve with the changed location of the UE, based on straightforward geometry at each time t_n as shown in Figure. 1. Since we focus on the UE, we remove superscripts in θ_{l,r_l} for clarity. The rotation of UE results in the change of AOA of all rays. We denote UE array rotational speed as $\delta\phi/\delta t$. In summary, the time varying channel parameter evolves as

$$\begin{aligned}\phi_{l,r_l}^{(n)} &= \phi_{l,r_l}^{(n-1)} + \angle\left(\mathbf{z}_{l,r_l} - \mathbf{z}_{\mathrm{UE}}^{(n)}\right) - \angle\left(\mathbf{z}_{l,r_l} - \mathbf{z}_{\mathrm{UE}}^{(n-1)}\right) + \frac{\delta\phi}{\delta t}\Delta t \\ \tau_{l,r_l}^{(n)} &= \tau_{l,r_l}^{(n-1)} + \frac{\|\mathbf{z}_{\mathrm{UE}}^{(n)} - \mathbf{z}_{l,r_l}\| - \|\mathbf{z}_{\mathrm{UE}}^{(n-1)} - \mathbf{z}_{l,r_l}\|}{c}\end{aligned} \tag{2}$$

where c is speed of light and $\angle([x,y]^{\mathrm{T}}) \triangleq \tan^{-1}(y/x)$.

III. Wideband Channel Tracking

In this section, we present the channel tracking algorithm.

We assume that a baseline MIMO channel estimation, e.g., [14], provides $\hat{\mathrm{H}}^{(0)}[k]$, as well as beam steering angles at m^{th} RF chain of BS, $\bar{\theta}_m$, and UE $\bar{\phi}_m$ at t_0. Therefore, the RF beamforming at BS and UE are $\mathrm{F}_{\mathrm{RF}} = [\mathrm{a}_{\mathrm{t}}(\bar{\theta}_1), \cdots, \mathrm{a}_{\mathrm{t}}(\bar{\theta}_M)]$ and $\mathbf{W}_{\mathrm{RF}} = [\mathrm{a}_{\mathrm{r}}(\bar{\phi}_1), \cdots, \mathrm{a}_{\mathrm{r}}(\bar{\phi}_M)]$. Without loss of generality, we focus on the 1^{st} RF chain and drop the subscription m for clarity. The effective channel for 1^{st} RF chain after RF beamforming is $h^{(n)}[k] = \{\mathbf{W}_{\mathrm{RF}}\}_{:,1}^{\mathrm{H}} \mathrm{H}^{(n)}[k]\{\mathrm{F}_{\mathrm{RF}}\}_{:,1}\{\mathrm{F}_{\mathrm{BB}}\}_{1,1} + \{\mathbf{W}_{\mathrm{RF}}\}_{:,1}^{\mathrm{H}}\mathrm{v}[k]$. Such post-beamforming channel $h^{(n)}[k]$ can be easily estimated by pilots symbols [18]. We denote the estimated post-BF channel as $\tilde{h}^{(n)}[k]$. Note that $\tilde{h}^{(n)}[k]$ is function of SSP as $\tilde{h}^{(n)}[k] = g(k, \alpha_l^{(n)}, \tau_{l,r_l}^{(n)}, \phi_{l,r_l}^{(n)}, \theta_{l,r_l})$, where

$$\begin{aligned} g(k, \alpha_l^{(n)}, \tau_{l,r_l}^{(n)}, \phi_{l,r_l}^{(n)}, \theta_{l,r_l}) = \sum_{r_1=1}^{R}\left[\alpha_1^{(n)} \exp\left(-\jmath\frac{2\pi k \tau_{1,r_1}^{(n)}}{KT_{\mathrm{s}}}\right)\right. \\ \left.\cdot \frac{1 - e^{\jmath\pi N_{\mathrm{r}}\Phi_{1,r_1}^{(n)}}}{1 - e^{\jmath\pi\Phi_{1,r_1}^{(n)}}} \frac{1 - e^{\jmath\pi N_{\mathrm{t}}\Theta_{1,r_1}}}{1 - e^{\jmath\pi\Theta_{1,r_1}}}\right] + \sum_{j=2}^{L} I_j^{(n)}[k] + \tilde{v}[k] \end{aligned} \tag{3}$$

where $\Theta_{l,r_l} \triangleq \sin(\theta_{l,r_l}) - \sin(\bar{\theta}_1)$ and $\Phi_{l,r_l}^{(n)} \triangleq \sin(\phi_{l,r_l}^{(n)}) - \sin(\bar{\phi}_1)$ and the associated terms represents array gain for such multipath cluster. In the above equation, $\tilde{v}[k]$ is AWGN after RF combining. $I_j^{(n)}[k]$ is the interference from sidelobes from other propagation paths corresponding to jth cluster:

$$I_j^{(n)}[k] = \sum_{r_j=1}^{R} \alpha_j^{(n)} e^{\frac{-\jmath 2\pi k \tau_{j,r_j}^{(n)}}{KT_{\mathrm{s}}}} \underbrace{\mathrm{a}_{\mathrm{r}}^{\mathrm{H}}(\bar{\phi}_1)\mathrm{a}_{\mathrm{r}}(\phi_{j,r_j}^{(n)})\mathrm{a}_{\mathrm{t}}^{\mathrm{H}}(\theta_{j,r_j}^{(n)})\mathrm{a}_{\mathrm{t}}(\bar{\theta}_1)}_{\text{Sidelobe Gain}}.$$

The AOA and AOD of the j^{th} multipath clusters are typically well-separated from the 1^{st} cluster and its sidelobe gain is negligible. Thus, we treat $I_j^{(n)}[k]$ as noise aggregated in $\tilde{v}[k]$ in following derivation.

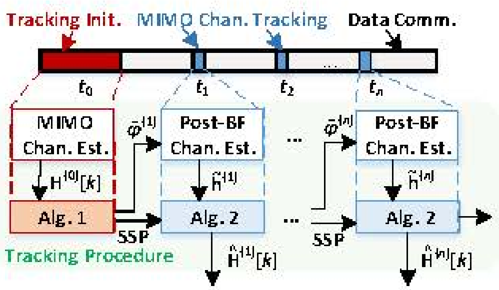

Fig. 2. Proposed tracking procedure and two complementary algorithms (Alg.) for wideband MIMO channel tracking at UE.

In order to track the time varying channel, the proposed algorithm tracks SSP, i.e., $\{\phi_{l,r_l}^{(n)}, \tau_{l,r_l}^{(n)}\}$. Jointly tracking all parameters including $\alpha_l^{(n)}$ potentially improves the performance, but we leave it as future work. As shown in Fig. 2, we first use baseline estimation $\mathbf{H}^{(0)}[k]$ and extract SSP $\{\alpha_{l,r_l}^{(0)}, \tau_{l,r_l}^{(0)}, \phi_{l,r_l}^{(0)}, \theta_{l,r_l}\}$. During tracking, the UE estimates post-BF channel estimation $\tilde{\mathbf{h}}^{(n)} = [\tilde{h}^{(n)}[1], \cdots, \tilde{h}^{(n)}[K]]^T$, which only requires one training symbol, and uses them to update CSI at t_n. It is worth mentioning that receiving angle, $\bar{\phi}$, in post-BF channel estimation is updated by our algorithm over time and it is denoted as $\bar{\phi}^{(n)}$.

The tracking initialization is presented in **Algorithm 1** for the 1st cluster and it is easily extended to find SSP in the l^{th} cluster with $l \neq 1$ using additional RF chains. Since $\bar{\phi}_1$ and $\bar{\theta}_1$ are good approximations of AOA and AOD of rays in the 1st cluster, they are used as initial guess of angles. We propose to use orthogonal matching pursuit (OMP) to search the delay of each rays. The channel parameters can be further refined since (3) maps them into channel post-beamforming channel. We propose to use iterative least square (LS), in which an LS problem is solved for one set of parameter while fixing the rest. Note that in the iterative refinement stage, we use superscript with bracket, e.g., $\alpha^{[n]}$ as indicator of iteration index. The specific steps of Algorithm 1 is explained as follows.

OMP: We create a delay dictionary $\Psi \in \mathbb{C}^{K\times G}$ which contains G delay candidates. Each element of Ψ is defined as $\{\Psi\}_{k,i} = e^{-\jmath k i \Delta\tau/(KT_s)}$ where $\Delta\tau = \tau_{\max}/G$ is the desired resolution of delay with maximum delay $\tau_{\max}$. The best R delay estimation τ_{l,r_l} computed by OMP becomes initial guess of $\hat{\mathbf{t}}^{[0]} \triangleq [\hat{\tau}_{1,1}^{[0]}, \cdots, \hat{\tau}_{1,R}^{[0]}]$.

Gain Refinement: In this step, we solve for $\hat{\mathbf{a}}^{[n]} \triangleq [\alpha_{1,1}^{[n]}, \cdots, \alpha_{1,R}^{[n]}]^{\mathrm{T}}$ by solving the following LS problem

$$\hat{\mathbf{a}}^{[n]} = \arg\min_{\mathbf{a}} \left\| \mathbf{H}_{\alpha}^{[n-1]} \mathbf{a}^{[n]} - \tilde{\mathbf{h}} \right\|^2, \tag{4}$$

where $\{\mathbf{H}_\alpha\}_{k,r}^{[n-1]} = \partial g(k,\alpha,\phi,\theta)/\partial\alpha_{1,r}$ in (3) and plug in the other required SSP with the estimated ones at iteration $n-1$.

Delay Refinement: In this step, we solve for $\Delta\hat{\mathbf{t}}^{[n]}$ and update $\hat{\mathbf{t}}^{[n]}$ as

$$\begin{aligned} \Delta\hat{\mathbf{t}}^{[n]} &= \arg\min_{\Delta\mathbf{t}} \left\| \hat{\mathbf{h}}^{[n-1]} + \mathbf{H}_{\tau}^{[n-1]} \Delta\mathbf{t} - \tilde{\mathbf{h}} \right\|^2, \\ \hat{\mathbf{t}}^{[n]} &= \hat{\mathbf{t}}^{[n-1]} + \Delta\hat{\mathbf{t}}^{[n]}. \end{aligned} \tag{5}$$

In (5), $\hat{\mathbf{h}}^{[n-1]}$ is formulated using (3) and estimated parameter at iteration $n-1$. $\mathbf{H}_\tau^{[n-1]} \in \mathbb{C}^{K\times R}$ is partial derivative with respect to propagation delay, i.e., $\{\mathbf{H}_\tau^{[n-1]}\}_{k,r} = \partial g(k,\alpha,\tau,\phi)/\partial\tau_{1,r}$. The numerical evaluation of $\mathbf{H}_\tau^{[n-1]}$ is obtained by first analytically taking derivate of (3) and plugging in estimated parameters set $\{\alpha,\tau,\phi\}$ from iteration $n-1$. $\hat{\mathbf{h}}^{[n]} \triangleq [\hat{h}^{[n]}[1], \cdots, \hat{h}^{[n]}[K]]^{\mathrm{T}}$ represents the channel with estimated SSP and $\hat{h}^{[n]}[k]$ is digitally computed by UE using estimated SSP from iteration $n-1$.

Angle Refinement: we solve for $\Delta\hat{\mathbf{p}}^{[n]}$ and update $\hat{\mathbf{p}}^{[n]}$ as

$$\begin{aligned} \Delta\hat{\mathbf{p}}^{[n]} &= \arg\min_{\Delta\mathbf{p}} \left\| \hat{\mathbf{h}}^{[n-1]} + \mathbf{H}_{\phi}^{[n-1]} \Delta\mathbf{p} - \tilde{\mathbf{h}} \right\|^2, \\ \hat{\mathbf{p}}^{[n]} &= \hat{\mathbf{p}}^{[n-1]} + \Delta\hat{\mathbf{p}}^{[n]}. \end{aligned} \tag{6}$$

where $\hat{\mathbf{p}}^{[n]} = [\phi_{1,1}^{[n]}, \cdots, \phi_{1,R}^{[n]}]$ are the estimated AOA at iteration n, $\{\mathbf{H}_\phi^{[n-1]}\}_{k,r} = \partial g(k,\alpha,\tau,\phi)/\partial\phi_{1,r}$ with estimated SSP at iteration $n-1$.

The estimated channel parameters at t_0 are used in tracking algorithm as described next.

Algorithm 1 Tracking Initialization

Input: Frequency domain channel $\tilde{\mathbf{h}}$ and steering angle $\bar{\phi}_1$, $\bar{\theta}_1$ via baseline channel estimation.

Output: Channel parameter estimation $\{\hat{\alpha}_{1,r_1}, \hat{\tau}_{1,r_1}^{(0)}, \hat{\phi}_{1,r_1}^{(0)}, \hat{\theta}_{1,r_1}\}$

Set $\mathbf{h}_{\text{res}} = \mathbf{h}$

——— Delay Search via OMP ———

for $r = 1 : R$ **do**

Matching pursuit among delay candidates

$$k_r = \arg\max_k \|\Psi_k^{\mathrm{H}} \mathbf{h}_{\text{res}}\| \tag{7}$$

Update τ candidates $\mathcal{T} = \mathcal{T} \cup k_r$ where $\mathcal{T}$ is the set that contains index of delay candidates of dictionary.

Orthogonalization:

$$\mathbf{h}_{\text{res}} = \frac{(\mathbf{I} - \Psi_{\mathcal{T}}\Psi_{\mathcal{T}}^{\dagger})\tilde{\mathbf{h}}}{\|(\mathbf{I} - \Psi_{\mathcal{T}}\Psi_{\mathcal{T}}^{\dagger})\tilde{\mathbf{h}}\|} \tag{8}$$

end for

Compute initial guess of channel parameters

$$\hat{\mathbf{t}}^{[0]} = \Delta\tau[\mathcal{T}_1, \cdots, \mathcal{T}_R]^{\mathrm{T}}, \hat{\mathbf{p}}^{[0]} = \bar{\phi}\mathbf{1} \tag{9}$$

——— Refinement via Iterative LS ———

for $n = 1 : N$ **do**

Using (4), (5) and (6) to refine SSP.

end for

Use elements of $\hat{\mathbf{t}}^{[N]}$, $\hat{\mathbf{a}}^{[N]}$ and $\hat{\mathbf{p}}^{[N]}$ as $\hat{\alpha}_{1,r_1}^{(0)}$, $\hat{\tau}_{1,r_1}^{(0)}$ and $\hat{\phi}_{1,r_1}^{(0)}$. Use $\hat{\theta}_{1,r_1} = \bar{\theta}_1$.

The tracking algorithm is presented in **Algorithm 2**. It uses previously estimated SSP and adjusts them based on the post-BF channel estimate, $\tilde{h}^{(0)}$. The tracking of SSP follows gradient descent as shown in (10) and new SSP is used to update CSI without excessive beam steering. The symbol $\hat{\mathbf{t}}^{(n)}$, $\hat{\mathbf{p}}^{(n)}$ are similarly defined as before except for t_n. The matrices $\mathbf{H}_\tau^{(n)}$ and $\mathbf{H}_\phi^{(n)}$ are the derivatives of (3) with estimated SSP in the previous tracking time slot.

Algorithm 2 Wideband Channel Tracking

Input: Estimated post-BF channel $\tilde{\mathbf{h}}^{(n)}$ at receiving angle $\bar{\phi}^{(n)}$ and parameters $\{\hat{\alpha}_l^{(0)}, \hat{\tau}_{l,r_l}^{(n-1)}, \hat{\phi}_{l,r_l}^{(n-1)}, \hat{\theta}_{l,r_l}\}$

Output: Estimated SSP $\{\hat{\tau}_{l,r_l}^{(n)}, \hat{\phi}_{l,r_l}^{(n)}\}$, MIMO channel $\hat{\mathbf{H}}^{(n)}[k]$ and steering angle for next time slot $\bar{\phi}^{(n+1)}$

1: Update channel parameters $\{\hat{\tau}_{l,r_l}^{(n)}, \hat{\phi}_{l,r_l}^{(n)}\}$ via gradient descent as

$$\begin{aligned}\hat{\mathbf{t}}^{(n)} &= \hat{\mathbf{t}}^{(n-1)} + \mu \bar{\mathbf{H}}_{\tau}^{(n-1)} (\tilde{\mathbf{h}}^{(n)} - \hat{\mathbf{h}}^{(n-1)}), \\ \hat{\mathbf{p}}^{(n)} &= \hat{\mathbf{p}}^{(n-1)} + \mu \bar{\mathbf{H}}_{\phi}^{(n-1)} (\tilde{\mathbf{h}}^{(n)} - \hat{\mathbf{h}}^{(n-1)}),\end{aligned} \tag{10}$$

for each RF chain, where μ is the stepsize, $\bar{\mathbf{H}}_{\tau}^{(n-1)}$ and $\bar{\mathbf{H}}_{\phi}^{(n-1)}$ are the column sum of $\mathbf{H}_{\tau}^{(n-1)}$ and $\mathbf{H}_{\phi}^{(n-1)}$, respectively

2: Estimate MIMO channel $\hat{\mathbf{H}}^{(n)}[k]$ via (1) using estimated SSP.

3: Update $\bar{\phi}^{(n+1)} = \bar{\phi}^{(n)} + \mu \bar{\mathbf{H}}_{\phi}^{(n-1)} (\tilde{\mathbf{h}}^{(n)} - \hat{\mathbf{h}}^{(n-1)})$.

IV. Numerical Evaluation

We simulate 28 GHz mobile system with single UE and BS with antenna array size being $N_\mathrm{t} = N_\mathrm{r} = 16$. The operation bandwidth is $1/T_\mathrm{s} = 1$ GHz and there are $K = 512$ OFDM subcarriers. There are $L = 2$ NLOS multipath clusters with equal power, each of which has $R = 20$ rays. The centroid of cluster is set as described in Section II with mean delay $\tau_1 = 250$ ns and $\tau_2 = 300$ ns. The cluster radius is chosen to be $\sigma_l = 3$ m such that the RMS intra-cluster delay spreads are around 15 ns as typically modeled [16]. The coordinates of UE and BS are $\mathbf{z}_{\mathrm{UE}}^{(0)} = [-30, 0]^\mathrm{T}$ m and $\mathbf{z}_{\mathrm{BS}} = [30, 0]^\mathrm{T}$ m, respectively and UE is moving with speed $\mathbf{v} = [10, 0]^\mathrm{T}$ m/s together with rotation of $\delta\phi/\delta t = 200$ deg/s. The correlation factor of complex gain is $\rho = 0.995$ [9]. The tracking frequency is $1/\Delta t = 500$ Hz. In the tracking initialization (Algorithm 1), we assume the MIMO channel estimate $\hat{\mathbf{H}}^{(0)}[k]$ has estimation error equal to Cramer-Rao lower bound as derived in [14]. The algorithm uses Ψ with delay resolution $\Delta\tau = 0.5$ ns and $N = 20$ in iterative LS for parameter refinement. $\tau_{max} = 500$ ns and $G = 1000$.

We use the spectral efficiency with estimated CSI as the performance metric. We consider two scenarios where UE is equipped with $M = 1$ and $M = 2$ RF chains for multiplexing. Therefore, the proposed algorithms are used to track M dominant multipath clusters. In order to evaluate the quality of estimated CSI, we use spectral efficiency with optimal beamforming, i.e., beamformers are obtained via SVD of $\hat{\mathbf{H}}^{(n)}[k]$. Spectral efficiency is defined as

$$C = \frac{1}{K} \sum_{k=1}^{K} \sum_{m_1=1}^{M} \log_2 \left(\frac{\lambda_{m_1,m_1}^2(\mathbf{H}[k])}{\sum_{m_2, m_2 \neq m_1}^{M} \lambda_{m_1,m_2}^2(\mathbf{H}[k]) + \sigma_\mathrm{n}^2} \right)$$

where $\lambda_{m_1,m_2}(\mathbf{H})$ is the product of the true channel $\mathbf{H}^{(n)}[k]$ with eigenvector of estimated channel $\hat{\mathbf{H}}^{(n)}[k]$, i.e., product m_1^{th} left primary eigenvector and m_2^{th} right primary eigenvector of $\hat{\mathbf{H}}^{(n)}[k]$. The results are evaluated under different pre-beamforming SNR as defines $\mathrm{SNR} = \mathbb{E}_k \|\mathbf{H}[k]\|_\mathrm{F}^2 / (N_\mathrm{t} N_\mathrm{r} \sigma_\mathrm{n}^2)$ with $\|.\|_\mathrm{F}$ represents the Frobenius norm of a matrix.

Figure. 3 shows average spectral efficiency in a time window up to $T_c = 100$ ms, which is a conservative value to assume fixed scatterer clusters. It can be observed that the proposed approach keeps 80% of the spectral efficiency after 100 ms as compared to the spectral efficiency at $t_0 = 0$. The benchmark approach uses channel SVD to compute beamformers at t_0 based on CSI with estimation error, $\mathbf{H}_\epsilon[k]$. The estimation at t_0 is assumed to have normalized mean square error (NMSE) equal to CRLB, and then remains unchanged over time. NMSE is defined as $\sum_k \|\mathbf{H}_\epsilon[k]\|_\mathrm{F}^2 / (K \|\mathbf{H}^{(0)}[k]\|_\mathrm{F}^2)$. Without tracking, the spectral efficiency drops quickly as seen in dotted curves. The proposed algorithm is resilient in low SNR situation as well since the receiver beams are aligned with dominant propagation path. It is worth mentioning that **Algorithm 1** introduces additional error in channel estimation and therefore the spectral efficiency at t_0 is lower for the proposed approach as compared to the benchmark approach.

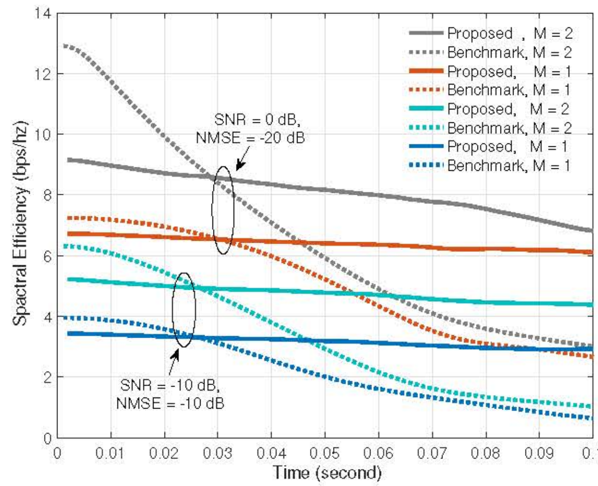

Fig. 3. Spectral efficiency time evolution with different SNR and RF chains. The proposed approach is compared with benchmark approach which only relies on independent channel estimating channel at t_0 using channel estimator with NMSE equals to CRLB.

In order to compare the training overhead, we assume the state-of-the-art compressive sensing based MIMO channel estimation requires 80 training frames [14]. If re-estimation is required once spectral efficiency drops below 50%, it would require 160 training frames in 100 ms. On the other hand, the proposed approach requires only 50 training frames, thus saving the training overhead by a factor of 3.2.

V. Conclusion and Future works

We have presented a novel wideband MIMO channel tracking algorithm. It is designed for the emerging hybrid analog and digital beamforming architecture and exploits the temporal correlation of sparse mmWave channel. Under the time varying model from mmMAGIC project, the channel small scale parameters demonstrate smooth variation and such changes can be tracked by significantly reduced beam steering. The developed algorithm achieves significant reduction in estimation overhead and retains up-to-date CSI under UE mobility. In the future, we will model the blockage in mmWave channel and investigate tracking algorithm with consideration of the scatterer birth and death process.

References

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What Will 5G Be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-Wave Enhanced Local Area Systems: A High-Data-Rate Approach for Future Wireless Networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1152–1163, Jun. 2014.

[3] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, pp. 335–349, May 2013.

[4] W. Hong, K. H. Baek, Y. Lee, Y. Kim, and S. T. Ko, "Study and Prototyping of Practically Large-Scale mmWave Antenna Systems for 5G Cellular Devices," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 63–69, Sep. 2014.

[5] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[6] J. He, T. Kim, H. Ghauch, K. Liu, and G. Wang, "Millimeter Wave MIMO Channel Tracking Systems," in *2014 IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 416–421.

[7] K. Gao, M. Cai, D. Nie, B. Hochwald, J. N. Laneman, H. Huang, and K. Liu, "Beampattern-Based Tracking for Millimeter Wave Communication Systems," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec. 2016, pp. 1–6.

[8] J. Bae, S. H. Lim, J. H. Yoo, and J. W. Choi, "New Beam Tracking Technique for Millimeter Wave-band Communications," in *arxiv.org*, Feb. 2017. [Online]. Available: http://arxiv.org/abs/1702.00276

[9] V. Va, H. Vikalo, and R. W. Heath, "Beam Tracking for Mobile Millimeter Wave Communication Systems," in *2016 IEEE GlobalSIP*, Dec. 2016, pp. 743–747.

[10] Z. Marzi, D. Ramasamy, and U. Madhow, "Compressive Channel Estimation and Tracking for Large Arrays in mm-Wave Picocells," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 514–527, Apr. 2016.

[11] J. C. Guey, M. P. Chang, C. H. Yu, and C. C. Su, "Modeling and Evaluation of Beam Tracking in Mobile Millimeter Wave Communication," in *2015 IEEE PIMRC*, Aug. 2015, pp. 775–780.

[12] J. P. Beltran, D. D. Donno, and J. Widmer, "Tracking mm-Wave Channel Dynamics: Fast Beam Training Strategies under Mobility," in *2017 IEEE Infocom*, May 2017.

[13] K. Venugopal, A. Alkhateeb, N. G. Prelcic, and R. W. Heath, "Channel Estimation for Hybrid Architecture Based Wideband Millimeter Wave Systems," *arxiv.org*, 2016. [Online]. Available: http://arxiv.org/abs/1611.03046

[14] J. Rodríguez-Fernández, N. G. Prelcic, K. Venugopal, and R. W. Heath, "Frequency-domain Compressive Channel Estimation for Frequency-Selective Hybrid mmWave MIMO Systems," *arxov.org*, 2017. [Online]. Available: http://arxiv.org/abs/1704.08572

[15] 5GPPP, "mmMAGIC D2.2 Measurement Results and Final mmMAGIC Channel Models," May 2017. [Online]. Available: http://5g-mmmagic.eu

[16] 3GPP, "TR 38.900 Study on Channel Model for Frequency Spectrum above 6 GHz," Sep. 2016. [Online]. Available: http://www.3gpp.org/DynaReport/38900.htm

[17] W. U. Bajwa, J. Haupt, A. M. Sayeed, and R. Nowak, "Compressed Channel Sensing: A New Approach to Estimating Sparse Multipath Channels," *Proc. IEEE*, vol. 98, no. 6, pp. 1058–1076, Jun. 2010.

[18] M. Morelli and U. Mengali, "A comparison of Pilot-Aided Channel Estimation Methods for OFDM Systems," *IEEE Trans. Signal Process.*, vol. 49, no. 12, pp. 3065–3073, Dec. 2001.