Directional Training and Fast Sector-based Processing Schemes for mmWave Channels

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***Abstract*—We consider a single-cell scenario involving a single base station (BS) with a massive array serving multi-antenna terminals in the downlink of a mmWave channel. We present a class of multiuser MIMO schemes, which rely on uplink training from the user terminals, and on uplink/downlink channel reciprocity. The BS employs *virtual* sector-based processing according to which, user-channel estimation and data transmission are performed in parallel over non-overlapping angular sectors.**

The uplink training schemes we consider are non-orthogonal, that is, we allow multiple users to transmit pilots on the same pilot dimension (thereby potentially interfering with one another). Elementary processing allows each sector to determine the subset of user channels that can be resolved on the sector (effectively pilot contamination free) and, thus, the subset of users that can be served by the sector. This allows resolving multiple users on the same pilot dimension at different sectors, thereby increasing the overall multiplexing gains of the system. Our analysis and simulations reveal that, by using appropriately designed directional training beams at the user terminals, the sector-based transmission schemes we present can yield substantial spatial multiplexing and ergodic user-rates improvements with respect to their orthogonal-training counterparts.

I. Introduction

5G standardization efforts and deployments are projected to bring great performance gains with respect to their predecessors in a multitude of performance metrics, including user and cell throughput, end-to-end delay, and massive device connectivity. It is widely expected that these 5G requirements will be met by utilizing a combination of additional resources, including newly available licensed and unlicensed bands, network densification, large antenna arrays, and new PHY/network layer technologies. To meet the throughput/unit area requirements, for instance, 5G systems would need to provide much higher spatial multiplexing gains (e.g., number of users served simultaneously) than their 4G counterparts.

Large antenna arrays and massive MIMO are considered as key technologies for 5G and beyond. It is expected that new generation deployments would have to utilize the cm and mmWave bands where wide chunks of spectrum are readily available. Note that the spacing of antenna arrays is proportional to the wavelength, at mmWave, so large arrays can be packed even on small footprints. Such large-size arrays will be critical in combatting with the harsher propagation characteristics experienced at mmWave.

Massive MIMO, originally introduced in [1], [2], can yield large spectral efficiencies and spatial multiplexing gains through the use of a large number of antennas at the base stations (BSs). Large arrays enable focusing the radiated signal power and creating sharp beams to several users simultaneously, allowing a BS to serve them simultaneously at large spectral efficiencies.

In order to achieve large spectral efficiencies in the downlink (DL) via multiuser (MU) MIMO, channel state information at the transmitter (CSIT) is needed. Following the massive MIMO approach [2], CSIT can be obtained from the users' uplink (UL) pilots via Time-Division Duplexing (TDD) and UL/DL radio-channel reciprocity. This allows training large antenna arrays by allocating as few UL pilot dimensions as the number of single-antenna users simultaneously served.

As is well known, with isotropic channels, the number of users that can be simultaneously trained (or the system multiplexing gains) is limited by the coherence time and bandwidth of the channel [3], [4]. Noting that the coherence time is inversely proportional to the carrier frequency, increasing the carrier frequency ten-fold, e.g., from 3 GHz to 30 GHz, results in a ten-fold decrease in coherence time, and, thereby, in the number of user channels that can be simultaneously trained within the coherence time of the channel.

In this paper we focus on single-cell DL transmission over a mmWave channel, enabled by UL training and UL/DL channel reciprocity [5]. We take advantage of the sparsity of mmWave channels in the angular domain to devise schemes that yield increases in the system spatial multiplexing gains. Indeed, typical mmWave channels are characterized by fewer multipath components than channels at lower frequencies [6], [7], [8], [9] resulting in a sparser angular support, both at the BS and the user terminal. This channel sparsity can be exploited to train multiple user channels simultaneously, that is, training multiple users using the same pilot dimension.

We consider a combination of non-orthogonal UL training from the user terminals based on pilot designs in [10] and sector-based processing and precoding from the BS with the goal to increase aggregate spatial multiplexing gains and user rates. The challenge with more than one user transmitting pilots on the same pilot dimension is pilot contamination which can substantially limit massive MIMO performance, as the beam used to send data (and therefore beamforming) to one user also beamforms unintentionally at the other (contaminating) user terminal.

In this work, multiple users, each equipped with many antenna elements and a single RF chain, are scheduled to transmit beamformed pilots on the same pilot dimension, thereby increasing the number of users simultaneously transmitting pilots for training. We exploit the presence of a massive Uniform Linear Array (ULA) at the BS and a form of pre-sectorization in the Angle of Arrival (AoA) domain. Elementary processing at each sector allows determining the subset of user channels that can be *resolved* on the sector, effectively pilot contamination free. Each sector then serves only the subset of users whose channels it can resolve. This allows resolving multiple users on the same pilot dimension at different sectors, thereby increasing the overall multiplexing gains of the system.

Our approach has strong connections but also important differences with respect to joint spatial division and multiplexing (JSDM), a two-stage method proposed in [11]. JSDM partitions users into groups with approximately similar channel covariances, and exploits two-stage downlink beamforming. In particular, precoding comprises a pre-beamformer, which depends on the user-channel covariances and minimizes interference across groups, in cascade with a MU MIMO precoder, which uses instantaneous CSI to multiplex users within a group. Using JSDM, two users with no overlapping AoA support in their channels can be trained and served simultaneously. JSDM has also been studied over mmWave band channels [12]; assuming full knowledge of the angular spectra of all the users, user scheduling algorithms were devised to maximize the spatial multiplexing, or received signal power. Our work similarly harvests spatial multiplexing gains, but the support of each user's spectra are not a priori known and no special scheduling is employed.

We also study how varying the user beam width can affect these harvested multiplexing gains. Indeed, using a directional beam at a user terminal makes its user-channel sparser in terms of the number of sectors that are excited at the BS, thereby leaving more sectors available to resolve other users' channels. Our analysis and simulations reveal that a proper choice of the user beam width can positively impact both multiplexing gains and long-term user rates.

II. System Model

We consider a single-cell scenario, involving a single BS serving K_{tot} user terminals. The BS is equipped with an M-element ULA and M RF chains (i.e., one RF chain per antenna), while each terminal is equipped with an $\tilde{M}$-element ULA and a single RF chain. We assume OFDM and a quasistatic block fading channel model whereby the channel of the k-th user stays fixed within a fading block (within the coherence time and bandwidth of the channel). During a given fading block, the channel response between the BS and user k is the $M \times \tilde{M}$ matrix[1] [6], [13]:

$$\mathbf{H}_k(f) = \sum_{n=1}^{N_p} \beta_n \mathbf{a}(\theta_n) \tilde{\mathbf{a}}^{\mathsf{H}}(\tilde{\theta}_n) e^{-j2\pi\tau_n f},$$

where N_p is the number of paths, and β_n and τ_n denote the complex gain and relative delay, respectively, associated with the n-th path[2]. The $M \times 1$ vector $\mathbf{a}(\theta)$ and the $\tilde{M} \times 1$ vector $\tilde{\mathbf{a}}(\theta)$ represent the array response and steering vectors, and are 1-periodic in θ. The normalized angle θ is related to the physical angle ϕ (measured with respect to array broadside) as $\theta = D\sin(\phi)$, where D is the antenna spacing between two antenna elements normalized by the carrier wavelength. Assuming a maximally spread channel in angular domain, the support of both $\mathbf{a}(\theta)$ and $\tilde{\mathbf{a}}(\theta)$ are $[-1/2, 1/2]$, as in [6].

In this paper, we assume TDD operation and focus on DL data transmission enabled by UL pilot transmissions from the user terminals and reciprocity-based training [2]. As a result, in the case of uplink pilot (downlink data) transmission, θ_n and $\tilde{\theta}_n$ denote the n-th path angles of arrival (departure) and departure (arrival).

Spatial filtering can be applied at both the BS and the user terminal side. Given that each user terminal has a single RF chain, a user may transmit its pilot on an arbitrary $\tilde{M} \times 1$ beam $\mathbf{b}$. Letting $\alpha_n(\mathbf{b}) = \beta_n \tilde{\mathbf{a}}^{\mathsf{H}}(\tilde{\theta}_n)\mathbf{b}$, and using $\mathcal{P}(\mathbf{b})$ to denote the set of indices of paths that are excited with user's UL transmission via beam $\mathbf{b}$, the physical model for the vector channel can be written as follows:

$$\mathbf{h}_k(f) = \mathbf{h}_k(f;\mathbf{b}) = \sum_{n\in\mathcal{P}(\mathbf{b})} \alpha_n(\mathbf{b})\mathbf{a}(\theta_n) e^{-j2\pi\tau_n f}. \tag{1}$$

We let $\mathbf{R}_k \triangleq \mathbb{E}\left[\mathbf{h}_k(f)\mathbf{h}_k^{\mathsf{H}}(f)\right]$ denote the k-th user channel covariance matrix and note that, due to uncorrelated scattering, $\mathbf{R}_k$ is independent of the tone index, f. Given that our focus is on the large M case, we will assume that the DFT matrix whitens $\mathbf{R}_k$ and, as a result, $\mathbf{R}_k$ is circulant[3]. Hence, the eigendecomposition of $\mathbf{R}_k$ is given by $\mathbf{R}_k = \mathbf{F}\mathbf{\Lambda}_k\mathbf{F}^{\mathsf{H}}$, with $\mathbf{F}$ denoting the $M \times M$ DFT matrix, and $\mathbf{\Lambda}_k = \mathrm{diag}\left(\lambda_{1,k}\ldots,\lambda_{M,k}\right)$ where $\lambda_{1,k}\ldots,\lambda_{M,k}$ are the eigenvalues of $\mathbf{R}_k$.

The MU MIMO schemes we consider in this paper combine a form of spatial division and multiplexing based on instantaneous CSI. The schemes rely on a form of pre-sectorization in the AoA domain. First $\mathbf{h}_k(f)$ is projected onto $\mathbf{F}$ to generate the $M \times 1$ vector of channel observations $\mathbf{g}_k(f) \triangleq \mathbf{F}^{\mathsf{H}}\mathbf{h}_k(f)$. Subsequently, the M entries of $\mathbf{g}_k(f)$ are split into S non-overlaping "sector" groups. In particular, assuming without loss of generality, that $g = M/S$ is an integer, each sector comprises g consecutive entries of $\mathbf{g}_k(f)$.[4]

[1] We assume reciprocal uplink and downlink channels hence we use $\mathbf{H}_k(f)$ for both. See [5].

[2] For notational convenience, we have suppressed the dependence of N_p, β_n, τ_n, θ_n and $\tilde{\theta}_n$ on the user index k.

[3] Indeed, for ULAs with large M, the eigenvectors of the channel covariance matrix are accurately approximated by the columns of a DFT matrix [11].

[4] If M is not divisible by S, groups of different sizes can be arranged.