Fast Channel Tracking for Terahertz Beamspace Massive MIMO Systems

Xinyu Gao, *Student Member, IEEE*, Linglong Dai, *Senior Member, IEEE*, Yuan Zhang, *Student Member, IEEE*, Tian Xie, *Student Member, IEEE*, Xiaoming Dai, *Member, IEEE*, and Zhaocheng Wang, *Senior Member, IEEE*

***Abstract*—The recent concept of beamspace multiple input multiple output (MIMO) with discrete lens array can utilize beam selection to reduce the number of radio-frequency chains (RF) required in terahertz (THz) massive MIMO systems. However, to achieve the capacity-approaching performance, beam selection requires information on a beamspace channel of large size. This is difficult to obtain since the user mobility usually leads to the fast variation of THz beamspace channels, and the conventional real-time channel estimation schemes involve unaffordable pilot overhead. To solve this problem, in this paper, we propose the *a priori* aided (PA) channel tracking scheme. Specifically, by considering a practical user motion model, we first excavate a temporal variation law of the physical direction between the base station and each mobile user. Then, based on this law and the special sparse structure of THz beamspace channels, we propose to utilize the obtained beamspace channels in the previous time slots to predict the prior information of the beamspace channel in the following time slot without channel estimation. Finally, aided by the obtained prior information, the time-varying beamspace channels can be tracked with low pilot overhead. Simulation results verify that to achieve the same accuracy, the proposed PA channel tracking scheme requires much lower pilot overhead and signal-to-noise ratio (SNR) than the conventional schemes.**

***Index Terms*—Beamspace, channel tracking, massive multiple input multiple output (MIMO), terahertz (THz) communications.**

I. Introduction

THE explosive growth of the data traffic in future wireless communications can be leveraged by exploiting higher unlicensed spectrum band, and terahertz (THz) communication has been considered as a promising solution, since it can provide tens of GHz bandwidth [1]–[3]. However, the severe signal attenuation induced by the extremely high THz frequencies (0.1–10 THz) is still a critical problem [1]. To this end, massive multiple input multiple output (MIMO) with a very large antenna array (e.g., 256 antennas) can be used in THz communications to provide enough array gain to compensate for such severe signal attenuation [4]. Unfortunately, realizing THz massive MIMO is not a trivial task. One of the most challenging problems is that each antenna in the MIMO systems usually requires one dedicated radio-frequency (RF) chain (including digital-to-analog converter, up converter, etc.). This will result in unaffordable hardware cost and energy consumption in THz massive MIMO systems [4], as the number of antennas becomes huge and the energy consumption of RF chain is high [5], [6]. To reduce the number of required RF chains, we can resort to the recently proposed beamspace MIMO with discrete lens array (DLA), which has been successfully employed in millimeter-wave (mmWave) communications [7]. Since both the mmWave and THz signals are quasi-optical, the mmWave MIMO channel and the THz MIMO channel share the similar channel characteristics [4]. As a result, the beamspace MIMO with DLA can be also employed in THz communications. By employing DLA, beamspace MIMO can transform the conventional spatial channel into a beamspace channel by concentrating the signals from different paths (beams) on different antennas [8]. Since the THz signals are quasi-optical [9], the number of effective prorogation paths in THz communications is quite limited [10], [11], occupying only a small number of beams. Therefore, the THz beamspace channel is sparse, and we can select a small number of dominant beams according to the sparse beamspace channel to significantly reduce the dimension of the MIMO systems and the number of required RF chains without obvious performance loss [12]–[15].

Nevertheless, to achieve the capacity-approaching performance, beam selection requires the base station (BS) to obtain the accurate information of the beamspace channel of large size, which is a challenging task. This is mainly caused by the fact that the user mobility usually leads to the fast variation of THz beamspace channels [16]–[18]. If we adopt the conventional real-time channel estimation schemes, the pilot overhead will be unaffordable [19], [20]. Therefore, more efficient channel tracking schemes exploiting the temporal correlation of the time-varying channels are preferred in practice. Existing channel tracking schemes can be divided into two categories. The first category is widely adopted at microwave frequencies, and its key idea is to model the time-varying channels in adjacent time slots by a one-order Markov process, and then the classical Kalman filter can be utilized to track the time-varying channels with low pilot overhead [21], [22]. Unfortunately, this category of schemes cannot be directly extended to THz beamspace massive MIMO systems, since the THz beamspace channels with spe-

Manuscript received March 29, 2016; revised August 13, 2016; accepted September 24, 2016. Date of publication October 4, 2016; date of current version July 14, 2017. This work was supported in part by the National Key Basic Research Program of China under Grant 2013CB329203, in part by the National Natural Science Foundation of China under Grant 61571270 and Grant 61271266, in part by the Beijing Natural Science Foundation under Grant 4142027, and in part by the Foundation of Shenzhen government. The review of this paper was coordinated by Dr. S. Mumtaz.

X. Gao, L. Dai, Y. Zhang, T. Xie, and Z. Wang are with the Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: xy-gao14@mails.tsinghua.edu.cn; daill@tsinghua.edu.cn; zhang.yuan0313@163.com; xiet15@mails.tsinghua.edu.cn; zcwang@tsinghua.edu.cn).

X. Dai is with the School of Computer and Communication Engineering, University of Science and Technology Beijing, Beijing 100030, China (e-mail: daixiaoming@ustb.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2016.2614994

cial sparse structure cannot be modeled by the one-order Markov process. The second category is usually applied at mmWave frequencies, which aims to search several candidate beam pairs for fast channel tracking by a beam training procedure between the BS and the user [23]–[26]. However, this category of schemes is mainly designed for point-to-point scenarios, while for multiuser scenarios, the pilot overhead is still high [27]. To the best of our knowledge, the channel tracking for THz beamspace massive MIMO systems has not been well addressed in the literature.

In this paper, we propose *a priori* aided (PA) channel tracking scheme for the THz beamspace massive MIMO systems.[1] Specifically, by considering a practical user motion model [28], we first excavate a temporal variation law of the physical direction between the BS and each mobile user. After that, by combing the proposed temporal variation law with the special sparse structure of the THz beamspace channels, we propose to utilize the obtained beamspace channels in the previous time slots to predict the prior information, i.e., the support (the index set of nonzero elements in a sparse vector), of the beamspace channel in the following time slot without channel estimation. Finally, with the known supports, the time-varying beamspace channels can be tracked with low pilot overhead. Simulation results verify that to achieve the same accuracy, the proposed PA channel tracking scheme requires much lower pilot overhead and signal-to-noise ratio (SNR) than the conventional schemes.

The rest of the paper is organized as follows. In Section II, the system model of THz beamspace massive MIMO is described. In Section III, we specify the proposed PA channel tracking scheme. Finally, the simulation results are provided in Section IV, and conclusions are drawn in Section V.

Notation: Lower case and upper case boldface letters $\mathbf{a}$ and $\mathbf{A}$ denote a vector and a matrix, respectively; $\mathbf{A}^H$, $\mathbf{A}^{-1}$, and tr$(\mathbf{A})$ denote the conjugate transpose, inversion, and trace of matrix $\mathbf{A}$, respectively; $|a|$ denotes the amplitude of scalar a; Card $(\mathcal{A})$ denotes the cardinality of set $\mathcal{A}$; and finally, $\mathbf{I}_K$ is the $K \times K$ identity matrix.

II. System Model

We consider a typical THz massive MIMO system in this paper, where the BS employs N antennas and $N_{\rm RF}$ RF chains to simultaneously serve K single-antenna users [12]–[15].

A. Traditional MIMO in the Spatial Domain

As shown in Fig. 1(a), for traditional MIMO in the spatial domain, the $K \times 1$ received signal vector $\mathbf{y}$ for all K users in the downlink can be presented as

$$\mathbf{y} = \mathbf{H}^H \mathbf{x} + \mathbf{n} = \mathbf{H}^H \mathbf{P}\mathbf{s} + \mathbf{n} \tag{1}$$

where $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K]$ is the MIMO channel matrix of size $N \times K$; and $\mathbf{h}_k$ of size $N \times 1$ is the channel vector between the BS and the kth user as will be discussed in detail later; $\mathbf{x} = \mathbf{P}\mathbf{s}$ is the $N \times 1$ transmitted signal vector, $\mathbf{s}$ of size $K \times 1$ is the original signal vector for all K users with normalized power $\mathbb{E}\left(\mathbf{s}\mathbf{s}^H\right) = \mathbf{I}_K$; and $\mathbf{P}$ of size $N \times K$ is the precoding matrix satisfying the total transmit power constraint as tr $\left(\mathbf{P}\mathbf{P}^H\right) \le \rho$, where ρ is the total transmit power. Finally, $\mathbf{n} \sim \mathcal{CN}\left(0, \sigma^2 \mathbf{I}_K\right)$ is the $K \times 1$ additive white Gaussian noise (AWGN) vector. It is obvious from Fig. 1(a) that for traditional MIMO systems, the number of required RF chains is $N_{\rm RF} = N$, which is usually large for THz massive MIMO systems, e.g., $N_{\rm RF} = N = 256$ [4].

[1]The simulation codes are provided to reproduce the results in the paper that can be found here: http://oa.ee.tsinghua.edu.cn/dailinglong/

Next, we will introduce the channel vector $\mathbf{h}_k$ of the kth user. In this paper, we adopt the widely used Saleh–Valenzuela channel model for THz communications as [4]

$$\mathbf{h}_k = \beta_k^{(0)} \mathbf{a}\left(\psi_k^{(0)}\right) + \sum_{i=1}^{L} \beta_k^{(i)} \mathbf{a}\left(\psi_k^{(i)}\right) \tag{2}$$

where $\beta_k^{(0)} \mathbf{a}(\psi_k^{(0)})$ is the line-of-sight (LoS) component of the kth user with $\beta_k^{(0)}$ presenting the complex gain and $\psi_k^{(0)}$ denoting the spatial direction, $\beta_k^{(i)} \mathbf{a}(\psi_k^{(i)})$ for $1 \le i \le L$ is the ith non-LoS (NLoS) component of the kth user, L is the total number of NLoS components, and $\mathbf{a}(\psi)$ is the $N \times 1$ array steering vector. For the typical uniform linear array with N antennas, we have

$$\mathbf{a}(\psi) = \frac{1}{\sqrt{N}} \left[e^{-j2\pi\psi m}\right]_{m \in \mathcal{I}(N)} \tag{3}$$

where $\mathcal{I}(N) = \{l - (N-1)/2,\ l = 0, 1, \ldots, N-1\}$ is a symmetric set of indices centered around zero. The spatial direction is defined as $\psi \triangleq \frac{d}{\lambda} \sin\theta$ [7], where θ is the physical direction, λ is the signal wavelength, and d is the antenna spacing that usually satisfies $d = \lambda/2$. Note that the scattering at THz frequencies induces more than 20 dB attenuation, which means that almost only the LoS component can be used for reliable high-rate transmission in THz communications [10]. Therefore, in this paper, we mainly consider the channel with only LoS component as $\mathbf{h}_k = \beta_k \mathbf{a}(\psi_k)$, where the subscript (0) is omitted for simplification. It is also worth pointing out that the performance loss induced by the consideration that only LoS component exists is negligible, since the number of NLoS components is quite limited and the power of NLoS components is much weaker (more than 20 dB) than that of LoS component in THz communications [4], [29].

B. Beamspace MIMO

The conventional spatial channel (2) can be transformed to the beamspace channel by a carefully designed DLA [7] in the beamspace MIMO systems, as shown in Fig. 1(b). Essentially, such DLA plays the role of an $N \times N$ spatial discrete Fourier transform matrix $\mathbf{U}$, which contains the array steering vectors of N orthogonal directions (beams) covering the entire space as

$$\mathbf{U} = \left[\mathbf{a}\left(\bar{\psi}_1\right), \mathbf{a}\left(\bar{\psi}_2\right), \ldots, \mathbf{a}\left(\bar{\psi}_N\right)\right]^H \tag{4}$$

where $\bar{\psi}_n = \frac{1}{N}(n - \frac{N+1}{2})$ for $n = 1, 2, \ldots, N$ are the spatial directions predefined by DLA. Then, according to Fig. 1(b), the system model of THz beamspace massive MIMO can be represented by

$$\tilde{\mathbf{y}} = \mathbf{H}^H \mathbf{U}^H \mathbf{P}\mathbf{s} + \mathbf{n} = \tilde{\mathbf{H}}^H \mathbf{P}\mathbf{s} + \mathbf{n} \tag{5}$$

where $\tilde{\mathbf{y}}$ is the received signal vector in the beamspace, and the beamspace channel $\tilde{\mathbf{H}}$ is defined as

$$\tilde{\mathbf{H}} = \left[\tilde{\mathbf{h}}_1, \tilde{\mathbf{h}}_2, \ldots, \tilde{\mathbf{h}}_K\right] = \mathbf{U}\mathbf{H} = [\mathbf{U}\mathbf{h}_1, \mathbf{U}\mathbf{h}_2, \ldots, \mathbf{U}\mathbf{h}_K] \tag{6}$$

where $\tilde{\mathbf{h}}_k$ is the beamspace channel of the kth user. In (6), the N rows (elements) of $\tilde{\mathbf{H}}$ ($\tilde{\mathbf{h}}_k$) correspond to N orthogonal beams

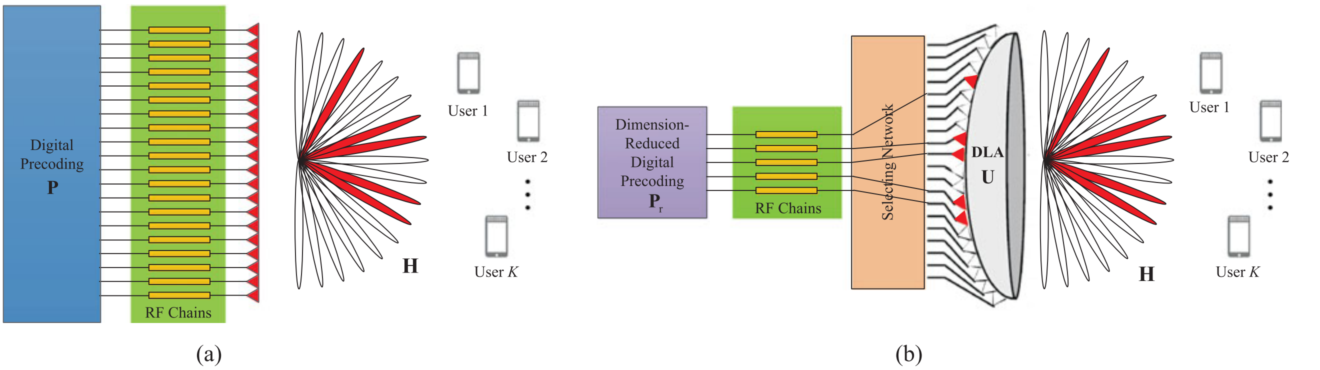


Fig. 1. Comparison of MIMO system architectures. (a) Traditional MIMO in the spatial domain and (b) beamspace MIMO.

whose spatial directions are $\bar{\psi}_1, \bar{\psi}_2, \ldots, \bar{\psi}_N$, respectively. Since almost only the LoS component can be used for reliable high-rate transmission in THz communications [10], the beamspace channel $\tilde{\mathbf{H}}$ ($\tilde{\mathbf{h}}_k$) at THz frequencies enjoys a sparse structure [7]. Therefore, we can select only a small number of dominant beams according to the sparse beamspace channel to reduce the dimension of the MIMO systems without obvious performance loss as

$$\tilde{\mathbf{y}} \approx \tilde{\mathbf{H}}_{\mathrm{r}}^H \mathbf{P}_{\mathrm{r}} \mathbf{s} + \mathbf{n} \tag{7}$$

where $\tilde{\mathbf{H}}_{\mathrm{r}} = \tilde{\mathbf{H}}(s,:)_{s\in\mathcal{B}}$, $\mathcal{B}$ contains the indices of selected beams, $\mathbf{P}_{\mathrm{r}}$ is the dimension-reduced digital precoding matrix. As the dimension of $\mathbf{P}_{\mathrm{r}}$ in (7) is much smaller than that of $\mathbf{P}$ in (1), beamspace MIMO can significantly reduce the number of required RF chains, as shown in Fig. 1(b). Note that the smallest number of required RF chains should be $N_{\mathrm{RF}} = K$ to guarantee the spatial multiplexing gains of K users. Therefore, we consider $N_{\mathrm{RF}} = K$ without the loss of generality in this paper.

However, beam selection requires the BS to obtain the accurate information of the beamspace channel of large size. This is not a trivial task, since the user mobility usually leads to the fast variation of THz beamspace channels, and the conventional real-time channel estimation schemes involve unaffordable pilot overhead [19]. Therefore, a more efficient channel tracking scheme, which can exploit the temporal correlation of the time-varying channels, is preferred for practical THz beamspace massive MIMO systems.

III. Beamspace Channel Tracking

In this section, we first excavate a temporal variation law of the physical direction of each mobile user by considering a practical user motion model. Then, we propose to use the physical direction to obtain the prior information, i.e., the support, of sparse beamspace channel without channel estimation. Finally, a PA channel tracking scheme is proposed to track the time-varying beamspace channels with low pilot overhead.

A. Temporal Variation Law of the Physical Direction

Our target is to track the beamspace channel $\tilde{\mathbf{h}}_k$ of user k, and the similar method can be directly applied to other users. As shown in (2)–(4), for the beamspace channel $\tilde{\mathbf{h}}_k$, the physical direction θ_k (or equivalently, the spatial direction ψ_k) of the LoS component is a crucial parameter. Therefore, if we can exploit the temporal variation law of the physical direction, $\tilde{\mathbf{h}}_k$ can be tracked with low pilot overhead.

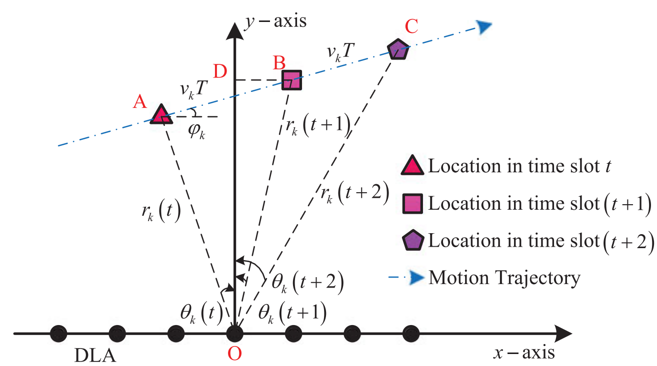


Fig. 2. Geometrical relationship between the DLA at BS and the kth mobile user.

To this end, in this paper we consider a linear user motion model [28]. Without loss of generality, we set the center of the DLA at BS as the origin, and assume that the directions parallel and vertical to DLA are the x-axis and the y-axis, respectively. Then, the geometrical relationship between the DLA and the kth mobile user can be represented in Fig. 2, where $r_k(t)$ and $\theta_k(t)$ are the distance and physical direction[2] between the DLA and the kth user in the tth time slot, respectively; T is the time slot interval; and v_k and φ_k are the motion speed and motion direction of the kth user, respectively, which are unknown but not time varying as we consider that each user moves linearly and uniformly in the linear user motion model.[3] We define a motion state vector $\mathbf{m}_k(t) \triangleq [\theta_k(t), \lambda_k(t), \varphi_k]^T$ to describe the motion feature of user k in time slot t, where $\lambda_k(t) \triangleq \frac{v_k}{r_k(t)}$ can be regarded as the angular speed. Then, based on the geometrical relationship as illustrated in Fig. 2, we have *Lemma 1*.

Lemma 1: The relationship between $\mathbf{m}_k(t)$ and $\mathbf{m}_k(t+1)$ can be presented as

$$\begin{aligned}\mathbf{m}_k(t+1) &= \Theta(\mathbf{m}_k(t)) \\ &= \begin{bmatrix} \arctan\left\{\frac{\sin[\theta_k(t)]+T\lambda_k(t)\cos\varphi_k}{\cos[\theta_k(t)]+T\lambda_k(t)\sin\varphi_k}\right\} \\ \frac{\lambda_k(t)}{\sqrt{1+2T\lambda_k(t)\sin[\theta_k(t)+\varphi_k]+T^2\lambda_k^2(t)}} \\ \varphi_k \end{bmatrix}\end{aligned} \tag{8}$$

[2] In this paper, if the user is located on the left side of the origin, the physical direction is considered as negative, i.e., $\theta_k(t) < 0$.

[3] In Section III-C, we will show that the proposed PA channel tracking scheme can be also employed for nonlinear user motion model with time-varying motion speed.

where $\Theta\left(\mathbf{m}_k\left(t\right)\right)$ *is a function of* $\mathbf{m}_k\left(t\right)$.

Proof: At first, we focus on the physical direction $\theta_k\left(t\right)$. By considering the triangle OBD in Fig. 2, we have

$$\begin{aligned}\tan\left(\theta_k\left(t+1\right)\right) &= \frac{r_k\left(t\right)\sin\left[\theta_k\left(t\right)\right]+v_kT\cos\varphi_k}{r_k\left(t\right)\cos\left[\theta_k\left(t\right)\right]+v_kT\sin\varphi_k}\\ &\overset{(a)}{=} \frac{\sin\left[\theta_k\left(t\right)\right]+T\lambda_k\left(t\right)\cos\varphi_k}{\cos\left[\theta_k\left(t\right)\right]+T\lambda_k\left(t\right)\sin\varphi_k}\end{aligned} \tag{9}$$

where (a) is true due to the definition $\lambda_k\left(t\right)=\frac{v_k}{r_k(t)}$. From (9), we can conclude that

$$\theta_k\left(t+1\right)=\arctan\left\{\frac{\sin\left[\theta_k\left(t\right)\right]+T\lambda_k\left(t\right)\cos\varphi_k}{\cos\left[\theta_k\left(t\right)\right]+T\lambda_k\left(t\right)\sin\varphi_k}\right\}. \tag{10}$$

Next, we consider the angular speed $\lambda_k\left(t\right)$. By utilizing the law of cosine in the triangle OAB in Fig. 2, we have

$$\cos\left[\frac{\pi}{2}+\theta_k\left(t\right)+\varphi_k\right]=\frac{r_k^2\left(t\right)+\left(v_kT\right)^2-r_k^2\left(t+1\right)}{2v_kTr_k\left(t\right)}. \tag{11}$$

Substituting $\lambda_k\left(t\right)=\frac{v_k}{r_k(t)}$ into (11) and utilizing the fact that $\cos[\frac{\pi}{2}+\theta_k(t)+\varphi_k]=-\sin[\theta_k(t)+\varphi_k]$, we have

$$\begin{aligned}\sin\left[\theta_k\left(t\right)+\varphi_k\right] &= \frac{r_k^2\left(t+1\right)-r_k^2\left(t\right)-\left(v_kT\right)^2}{2v_kTr_k\left(t\right)}\\ &= \frac{\frac{r_k^2(t+1)}{r_k^2(t)}-1-T^2\lambda_k^2\left(t\right)}{2T\lambda_k\left(t\right)}\\ &= \frac{\frac{\lambda_k^2(t)}{\lambda_k^2(t+1)}-1-T^2\lambda_k^2\left(t\right)}{2T\lambda_k\left(t\right)}.\end{aligned} \tag{12}$$

Rewriting (12), we can conclude that

$$\lambda_k\left(t+1\right)=\frac{\lambda_k\left(t\right)}{\sqrt{1+2T\lambda_k\left(t\right)\sin\left[\theta_k\left(t\right)+\varphi_k\right]+T^2\lambda_k^2\left(t\right)}}. \tag{13}$$

Combining (10), (13), and the fact that the motion direction φ_k is not time varying, we can obtain the conclusion (8). ■

After the relationship between $\mathbf{m}_k\left(t\right)$ and $\mathbf{m}_k\left(t+1\right)$ has been found, to excavate the temporal variation law of the physical direction, we still need to reformulate $\lambda_k\left(t\right)$ and φ_k in $\mathbf{m}_k\left(t\right)$ by the physical direction. To this end, we can observe the triangles OAB and OAC in Fig. 2. Then, by using the law of sine, we have the following two groups of equations as

$$\begin{cases}\lambda_k\left(t+1\right)=\dfrac{v_k}{d_k\left(t+1\right)}=\dfrac{\sin\left[\theta_k\left(t+1\right)-\theta_k\left(t\right)\right]}{T\cos\left[\theta_k\left(t\right)+\varphi_k\right]}\\ \lambda_k\left(t\right)=\dfrac{v_k}{d_k\left(t\right)}=\dfrac{\sin\left[\theta_k\left(t+1\right)-\theta_k\left(t\right)\right]}{T\cos\left[\theta_k\left(t+1\right)+\varphi_k\right]}\end{cases} \tag{14}$$

$$\begin{cases}\lambda_k\left(t+2\right)=\dfrac{v_k}{r_k\left(t+2\right)}=\dfrac{\sin\left[\theta_k\left(t+2\right)-\theta_k\left(t\right)\right]}{2T\cos\left[\theta_k\left(t\right)+\varphi_k\right]}\\ \lambda_k\left(t\right)=\dfrac{v_k}{r_k\left(t\right)}=\dfrac{\sin\left[\theta_k\left(t+2\right)-\theta_k\left(t\right)\right]}{2T\cos\left[\theta_k\left(t+2\right)+\varphi_k\right]}.\end{cases} \tag{15}$$

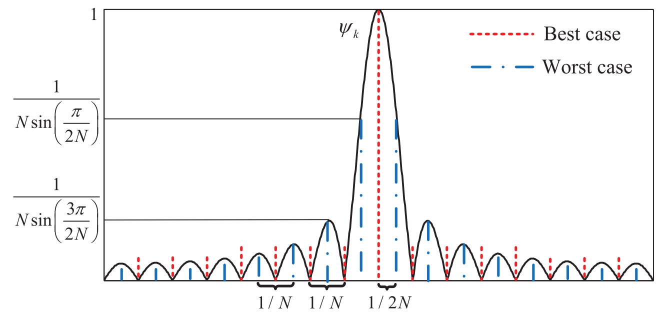


Fig. 3. Normalized amplitude distribution of the elements in $\tilde{\mathbf{h}}_k$.

According to (14) and (15), we have

$$\lambda_k\left(t+2\right)=\frac{\sin\left[\theta_k\left(t+2\right)-\theta_k\left(t\right)\right]}{2T\cos\left[\theta_k\left(t\right)+\varphi_k\right]} \tag{16}$$

$$\varphi_k=\frac{2a_k\cos\left[\theta_k\left(t+2\right)\right]-b_k\cos\left[\theta_k\left(t+1\right)\right]}{2a_k\sin\left[\theta_k\left(t+2\right)\right]-b_k\sin\left[\theta_k\left(t+1\right)\right]} \tag{17}$$

where we define $a_k\triangleq\sin[\theta_k(t+1)-\theta_k(t)]$ and $b_k\triangleq\sin[\theta_k(t+2)-\theta_k(t)]$.

Based on (16), (17), and the relationship $\mathbf{m}(t+3)=\Theta(\mathbf{m}(t+2))$ in *Lemma 1*, we can conclude that once we have estimated the physical directions in time slots t, $(t+1)$, and $(t+2)$, the physical direction in the following time slot $(t+3)$ can be predicted in advance without channel estimation.

B. Support of THz Beamspace Channel

In this section, we propose to use the physical direction to obtain the support of the THz beamspace channel without channel estimation. This is achieved by exploiting the special sparse structure of the THz beamspace channels, which is proved in *Lemma 2*.

Lemma 2: Consider the beamspace channel $\tilde{\mathbf{h}}_k$ of user k, and assume V is an even integer without loss of generality. The ratio between the power P_V of V strongest elements of $\tilde{\mathbf{h}}_k$ and the total channel power P_T can be lower-bounded by

$$\frac{P_V}{P_T}\geq\frac{2}{N^2}\sum_{i=1}^{V/2}\frac{1}{\sin^2\left(\frac{(2i-1)\pi}{2N}\right)}. \tag{18}$$

Moreover, once the position n_k^* *of the strongest element of* $\tilde{\mathbf{h}}_k$ *is determined, the other* $V-1$ *strongest elements will uniformly locate around it.*

Proof: Based on (2)–(6), the beamspace channel $\tilde{\mathbf{h}}_k$ can be presented as

$$\tilde{\mathbf{h}}_k=\beta_k\left[\Upsilon\left(\bar{\psi}_1-\psi_k\right),\ldots,\Upsilon\left(\bar{\psi}_N-\psi_k\right)\right]^H \tag{19}$$

where $\Upsilon\left(x\right)\triangleq\frac{\sin N\pi x}{N\sin\pi x}$. Fig. 3 shows the normalized amplitude (without β_k) distribution of the elements in $\tilde{\mathbf{h}}_k$, where the set of red dash lines (or blue dot dash lines) presents the spatial directions $\bar{\psi}_n=\frac{1}{N}(n-\frac{N+1}{2})$ for $n=1,2,\ldots,N$ predefined by DLA. From Fig. 3, we can observe that when the practical spatial direction ψ_k is exactly equal to one predefined spatial direction, there is only one strongest element containing all the power of $\tilde{\mathbf{h}}_k$, which is the best case. In contrast, the worst case happens when the distance between ψ_k and one predefined spatial direction equals to $1/2N$. In this case, the power P_V of V strongest elements of $\tilde{\mathbf{h}}_k$ is

$$P_V = \frac{2\beta_k^2}{N^2} \sum_{i=1}^{V/2} \frac{1}{\sin^2\left(\frac{(2i-1)\pi}{2N}\right)}. \quad (20)$$

Besides, according to (19), the total power P_T of $\tilde{\mathbf{h}}_k$ can be calculated as

$$P_T = \tilde{\mathbf{h}}_k^H \tilde{\mathbf{h}}_k = \beta_k^2. \quad (21)$$

Based on (20) and (21), we can conclude that P_V/P_T is lower bounded by (18). Moreover, as we can also observe from Fig. 3, once the position n_k^* of the strongest element of $\tilde{\mathbf{h}}_k$ is determined, the other $V-1$ strongest elements will uniformly locate around it. ■

From *Lemma 2*, we can derive two conclusions. The first one is that $\tilde{\mathbf{h}}_k$ can be considered as a sparse vector, since the most power of $\tilde{\mathbf{h}}_k$ is focused on a small number of dominant elements. For example, when $N = 256$ and $V = 16$, the lower bound of P_V/P_T is about 98%. The second one is that the support of $\tilde{\mathbf{h}}_k$ can be uniquely determined by n_k^* as[4]

$$\text{supp}\left(\tilde{\mathbf{h}}_k\right) = \text{mod}_N \left\{ n_k^* - \frac{V}{2}, \ldots, n_k^* + \frac{V-2}{2} \right\} \quad (22)$$

where $\text{Card}(\text{supp}(\tilde{\mathbf{h}}_k)) = V$, and $\text{mod}_N(\cdot)$ is the modulo operation with respect to N, which guarantees that all indices in $\text{supp}(\tilde{\mathbf{h}}_k)$ belong to $\{1, 2, \ldots, N\}$.

It is worth pointing out that n_k^* depends on ψ_k (or θ_k) as we have discussed in *Lemma 2*. Based on (2) and (4), the corresponding relationship can be presented as

$$n_k^* = \arg\min_{1\le n\le N} \left|\bar{\psi}_n - \psi_k\right| = \arg\min_{1\le n\le N} \left|\bar{\psi}_n - \frac{d}{\lambda}\sin\theta_k\right|. \quad (23)$$

Therefore, once we have obtained the physical direction θ_k, the support $\text{supp}(\tilde{\mathbf{h}}_k)$ of the beamspace channel $\tilde{\mathbf{h}}_k$ can be directly detected according to (22) and (23) without channel estimation.

C. PA Channel Tracking Scheme

Based on the conclusions derived above, the PA channel tracking scheme is proposed. Its key idea is to utilize the estimated physical directions in the previous time slots to predict the one in the following time slot. Then, utilizing the predicted physical direction, we can obtain the support of the beamspace channel in the following time slot without channel estimation. Finally, with the known supports, we can track the time-varying beamspace channels with low pilot overhead. The pseudocode of the proposed PA channel tracking scheme can be summarized in *Algorithm 1*,[5] which is divided into two parts. Next, we will explain each part in details.

[4]Correspondingly, when V is odd, the support of $\tilde{\mathbf{h}}_k$ should be $\text{supp}\left(\tilde{\mathbf{h}}_k\right) = \text{mod}_N \left\{ n_k^* - \frac{V-1}{2}, \ldots, n_k^* + \frac{V-1}{2} \right\}$.

[5]Note that the proposed PA channel tracking scheme can be directly extended to mmWave massive MIMO systems, since the mmWave MIMO channel is similar to THz MIMO channel [4]. For the conventional massive MIMO systems at cellular frequencies (e.g., 2–3 GHz), the proposed PA channel tracking scheme can be used as an initial solution to simplify the conventional channel estimation schemes [19], [30].

Algorithm 1: The proposed PA channel tracking scheme.

for $1 \le t \le 3$ *Conventional channel estimation*
1) Estimate the beamspace channel $\tilde{\mathbf{h}}_k(t)$;
2) Approximate the physical direction $\theta_k(t)$ as
$\theta_k(t) \approx \arcsin\frac{\lambda}{Nd}\left(n_k^*(t) - \frac{(N+1)}{2}\right)$;
end for
for $t > 3$ *Channel tracking*
3) Predict $\theta_k(t)$ using $\theta_k(t-3)$, $\theta_k(t-2)$, and $\theta_k(t-1)$;
4) Detect $\text{supp}(\tilde{\mathbf{h}}_k(t))$ according to (22) and (23);
5) Estimate the nonzero elements of $\tilde{\mathbf{h}}_k(t)$;
6) Refine the physical direction $\theta_k(t)$ based on $n_k^*(t)$;
end for

The first part is the conventional channel estimation in the first three time slots. During the first part, $\tilde{\mathbf{h}}_k(t)$ is estimated in step 1 using conventional beamspace channel estimation schemes, such as the one proposed in [27]. Based on the estimated channel, we can obtain the position $n_k^*(t)$ of the strongest element. Then, in step 2, utilizing the relationship in (23), the spatial direction $\psi_k(t)$ can be approximated as

$$\psi_k(t) \approx \bar{\psi}_{n_k^*(t)}. \quad (24)$$

Substituting $\psi_k(t) = \frac{d}{\lambda}\sin\theta_k(t)$ (3) into (24), we can equivalently approximate the physical direction $\theta_k(t)$ as

$$\theta_k(t) \approx \arcsin\frac{\lambda}{d}\bar{\psi}_{n_k^*(t)} \overset{(a)}{=} \arcsin\frac{\lambda}{Nd}\left(n_k^*(t) - \frac{(N+1)}{2}\right) \quad (25)$$

where (a) is due to the definitions in (4).

After the physical directions in the first three time slots have been obtained, the channel tracking in the second part can be executed. Specifically, in step 3, we first utilize $\theta_k(t-3)$, $\theta_k(t-2)$, and $\theta_k(t-1)$ to predict $\theta_k(t)$ based on (16), (17), and *Lemma 1*. After that, in step 4, we can detect the support of $\tilde{\mathbf{h}}_k(t)$ according to (22) and (23) without channel estimation. Then, the nonzero elements of $\tilde{\mathbf{h}}_k(t)$ are estimated in step 5. To do this, the user k should transmit Q known pilots to the BS over a total of Q instants within the time slot interval, and $\tilde{\mathbf{h}}_k(t)$ is considered to remain unchanged within the Q instants. Since the BS employs $N_{\text{RF}} = K$ RF chains for each instant, we can utilize the selecting network as shown in Fig. 1(b) to select K beams according to $\text{supp}(\tilde{\mathbf{h}}_k(t))$, and directly estimate K corresponding nonzero elements of $\tilde{\mathbf{h}}_k(t)$ using the classical least-squares algorithm. As a result, the smallest number of instants required to completely estimate $\tilde{\mathbf{h}}_k(t)$ with $\text{Card}(\text{supp}(\tilde{\mathbf{h}}_k)) = V$ nonzero elements is only V/K. It is worth pointing out that V is much smaller than the number of antennas N as proved in *Lemma 2*. Therefore, step 5 involves quite low pilot overhead. Finally, after $\tilde{\mathbf{h}}_k(t)$ has been tracked, the physical direction $\theta_k(t)$ is further refined by $n_k^*(t)$ based on (25) for two reasons: 1) the impact of error propagation induced by the approximation in step 2 can be avoided; 2) the proposed PA channel tracking scheme can be employed in a nonlinear user motion model with time-varying motion speed, since the deviation induced by the prediction in step 3 can be adaptively modified when the motion direction φ_k or motion speed v_k have changed. In the end, it should be pointed out that sometimes the LoS path may be unavailable due to blockage. In this case, we can model the physical directions

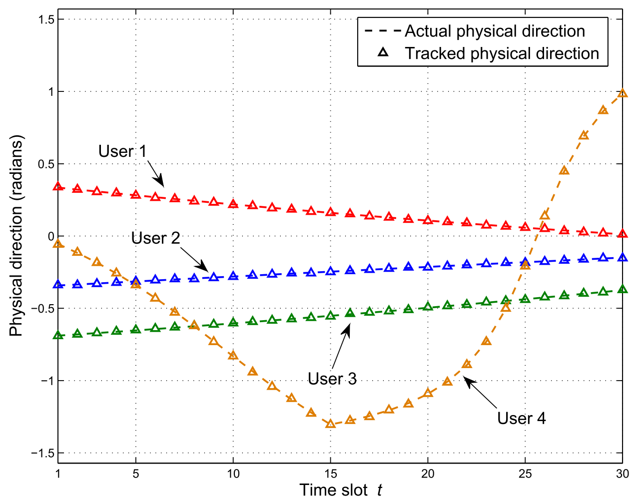


Fig. 4. Physical direction tracking accuracy.

of an NLoS path in two adjacent time slots by the one-order Markov process. Then, the scheme proposed in [31] can be used as an alternative to track the time-varying channels.

IV. Simulation Results

In this section, we consider a typical THz beamspace massive MIMO system, where the BS equips an $N = 256$-element DLA with $d = \lambda/2$ and $N_{\mathrm{RF}} = 4$ RF chains to simultaneously serve $K = 4$ users. For each user in each time slot, we regard the beamspace channel as a sparse vector with sparsity $V = 16$, and assume that the complex channel gain follows $\mathcal{CN}(0,1)$. We totally observe 30 time slots with the time slot interval $T = 1$. The motion states of users 1–3 in the initial time slot 1 are set as $\mathbf{m}_1(1) = \left[\frac{\pi}{9}, 0.0154, \frac{3\pi}{4}\right]^T$, $\mathbf{m}_2(1) = \left[-\frac{\pi}{9}, 0.0071, \frac{\pi}{6}\right]^T$, and $\mathbf{m}_3(1) = \left[-\frac{2\pi}{9}, 0.0114, 0\right]^T$, respectively. For user 4, we consider a nonlinear motion model, with $\mathbf{m}_4(1) = \left[0, 0.074, \frac{-3\pi}{4}\right]^T$ in time slots 1–15 and $\mathbf{m}_4(16) = \left[\theta_1(16), \lambda_1(16), 0\right]^T$ in time slots 16–30.

Fig. 4 shows the physical direction tracking accuracy of the proposed PA channel tracking scheme, where the SNR is set as 10 dB. In the first three time slots, we adopt the orthogonal matching pursuit (OMP) channel estimation scheme proposed in [27] to estimate the beamspace channel with $Q = 128$ pilots per time slot. After that, the beamspace channel is tracked by *Algorithm 1* with only $Q = (V/K)K = 16$ pilots per time slot. We can observe from Fig. 4 that the proposed PA channel tracking scheme can track the physical directions of all users accurately with low pilot overhead, where the deviation between the tracked physical direction and the actual physical direction is negligible, even for user 4 who moves nonlinearly with time-varying motion speed.

Fig. 5 compares the normalized mean square error (NMSE) performance between the proposed PA channel tracking scheme and the conventional real-time OMP channel estimation scheme [27]. For fair comparison, we set $Q = 16$ pilots per time slot for both of the two schemes. From Fig. 5, we can observe that the proposed PA channel tracking scheme can achieve much better NMSE performance than the conventional OMP channel estimation scheme. For example, when SNR = 10 dB, the NMSE achieved by PA channel tracking scheme is

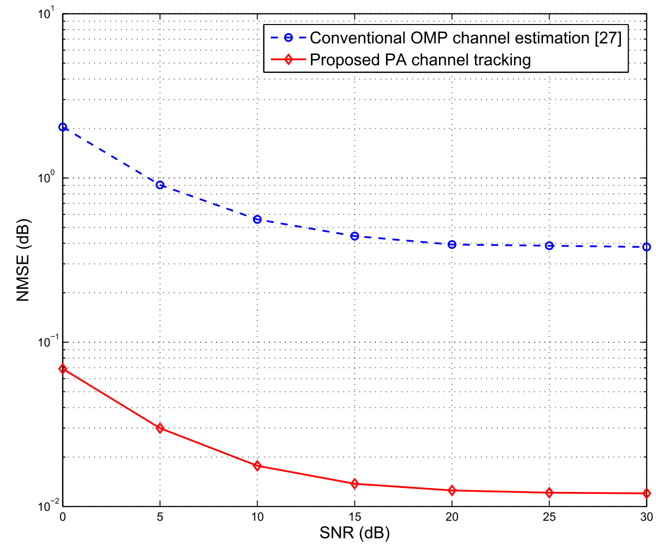


Fig. 5. NMSE performance comparison against SNR.

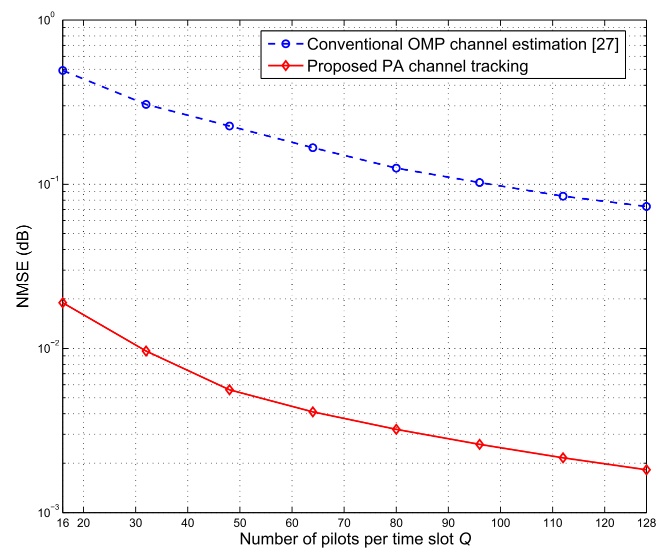


Fig. 6. NMSE performance comparison against pilot overhead.

about 2×10^{-2}, while OMP channel estimation scheme can only achieve the NMSE of 6×10^{-1}. This can be explained by the fact that the proposed PA channel tracking scheme can fully exploit the temporal variation law of the physical direction to accurately acquire the supports of time-varying THz beamspace channels in advance.

Fig. 6 further shows the NMSE performance comparison against pilot overhead, where the SNR is set as 10 dB. From Fig. 6, we can observe that to achieve the same accuracy, the number of pilots per time slot Q required by the proposed PA channel tracking scheme is much lower than the one required by the conventional OMP channel estimation scheme, which means that the proposed PA channel tracking scheme can efficiently track the time-varying beamspace channels with low pilot overhead.

Finally, we will evaluate the impact of PA channel tracking scheme on beam selection. We adopt the maximization of capacity (MC) beam selection proposed in [14] as it can support

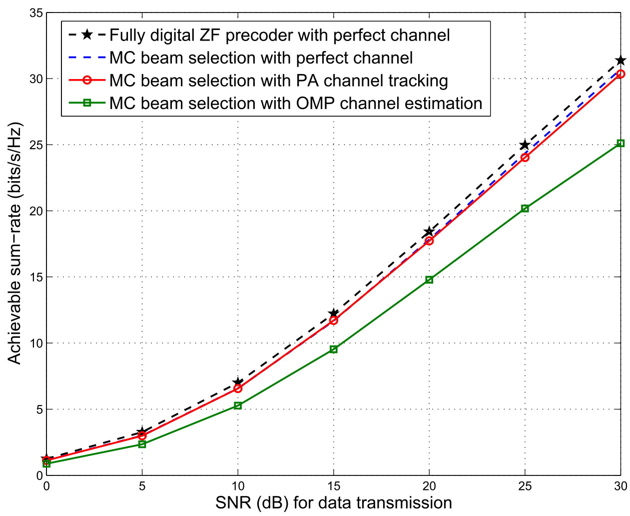


Fig. 7. Sum-rate performance of MC beam selection with different channels.

the $N_{\mathrm{RF}} = K$ scenario, and the dimension-reduced digital precoder $\mathbf{P}_{\mathrm{r}}$ in (7) is selected as the zero-forcing (ZF) precoder. Fig. 7 provides the sum-rate performance of the MC beam selection with different channels, where the performance of the fully digital ZF precoder using all beams (256 RF chains) with perfect channel is also included as the benchmark for comparison. For both PA channel tracking scheme and OMP channel estimation scheme, we set SNR $=$ 10 dB and $Q = 16$ pilots per time slot. From Fig. 7, we can observe that by utilizing the proposed PA channel tracking scheme, MC beam selection can achieve better performance, which is quite close to the one with perfect channel. In contrast, MC beam selection with OMP channel estimation suffers from serious performance loss. For example, when the SNR for data transmission is 30 dB, the sum-rate performance gap between the MC beam selection with OMP channel estimation and the MC beam selection with perfect channel is about 5 bits/s/Hz. More importantly, we can observe that the MC beam selection with PA channel tracking scheme, which only requires 16 RF chains, can achieve the sum-rate performance quite close to the fully digital ZF precoder using 256 RF chains with perfect channel. Therefore, we can conclude that the proposed PA channel tracking scheme is attractive for THz beamspace massive MIMO systems.

V. Conclusion

In this paper, we propose a PA channel tracking scheme for THz beamspace massive MIMO systems. Specifically, we first excavate a temporal variation law of the physical direction. Then, based on this law and the special sparse structure of THz beamspace channels, we propose to utilize the obtained beamspace channels in the previous time slots to predict the support of the beamspace channel in the following time slot without channel estimation. Finally, with the known supports, the time-varying beamspace channels can be tracked with low pilot overhead. Simulation results verify that the proposed PA channel tracking scheme can accurately track the time-varying physical directions with low pilot overhead for both linear and nonlinear user motion model. Moreover, to achieve the same NMSE performance, PA channel tracking scheme requires much lower pilot overhead and SNR than the conventional OMP channel estimation scheme, which makes it attractive for THz beamspace massive MIMO systems.

References

[1] H.-J. Song and T. Nagatsuma, "Present and future of terahertz communications," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 256–263, Sep. 2011.

[2] I. Akyildiz, J. M. Jornet, and C.-C. Han, "TeraNets: Ultra-broadband communication networks in the terahertz band," *IEEE Wireless Commun.*, vol. 21, no. 4, pp. 130–135, Aug. 2014.

[3] I. Hosako *et al.*, "At the dawn of a new era in terahertz technology," *Proc. IEEE*, vol. 95, no. 8, pp. 1611–1623, Aug. 2007.

[4] C. Lin and G. Y. Li, "Indoor terahertz communications: How many antenna arrays are needed?" *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3097–3107, Jun. 2015.

[5] X. Gao, L. Dai, S. Han, C.-L. I, and R. W. Heath, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[6] A. Alkhateeb, J. Mo, N. González-Prelcic, and R. Heath, "MIMO precoding and combining solutions for millimeter-wave systems," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 122–131, Dec. 2014.

[7] J. Brady, N. Behdad, and A. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, Jul. 2013.

[8] Y. Zeng and R. Zhang, "Millimeter wave MIMO with lens antenna array: A new path division multiplexing paradigm," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1557–1571, Apr. 2016.

[9] R. Piesiewicz *et al.*, "Short-range ultra-broadband terahertz communications: Concepts and perspectives," *IEEE Antennas Propag. Mag.*, vol. 49, no. 6, pp. 24–39, Dec. 2007.

[10] C. Han, A. O. Bicen, and I. F. Akyildiz, "Multi-ray channel modeling and wideband characterization for wireless communications in the terahertz band," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2402–2412, May 2015.

[11] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3211–3221, Oct. 2011.

[12] X. Gao, L. Dai, Z. Chen, Z. Wang, and Z. Zhang, "Near-optimal beam selection for beamspace mmWave massive MIMO systems," *IEEE Commun. Lett.*, vol. 20, no. 5, pp. 1054–1057, May 2016.

[13] A. Sayeed and J. Brady, "Beamspace MIMO for high-dimensional multiuser communication at millimeter-wave frequencies," in *Proc. IEEE Global Commun. Conf.*, Dec. 2013, pp. 3679–3684.

[14] P. Amadori and C. Masouros, "Low RF-complexity millimeter-wave beamspace-MIMO systems by beam selection," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2212–2222, Jun. 2015.

[15] J. Brady and A. Sayeed, "Beamspace MU-MIMO for high-density gigabit small cell access at millimeter-wave frequencies," in *Proc. IEEE 15th Int. Workshop Signal Process. Adv. Wireless Commun.*, Jun. 2014, pp. 80–84.

[16] S. Mumtaz *et al.*, "Cognitive vehicular communication for 5G," *IEEE Commun. Mag.*, vol. 53, no. 7, pp. 109–117, Jul. 2015.

[17] S. Mumtaz, S. Huq, K. Mohammed, and J. Rodriguez, "Direct mobile-to-mobile communication: Paradigm for 5G," *IEEE Wireless Commun.*, vol. 21, no. 5, pp. 14–23, Oct. 2014.

[18] L. Dai, Z. Wang, and Z. Yang, "Spectrally efficient time-frequency training OFDM for mobile large-scale MIMO systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 251–263, Feb. 2013.

[19] Z. Gao, L. Dai, Z. Wang, and S. Chen, "Spatially common sparsity based adaptive channel estimation and feedback for FDD massive MIMO," *IEEE Trans. Signal Process.*, vol. 63, no. 23, pp. 6169–6183, Dec. 2015.

[20] L. Dai, J. Wang, Z. Wang, P. Tsiaflakis, and M. Moonen, "Time domain synchronous OFDM based on simultaneous nanonet multi-channel reconstruction," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2013, pp. 2984–2989.

[21] O. Mehanna and N. Sidiropoulos, "Channel tracking and transmit beamforming with frugal feedback," *IEEE Trans. Signal Process.*, vol. 62, no. 24, pp. 6402–6413, Dec. 2014.

[22] N. Kabaoğlu, "Target tracking using particle filters with support vector regression," *IEEE Trans. Veh. Technol.*, vol. 58, no. 5, pp. 2569–2573, Jun. 2009.

[23] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013.

[24] J. Wang *et al.*, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1390–1399, Oct. 2009.

[25] M. Cudak, T. Kovarik, T. A. Thomas, A. Ghosh, Y. Kishiyama, and T. Nakamura, "Experimental mmWave 5G cellular system," in *Proc. IEEE Globecom Workshops*, Dec. 2014, pp. 377–381.

[26] Z. Xiao, T. He, P. Xia, and X.-G. Xia, "Hierarchical codebook design for beamforming training in millimeter-wave communication," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3380–3392, May 2016.

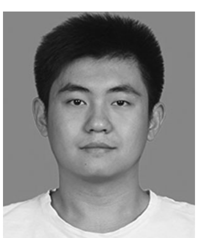
[27] R. Mendez-Rial, C. Rusu, A. Alkhateeb, N. González-Prelcic, and R. W. Heath, "Channel estimation and hybrid combining for mmWave: Phase shifters or switches?" in *Proc. Inf. Theory Appl. Workshops*, Feb. 2015, pp. 90–97.

[28] Y. Zhou, P. C. Yip, and H. Leung, "Tracking the direction-of-arrival of multiple moving targets by passive arrays: Algorithm," *IEEE Trans. Signal Process.*, vol. 47, no. 10, pp. 2655–2666, Oct. 1999.

[29] C. Lin and G. Y. Li, "Antenna subarray partitioning with interference cancellation multi-user indoor terahertz communications," in *Proc. IEEE Global Commun. Conf.*, Dec. 2015, pp. 1–6.

[30] Z. Gao, L. Dai, Z. Lu, C. Yuen, and Z. Wang, "Super-resolution sparse MIMO-OFDM channel estimation based on spatial and temporal correlations," *IEEE Commun. Lett.*, vol. 18, no. 7, pp. 1266–1269, Jul. 2014.

[31] C. Zhang, D. Guo, and P. Fan, "Tracking angles of departure and arrival in a mobile millimeter wave channel," in *Proc. IEEE Int. Conf. Commun.*, May 2016, pp. 1–6.



Xinyu Gao (S'14) received the B.E. degree in communication engineering from the Harbin Institute of Technology, Harbin, China, in 2014. He is currently working toward the Ph.D. degree in electronic engineering with Tsinghua University, Beijing, China.

He has published several journal and conference papers in the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE ICC, IEEE GLOBECOM, etc. His research interests include massive multiple input multiple output and mmWave communications, with emphasis on signal detection and precoding.

Mr. Gao received the national scholarship in 2015.

Linglong Dai (M'11–SM'14) received the B.S. degree in electronic engineering from Zhejiang University, Hangzhou, China, in 2003; the M.S. degree (with the highest honor) in electronic engineering from the China Academy of Telecommunications Technology, Beijing, China, in 2006; and the Ph.D. degree (with the highest honor) from Tsinghua University, Beijing, in 2011, all in electronic engineering.

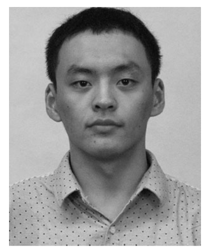
From 2011 to 2013, he was a Postdoctoral Research Fellow with the Department of Electronic Engineering, Tsinghua University, where he has been an Assistant Professor since July 2013 and then an Associate Professor since June 2016. He has published over 50 IEEE journal papers and over 30 IEEE conference papers. He also holds 13 granted patents. He is the coauthor of the book *mmWave Massive MIMO: A Paradigm for 5G* (Academic Press, 2016). His current research interests include massive multiple input multiple output, mmWave communications, multiple access, and sparse signal processing.

Dr. Dai currently serves as an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS, an Editor of the IEEE COMMUNICATIONS LETTERS, a Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Special Issue on millimeter-wave communications for future mobile networks), and the Co-Chair of the IEEE Special Interest Group on Signal Processing Techniques in 5G Communication Systems. Particularly, he is dedicated to reproducible research and has made a large amount of simulation code publicly available. He received the IEEE ICC Best Paper Award in 2013, the IEEE ICC Best Paper Award in 2014, the IEEE TRANSACTIONS ON BROADCASTING Best Paper Award in 2015, and the WCSP Best Paper Award in 2016.

Yuan Zhang (S'16) has been pursuing the B.E. degree with the Department of Electronic Engineering, Tsinghua University, Beijing, China, since 2013.

He joined the Tsinghua National Laboratory for Information Science and Technology (TNList) as a research student in 2015. His research interests include device-to-device (D2D) communication and massive multiple-input–multiple-output. He has published several papers in the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS and IEEE COMMUNICATIONS LETTERS, among others.

Mr. Zhang has participated in the science fair at the College Student Innovation and Entrepreneurship Education of Beijing with two research projects (top 3%). He has received the Student Award for Research and Innovation (top 2%) and the First-class Scholarship of Tsinghua University for four times, among other awards.



Tian Xie (S'15) received the B.S. degree in electronic engineering in 2015 from Tsinghua University, Beijing, China, where he is currently working toward the Master's degree in electronic engineering.

His research interests include wireless communications, with a focus on massive multiple input multiple output and mmWave communications.

Xiaoming Dai (M'16) received the B.S. degree in electrical engineering and automation from the Central South University of Technology, Changsha, China, in 1994 and the M.S. and Ph.D. degrees (with honors) in electrical engineering and automation from Shanghai Jiaotong University, Shanghai, China, in 1999 and 2002, respectively.

He is currently with the Institute of Advanced Network Technologies and New Services and is also with the Beijing Engineering and Technology Research Center for Convergence Networks and Ubiquitous Services, University of Science and Technology Beijing, Beijing, China. His research activity has led to numerous publications in leading international journals and conference proceedings and to fruitful industrial applications, most notably the recently proposed pattern division multiple access.

Dr. Dai was nominated for the Top 100 Ph.D. Thesis Award, sponsored by the Ministry of Education in China, for his Ph.D. dissertation on sequence designs.

Zhaocheng Wang (SM'10) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Tsinghua University, Beijing, China, in 1991, 1993, and 1996, respectively.

From 1996 to 1997, he was a Postdoctoral Fellow with Nanyang Technological University, Singapore. From 1997 to 1999, he was with the OKI Techno Centre (Singapore) Pte Ltd., as a Research Engineer and then as a Senior Engineer. From 1999 to 2009, he worked at SONY Deutschland GmbH, as a Senior Engineer and then as a Principal Engineer. He is currently a Professor with the Department of Electronic Engineering, Tsinghua University. His research interests include wireless communications, digital broadcasting, and mmWave communications.

Prof. Wang is a Fellow of the Institution of Engineering and Technology. He has also served as a Technical Program Committee Co-Chair/Member for many international conferences.