How Often Do We Need to Estimate Wireless Channels in Massive MIMO with Channel Aging?

Zhihao Tao and Shaowei Wang
School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China
Email: mg1823078@smail.nju.edu.cn, wangsw@nju.edu.cn

***Abstract*—In massive multiple-input-multiple-output (MIMO) systems, wireless channels are estimated at a fixed and short time interval for all users, which causes redundancy since most of users in practice might have a considerably larger coherence time than the prescribed time interval of estimation, and consequently wastes considerable signaling resources on channel acquisition. In this paper, we propose a novel channel estimation scheme for time-division-duplex massive MIMO systems, which can fully exploit the redundancy by exploring the temporal channel correlation underlying the channel aging effect. We also derive a rigorous lower bound on the achievable spectral efficiency, and maximize the lower bound to determine the optimal time interval of channel estimation. Numerical results show that the proposed estimation scheme can offer great spectral efficiency gains over the conventional one, and provide insights on how to put into practice the proposed scheme.**

***Index Terms*—Achievable spectral efficiency, channel aging, channel estimation, massive MIMO.**

I. Introduction

Massive multiple-input-multiple-output (MIMO), also referred to as large-scale antenna systems, is deemed as a breakthrough technology for future generation mobile communication systems. By deploying hundreds or thousands of antennas at base station (BS) to simultaneously serve a much smaller number of users, massive MIMO systems can offer considerable spectral and energy efficiency with simple linear processing approaches [1], [2]. Besides, massive MIMO can mitigate small-scale fading effectively and result in the so-called channel hardening effect [3]–[5]. Other benefits of massive MIMO include reducing latency on the air interface significantly, simplifying the multiple access layer and resource allocation, and increasing the robustness against intentional jamming [6].

Although promising, massive MIMO entails accurate channel state information (CSI) estimates so as to fully reap the aforementioned gains, and the signaling overhead for channel estimation is still unbearable for both the frequency-division-duplex (FDD) mode and the time-division-duplex (TDD) mode. In FDD massive MIMO systems, for which channel reciprocity does not hold, the CSI overhead is proportional to the number of antennas at the BS [7]. As a consequence, the CSI overhead for the FDD system will be prohibitively large when the number of BS antennas grows greatly. TDD massive MIMO also suffers an excessive amount of CSI overhead with the immense growth of mobile terminals and new applications, though its estimation overhead is independent of the number of BS antennas due to channel reciprocity [7], [8]. Moreover, conventional massive MIMO systems estimate wireless channels at a fixed time interval and apply it to all users [9], [10]. This time interval is usually assumed as very short for the sake of fitting the coherence interval of the worst-case communication scenarios. However, the users undergoing heterogeneous propagation environment and mobility have different channel coherence times, and most of them in practice might have a considerably larger coherence time than the assumed time slot duration [11]. Thus, the conventional CSI estimation scheme is a suboptimal solution and wastes a lot of signaling resources on estimating the channels more often than necessary, while it gives a robust channel estimation. To ease the overwhelming CSI overhead, it is exigent for massive MIMO systems to design an efficient channel estimation scheme that can exploit the heterogeneous user coherence times sufficiently.

As far as the authors have known, current researches mainly try to conceive novel downlink training techniques and uplink CSI feedback strategies to reduce the overhead of channel acquisition for massive MIMO systems [12]–[14], whereas only a few studies pay attention to ameliorating the conventional channel estimation scheme. Investigations show that there is no need for massive MIMO to consume the CSI overhead in every transmission slot when satisfying a particular condition [11]. In [9], the channel coherence time is assumed to be subject to user velocity based on Clark channel model, and the users are divided into a number of groups for different CSI estimation frequencies according to their velocities. In [10], [15], the authors propose that the massive MIMO systems can reuse outdated CSI estimates for saving the CSI overhead by taking into consideration the channel aging effect between time slots. In this case, the stationary Gauss-Markov channel model is assumed, based on which the authors introduce intermittent channel estimation schemes to design the user scheduling policy. Though the aforementioned CSI estimation schemes are sensible and achieve substantial performance improvements, they do not adequately exploit the diversity and redundancy among the actual user coherence times for transmitting data, since they design the estimation schemes mainly from the perspective of user scheduling. Furthermore, these works are based on simple theoretical channel models, which would be

This work was supported in part by the National Natural Science Foundation of China under Grants 61931023 and U1936202.

deviated from practical communication environments. In this paper, based on the realistic channels from COST 2100 model [16], we remedy these deficiencies by addressing directly the question: how often do we need to estimate wireless channels in massive MIMO with channel aging? Different from [9], we do not need to estimate the coherence time according to user velocity since the actual coherence time is dependent not only on user mobility but also on the propagation environment, which is intractable to estimate the coherence time in practice mobile communication scenarios. In contrast with [10], [11], [15], we focus more on how long the time should be allocated for data transmission per time slot for every user rather than how many users should be scheduled per cell, while we all need to maximize the spectral efficiency of massive MIMO systems for determine the frequency of CSI estimation.

We first propose a novel channel estimation scheme for TDD massive MIMO systems, in which the users with slow changing channels can estimate channels with lower frequencies (i.e. longer time interval) than users with fast changing channels by exploiting the temporal channel correlation underlying the channel aging effect. As compared to the conventional channel estimation scheme, our proposed method can fully utilize the diversity and redundancy among the actual user coherence times for transmitting payload data. Then, we derive a rigorous lower bound on the achievable spectral efficiency, which takes into account errors of both the channel estimation and the channel aging. By maximizing the lower bound and solving the optimization problem, we determine the optimal time intervals of CSI estimation for all users. Next, the performance gains of the conventional CSI estimation scheme and the proposed one with different parameter configurations are compared under the realistic COST 2100 channel model scenarios. Numerical results show that the user mobility and the payload transmission signal-to-noise ratio (SNR) can both influence the optimal time interval of channel estimation, and our proposed scheme can remarkably improve the achievable spectral efficiency over the conventional ones. Our research results also provide insights on how to put the proposed CSI estimation scheme into practice.

The remainder of the paper is organized as follows. Section II describes the system model we adopt. Section III illustrates our proposed channel estimation scheme for TDD massive MIMO systems and derives a rigorous lower bound on the achievable spectral efficiency under channel aging. A combinatorial optimization problem for determining the optimal time interval of CSI estimation is also formulated in this section. Section IV and Section V give numerical results and conclusions, respectively.

Notations: Throughout the paper, we use boldface uppercase letters, boldface lowercase letters and lowercase letters to denote matrices, column vectors and scalars, respectively. $\boldsymbol{X}^T$, $\boldsymbol{X}^*$, $\boldsymbol{X}^\dagger$, $\boldsymbol{X}^{-1}$, tr($\boldsymbol{X}$), $|\boldsymbol{X}|$, and $\|\boldsymbol{X}\|$ correspond to the transpose, complex conjugate, complex conjugate transpose, inverse, trace, modulus, two-norm of $\boldsymbol{X}$, respectively. The notation $\mathbb{E}[\cdot]$ and var$[\cdot]$ denote the expectation and variance operation, respectively.

II. SYSTEM MODEL

We start with a single-cell TDD massive MIMO system, where a central BS equipped with M antennas serves K single-antenna users simultaneously. We assume that the channel is constant during each transmission slot, and varies from slot to slot. Every transmission slot of the TDD system has a length of N_s symbols and consists of two phases: uplink channel training with N_p symbols and payload data transmission with $N_s - N_p$ symbols. We assume the proportions of uplink and downlink transmission are λ_{ul} and λ_{dl}, and $\lambda_{ul}+\lambda_{dl}=1$. Let $\boldsymbol{H} \in \mathbb{C}^{M\times K}$ be the actual channel matrix, where the kth column of $\boldsymbol{H}$, denoted by $\boldsymbol{h}_k$, represents the $M\times 1$ channel vector between the BS and the kth user. Before transmitting data, the BS needs to estimate CSI in the uplink training phase.

A. Channel Estimation

We employ the pilot-based channel estimation for the system model. In the training phase, the users send N_p known orthogonal pilot sequences to the BS, which is denoted by $\boldsymbol{\Phi} \in \mathbb{C}^{N_p\times K}$ satisfying $\boldsymbol{\Phi}^\dagger\boldsymbol{\Phi} = \boldsymbol{I}_K$. $N_p \geq K$ must hold and we choose $N_p = K$ for the highest payload data usage in the conventional estimation scheme. Let $\boldsymbol{\phi}_k$, the kth column of $\boldsymbol{\Phi}$, be a pilot signal dedicated for the kth user, and then the received training signal $\boldsymbol{Y}_p$ at the BS is

$$\boldsymbol{Y}_p = \sqrt{\rho_e}\sum_{k=1}^{K}\boldsymbol{h}_k\boldsymbol{\phi}_k^T + \boldsymbol{Z}_p, \tag{1}$$

where ρ_e is the SNR of channel estimation, and $\boldsymbol{Z}_p \in \mathbb{C}^{M\times K}$ is the additive noise matrix whose elements are i.i.d. Gaussian random variables with zero mean and unit variance. Using the least square estimator, the estimation of channel $\boldsymbol{h}_k$ can be given by

$$\begin{aligned}\hat{\boldsymbol{h}}_k &= \frac{1}{\sqrt{\rho_e}}\boldsymbol{Y}_p\boldsymbol{\phi}_k \\ &= \boldsymbol{h}_k\underbrace{\boldsymbol{\phi}_k^T\boldsymbol{\phi}_k}_{1} + \sum_{k'\neq k}^{K}\boldsymbol{h}_{k'}\underbrace{\boldsymbol{\phi}_{k'}^T\boldsymbol{\phi}_k}_{0} + \frac{1}{\sqrt{\rho_e}}\boldsymbol{Z}_p\boldsymbol{\phi}_k \\ &= \boldsymbol{h}_k + \boldsymbol{e}_k,\end{aligned} \tag{2}$$

where $\boldsymbol{e}_k \triangleq \boldsymbol{Z}_p\boldsymbol{\phi}_k/\sqrt{\rho_e}$ is the estimation error, and the mean-square estimation error $\mathbb{E}[\|\boldsymbol{e}_k\|^2] = M/\rho_e$. Note that the estimation accuracy in (2) depends on the number of BS antennas and the SNR of channel estimation.

B. Uplink and Downlink Transmission

On the uplink, the users synchronously transmit their respective signals to the BS. Let $x_{ul,k}$, where $\mathbb{E}[|x_{ul,k}|^2] = 1$, be the transmitted symbol sent by the kth user, and $\boldsymbol{x}_{ul} \triangleq [x_{ul,1},\ldots,x_{ul,k},\ldots,x_{ul,K}]^T$ is the symbol vector transmitted by the K users. The subscript ul denotes the uplink. Then, the received signal vector at the BS can be given by

$$\boldsymbol{y}_{ul} = \sqrt{\rho_u}\boldsymbol{H}\boldsymbol{x}_{ul} + \boldsymbol{z}_{ul}, \tag{3}$$

where ρ_u is the average SNR during the uplink data transmission, and $\boldsymbol{z}_{ul} \in \mathbb{C}^{M\times 1}$ is the additive noise vector whose elements are i.i.d. Gaussian random variables with zero mean and unit variance. We apply a zero-forcing (ZF) detector $\boldsymbol{A} \in \mathbb{C}^{M\times K}$ at the BS to detect $\boldsymbol{x}_{ul}$, where the kth column of $\boldsymbol{A}$ is denoted as $\boldsymbol{a_k}$. The decoding matrix $\boldsymbol{A}$ can be obtained by the channel matrix $\boldsymbol{H}$, i.e., $\boldsymbol{A} = \boldsymbol{H}(\boldsymbol{H}^{\dagger}\boldsymbol{H})^{-1}$. We use $\boldsymbol{a}_k$ to decode $x_{ul,k}$, and the post-processed received signal for the kth user is

$$\begin{aligned}\tilde{y}_{ul,k} &= \boldsymbol{a}_k^{\dagger}\boldsymbol{y}_{ul} \\ &= \underbrace{\sqrt{\rho_u}\boldsymbol{a}_k^{\dagger}\boldsymbol{h}_k x_{ul,k}}_{\text{desired signal}} + \underbrace{\sqrt{\rho_u}\sum_{k'\neq k}^{K}\boldsymbol{a}_k^{\dagger}\boldsymbol{h}_{k'}x_{ul,k'}}_{\text{interference}} + \underbrace{\boldsymbol{a}_k^{\dagger}\boldsymbol{z}_{ul}}_{\text{noise}}.\end{aligned} \tag{4}$$

On the downlink, the BS uses multi-user MIMO transmission techniques to broadcast data to all users. Let $x_{dl,k}$ be the downlink transmission symbol to the kth user, and the symbol vector sent by the BS to the users is denoted as $\boldsymbol{x}_{dl} \triangleq [x_{dl,1}, \ldots, x_{dl,k}, \ldots, x_{dl,K}]^T$, which satisfies $\mathbb{E}[\boldsymbol{x}_{dl}\boldsymbol{x}_{dl}^{\dagger}] = \boldsymbol{I}_K$. The subscript dl denotes the downlink. We employ a linear ZF precoder $\boldsymbol{W} \in \mathbb{C}^{M\times K}$, where the kth column of $\boldsymbol{W}$ is denoted as $\boldsymbol{w}_k$, to map $\boldsymbol{x}_{dl}$ to its transmit antennas. The precoding matrix $\boldsymbol{W}$ can be given by $\boldsymbol{W} = \boldsymbol{H}^*(\boldsymbol{H}^T\boldsymbol{H}^*)^{-1}$. Then the precoded transmission signal vector is $\boldsymbol{u} = \sqrt{\eta}\boldsymbol{W}\boldsymbol{x}_{dl}$, where η is a normalization factor satisfying the power constraint $\mathbb{E}[\|\boldsymbol{u}\|^2] = 1$ and can be calculated as

$$\eta = \frac{1}{\mathbb{E}[\mathrm{tr}(\boldsymbol{W}\boldsymbol{W}^{\dagger})]}. \tag{5}$$

The received signal vector of users is

$$\boldsymbol{y}_{dl} = \sqrt{\rho_d}\boldsymbol{H}^T\boldsymbol{u} + \boldsymbol{z}_{dl}, \tag{6}$$

where ρ_d is the average SNR during the downlink data transmission, and $\boldsymbol{z}_{dl} \triangleq [z_{dl,1}, \ldots, z_{dl,k}, \ldots, z_{dl,K}]^T$ is the additive noise vector whose elements are i.i.d. Gaussian random variables with zero mean and unit variance. Accordingly, the kth user observes

$$\begin{aligned}y_{dl,k} &= \sqrt{\rho_d}\boldsymbol{h}_k^T\boldsymbol{u} + z_{dl,k} \\ &= \underbrace{\sqrt{\eta\rho_d}\boldsymbol{h}_k^T\boldsymbol{w}_k\boldsymbol{x}_{dl,k}}_{\text{desired signal}} + \underbrace{\sqrt{\eta\rho_d}\sum_{k'\neq k}^{K}\boldsymbol{h}_k^T\boldsymbol{w}_{k'}\boldsymbol{x}_{dl,k'}}_{\text{interference}} + \underbrace{z_{dl,k}}_{\text{noise}}.\end{aligned} \tag{7}$$

III. Spectral Efficiency Maximization-Based Channel Estimation Scheme Design

A. Our Proposed Channel Estimation Scheme

The conventional massive MIMO systems apply a fixed time interval of CSI estimation T_s, which is also very short, to all users for the sake of fitting the coherence interval of the worst-case communication scenarios. In this case, all users need to send pilot signals to the BS at each time slot, which results in redundancy since many of them might have considerably larger coherence times than T_s, and consequently wastes radio resources on estimating the channels more often than necessary. Consider the channel aging effect, i.e. the channel varies between when it is learned and when it is used, which is caused by the time variation of propagation channel and processing delays, we can utilize the estimates of aging channels to decode or precode data in the current transmission slot. This is reasonable since there are temporal channel correlations underlying the channel aging effect [8]. Specifically, the channel in a given time slot is not independent, but correlated with the channels in previous and future time slots. Based on this phenomenon, we propose a novel channel estimation scheme for the TDD massive MIMO system (the extension to the FDD massive MIMO system is straightforward), in which the achievable time interval of CSI estimation for every user is, respectively, v_1T_s, ..., v_iT_s, ..., v_KT_s ($v_i \in \mathbb{N}^+$, $1 \le i \le K$). $v_i = 1$ means that the BS needs to continuously estimate the CSI in a conventional manner. For those users with $v_i > 1$ who do not need to send pilots at each transmission slot, the BS reuses the latest aged CSI estimation to detect and transmit data on the uplink and downlink, respectively. Though mismatched with the current channel, the aged channels still can provide effective spectral efficiency for the massive MIMO systems when there are strong temporal channel correlations [17]. In the proposed estimation scheme, the pilot transmission is periodically repeated every L time slots, where L is the least common multiple of v_1, ..., v_i, ..., v_K. Note that larger v_i can free more time for payload data transmission, but it leads to larger channel aging errors, which will cause a loss on the achievable spectral efficiency. It is also not appropriate to set the value of v_i as too small, since in this way we do not fully exploit the temporal channel correlation to improve the spectral efficiency. Thus, there exists optimal values of $\{v_i\}_{1\le i\le K}$ for maximal achievable spectral efficiency under channel aging. We give an example in Fig. 1 to illustrate our proposed scheme, where the BS serves six users and the optimal values of $\{v_i\}_{1\le i\le 6}$ have been obtained as 2, 2, 3, 3, 6, 6, respectively. It is observed from this example that $L = 6$ and every user sends the pilot signal at their respective frequency,

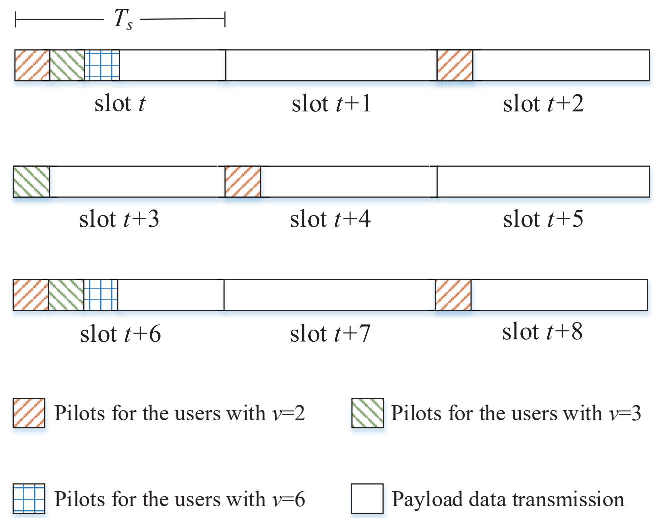

Fig. 1. An example of our proposed channel estimation scheme, where $v \in \{v_i\}_{1\le i\le K}$.

which saves the pilot resources and further improves the payload transmission rates.

B. Optimize Time Interval of CSI Estimation for Maximal Spectral Efficiency

For determining the optimal values of $\{v_i\}_{1\leq i\leq K}$, we first need effective signal-to-interference-plus-noise (SINR) expressions to evaluate the achievable spectral efficiency of massive MIMO under the channel estimation and aging. To this end, we use the technique developed in [18], which is also commonly applied in prior works [11], [15], [17], to derive rigorous lower bounds on the achievable spectral efficiencies of uplink and downlink, respectively. We can find from Fig. 1 that the BS has the following CSI: including only the current estimated CSI, including only the aged estimated CSI, and including both the current and aged estimated CSI, for which we use $\boldsymbol{F}[n]$ to denote and 'n' represents time n. Let $\boldsymbol{f}_k[n]$ denote the kth column of $\boldsymbol{F}[n]$. For the uplink transmission, we can rewrite $\tilde{y}_{ul,k}$ in (4) as

$$\begin{aligned}\tilde{y}_{ul,k}[n] &= \sqrt{\rho_u}\boldsymbol{a}_k^{\dagger}[n]\boldsymbol{f}_k[n]x_{ul,k}[n]\\ &+ \sqrt{\rho_u}\boldsymbol{a}_k^{\dagger}[n](\boldsymbol{h}_k[n]-\boldsymbol{f}_k[n])x_{ul,k}[n]\\ &+ \sqrt{\rho_u}\sum_{k'\neq k}^{K}\boldsymbol{a}_k^{\dagger}[n]\boldsymbol{f}_{k'}[n]x_{ul,k'}[n]+\boldsymbol{a}_k^{\dagger}[n]\boldsymbol{z}_{ul}[n],\end{aligned} \tag{8}$$

where $\boldsymbol{a}_k[n]$ can be obtained by $\boldsymbol{A}[n]=\boldsymbol{F}[n](\boldsymbol{F}^{\dagger}[n]\boldsymbol{F}[n])^{-1}$, and '$\boldsymbol{h}_k[n]-\boldsymbol{f}_k[n]$' represents the error due to the channel estimation or channel aging. Then we view $\tilde{y}_{ul,k}[n]$ as the received signal of a single-input single-output (SISO) system with the effective channel of $\boldsymbol{f}_k[n]$ while the remaining terms are treated as the worst-case uncorrelated additive noise, which is independent Gaussian noise of same variance. Therefore, the power of desired signal can be given by

$$\mathbb{D}_{ul,k}[n]=\rho_u|\boldsymbol{a}_k^{\dagger}[n]\boldsymbol{f}_k[n]|^2. \tag{9}$$

The power of interference plus noise is

$$\begin{aligned}\mathbb{I}_{ul,k}[n] &= \rho_u|\boldsymbol{a}_k^{\dagger}[n](\boldsymbol{h}_k[n]-\boldsymbol{f}_k[n])|^2\\ &+ \rho_u\sum_{k'\neq k}^{K}|\boldsymbol{a}_k^{\dagger}[n]\boldsymbol{f}_{k'}[n]|^2+|\boldsymbol{a}_k^{\dagger}[n]|^2.\end{aligned} \tag{10}$$

As a result, the post-processed SINR and achievable spectral efficiency for the kth user at time n can be written as, respectively

$$\mathrm{SINR}_{ul,k}[n]=\frac{\mathbb{D}_{ul,k}[n]}{\mathbb{I}_{ul,k}[n]}, \tag{11}$$

$$C_{ul,k}[n]=\log_2(1+\mathrm{SINR}_{ul,k}[n]). \tag{12}$$

For the downlink transmission, the received signal at the kth user $y_{dl,k}$ (see in (7)) can be rewritten as

$$\begin{aligned}y_{dl,k}[n] &= \sqrt{\eta\rho_d}\mathbb{E}[\boldsymbol{h}_k^T[n]\boldsymbol{w}_k[n]]x_{dl,k}[n]\\ &+ \sqrt{\eta\rho_d}(\boldsymbol{h}_k^T[n]\boldsymbol{w}_k[n]-\mathbb{E}[\boldsymbol{h}_k^T[n]\boldsymbol{w}_k[n]])x_{dl,k}[n]\\ &+ \sqrt{\eta\rho_d}\sum_{k'\neq k}^{K}\boldsymbol{h}_k^T[n]\boldsymbol{w}_{k'}[n]x_{dl,k'}[n]+z_{dl,k}[n],\end{aligned} \tag{13}$$

Where $\boldsymbol{w}_k[n]$ is obtained by $\boldsymbol{W}[n]=\boldsymbol{F}^*[n](\boldsymbol{F}^T[n]\boldsymbol{F}^*[n])^{-1}$. Similar to the processing for uplink, we consider $y_{dl,k}[n]$ as the received signal of a SISO system with the worst-case uncorrelated additive Gaussian noise. Then, we obtain the power of desired signal and interference plus noise as, respectively

$$\mathbb{D}_{dl,k}[n]=\eta\rho_d|\mathbb{E}[\boldsymbol{h}_k^T[n]\boldsymbol{w}_k[n]]|^2, \tag{14}$$

$$\begin{aligned}\mathbb{I}_{dl,k}[n] &= \eta\rho_d\mathrm{var}[\boldsymbol{h}_k^T[n]\boldsymbol{w}_k[n]]+1\\ &+ \eta\rho_d\sum_{k'\neq k}^{K}\mathbb{E}[|\boldsymbol{h}_k^T[n]\boldsymbol{w}_{k'}[n]|^2].\end{aligned} \tag{15}$$

The post-processed SINR and achievable spectral efficiency for the kth user at time n can be given by, respectively,

$$\mathrm{SINR}_{dl,k}[n]=\frac{\mathbb{D}_{dl,k}[n]}{\mathbb{I}_{dl,k}[n]}, \tag{16}$$

$$C_{dl,k}[n]=\log_2(1+\mathrm{SINR}_{dl,k}[n]). \tag{17}$$

So the combined spectral efficiency for the kth user at time n is

$$C_k[n]=\lambda_{ul}C_{ul,k}[n]+\lambda_{dl}C_{dl,k}[n]. \tag{18}$$

Now we try to maximize the average total spectral efficiency for the TDD system by choosing the proper values of $\{v_i\}_{1\leq i\leq K}$ for K users in the proposed scheme, which can be formulated as the following problem:

$$\begin{aligned}\max_{\{v_i\}_{1\leq i\leq K}} \quad & \lim_{J\to\infty}\frac{1}{J}\sum_{j=0}^{J-1}\frac{N_s-N_p[j]}{N_s}\sum_{i=1}^{K}C_i[j]\\ s.t. \quad & v_i\in\mathbb{N}^+, 1\leq i\leq K\\ & \theta_i[j]=\begin{cases}1, & \text{if } \mathrm{rem}(j,v_i)=0\\ 0, & \text{if } \mathrm{rem}(j,v_i)\neq 0\end{cases}\\ & \sum_{i=1}^{K}\theta_i[j]=N_p[j],\end{aligned} \tag{19}$$

where $\mathrm{rem}(j,v_i)$ denotes the remainder after division of j by v_i, $\theta_i[j]=1$ or 0 indicates the ith user needs or does not need to send pilot signals to the BS in the jth time slot, and $N_p[j]$ is the total number of users that need to send pilots in the jth time slot. Eq. (19) is a combinatorial optimization problem and can be solved by sequential search when the number of users is not very large.

IV. NUMERICAL RESULTS

In this section, we validate the proposed channel estimation scheme by using the COST 2100 channel model, which has close agreements with realistic massive MIMO channel measurements [16], and present our preliminary numerical results. We consider a TDD massive MIMO system, where $M=64$, $K=6$, $N_s=14$, $T_s=1$ ms, $\lambda_{ul}=\lambda_{dl}=1/2$. Through the COST 2100 model we construct an outdoor channel environment with a bandwidth of 20 MHz at central frequency 1.9 GHz. The channel estimation SNR ρ_e, uplink and downlink transmission SNR ρ_u and ρ_d are set depending on the specific simulation scenarios, and $\rho_u=\rho_d$ unless

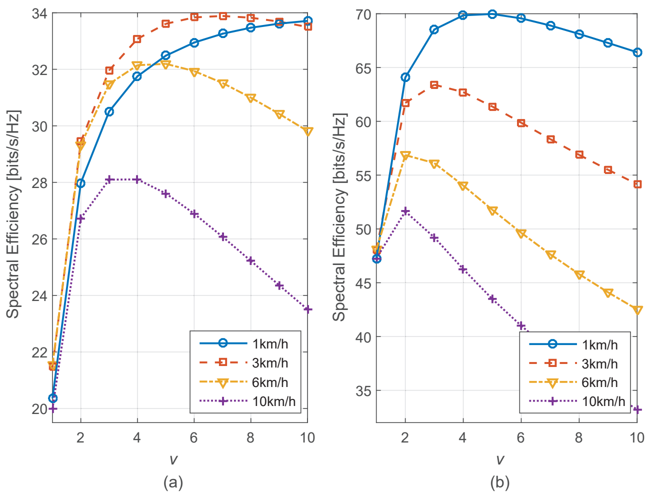

Fig. 2. Achievable spectral efficiency of the TDD system using our proposed scheme versus different v: a) $\rho_u = \rho_d = 0$ dB; b) $\rho_u = \rho_d = 30$ dB. $\rho_e = 20$ dB.

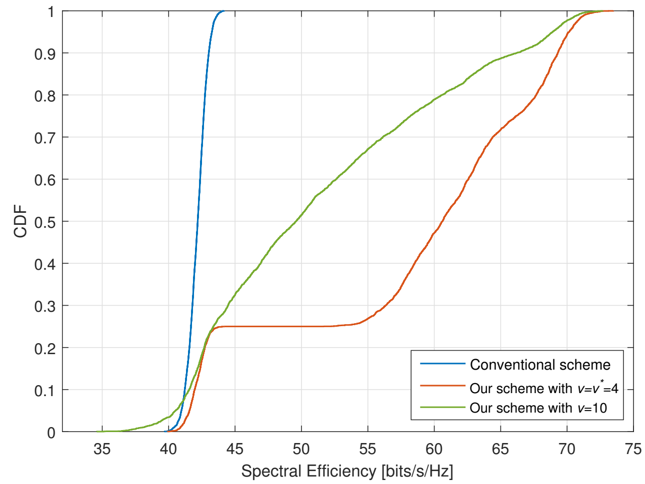

Fig. 3. CDF of achievable spectral efficiency among the conventional estimation scheme and the proposed ones. $\rho_e = \rho_u = \rho_d = 20$ dB.

otherwise specified. For simplification and tractability, we assume that the user moving speed is the same for each user, and all users have the identical value of $\{v_i\}_{1\leq i\leq K}$, i.e. $v_1 = ... = v_K = v$. In this case, we use the sequential search algorithm to solve (19), and the solved optimal value is denoted by v^*.

First, we compare the achievable spectral efficiency of the TDD system using our proposed channel estimation scheme with respect to the value of v, which are depicted in Fig. 2. Fig. 2a illustrates the scenario of low payload transmission SNR where $\rho_u = \rho_d = 0$ dB, and Fig. 2b shows the scenario of high payload transmission SNR where $\rho_u = \rho_d = 30$ dB. In both scenarios, the user moving speed is set to be [1, 3, 6, 10] km/h, respectively, and the channel estimation SNR $\rho_e = 20$ dB. We can see from Fig. 2 that the optimal value of v for maximal spectral efficiency decreases as we increase the user velocity. This is consistent with intuition since fast varying channels offer weak channel correlations over time, and using large v will lead significant channel aging errors as compared to the slow varying channels. For the users moving with high velocities, the losses on the achievable spectral efficiencies caused by the channel aging errors will be more likely to outperform the gains obtained by exploiting the aged channels, and consequently the optimal value of v for them would be smaller. Moreover, we observe that the optimal value of v with the same user velocity in Fig. 2a is obviously larger than the one in Fig. 2b, which demonstrates that the payload transmission SNR also has a considerable impact on the selecting of v^*. The reason behind this can be found in the expressions of achievable spectral efficiency considering the channel aging error (see (10) in Section III). Specifically, the channel aging error has a small impact on the achievable spectral efficiency as compared to the noise in the payload transmission when ρ_u and ρ_d are low. In this case, increasing v in the proposed scheme will be inclined to obtain more spectral efficiency gains since the channel aging error is suppressed by the payload transmission noise. In the scenario of high payload transmission SNR, the noise in the payload transmission is negligible as compared to the channel aging error, so the latter will dominate the achievable spectral efficiency and it is counterproductive to increase v.

Fig. 3 compares the cumulative distribution function (CDF) of achievable spectral efficiency among the conventional channel estimation scheme and the proposed ones. In this scenario, the user moving speed is 3 km/h, and $\rho_e = \rho_u = \rho_d = 20$ dB. We solve for $v^* = 4$ and choose v = 10 for comparison. From Fig. 3, we see that the achievable spectral efficiencies obtained by the conventional scheme are mainly in the range of [40, 45] bits/s/Hz, and the ones of our proposed schemes are mainly distributed above 45 bits/s/Hz. Meanwhile, we observe that the proposed scheme with $v = v^* = 4$ performs much better than the conventional scheme and the proposed one with $v = 10$ from the view of probability distribution of achievable spectral efficiency, which demonstrates that by adequately exploring the temporal channel correlations we can exploit the redundancy among actual user coherence times to remarkably improve the performance gains of conventional massive MIMO systems.

Note that the BS cannot obtain perfect CSI and it is impractical to use the actual channel $\boldsymbol{H}$ to compute the achievable spectral efficiency considering the channel estimation and aging; we adopt the estimated CSI $\hat{\boldsymbol{H}}$ to substitute $\boldsymbol{H}$ in (19) to solve for v^*. Though in this way the channel estimation error is ignored, we still can acquire correct v^* to some extent, which is substantiated in the following simulations. Fig. 4 illustrates v^* solved by respectively using the actual channel $\boldsymbol{H}$ and the estimated channel $\hat{\boldsymbol{H}}$ with respect to the payload transmission SNR. We set the user moving speed as 1 km/h, and the channel estimation SNR of Fig. 4a-c as 20 dB, 40 dB, 60 dB, respectively. We see in Fig. 4 that the solved v^* by $\boldsymbol{H}$ and $\hat{\boldsymbol{H}}$ are the same for relatively low payload transmission

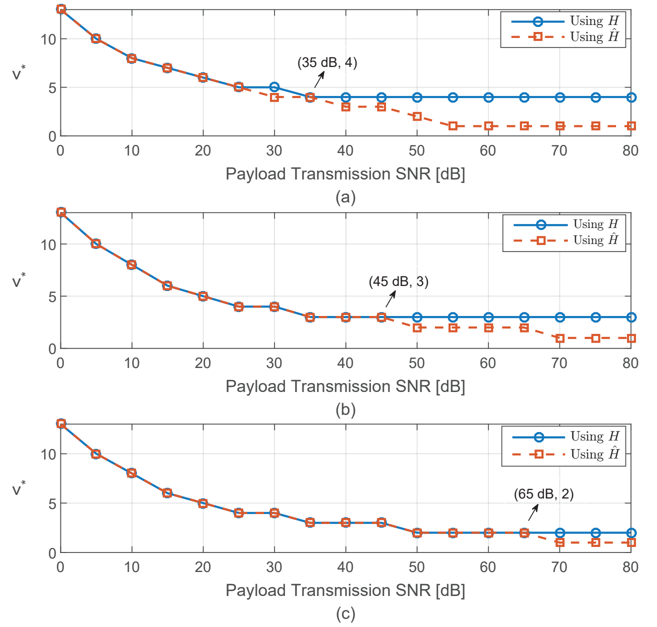

Fig. 4. Solved v^* by the actual channel $\boldsymbol{H}$ and the estimated channel $\hat{\boldsymbol{H}}$ versus payload transmission SNR: a) $\rho_e = 20$ dB; b) $\rho_e = 40$ dB; c) $\rho_e = 60$ dB.

SNR. This is because the payload transmission noise has a dominant impact on the achievable spectral efficiency as compared to the channel estimation error when ρ_u and ρ_d are low, which can be observed in (10). In this case, the impact of channel estimation error on using $\boldsymbol{H}$ to solve for v^* can be neglected, and consequently there is no difference between the solved v^* by $\boldsymbol{H}$ and $\hat{\boldsymbol{H}}$. In contrast, we find that the solved v^* by $\hat{\boldsymbol{H}}$ is inconsistent with the one solved by $\boldsymbol{H}$ and is always equal to 1 for relatively high payload transmission SNR. In other words, with high ρ_u and ρ_d the BS will wrongly choose to estimate CSI in a conventional manner when using $\hat{\boldsymbol{H}}$ to solve for v^*. This can be explained by the fact that the achievable spectral efficiency of the conventional scheme with ZF decoding/precoding will grow linearly, rather than saturate, as the payload transmission SNR increases, since we use $\hat{\boldsymbol{H}}$ to compute SINR and do not take the channel estimation error into account for high ρ_u and ρ_d [19]. So we can improve the robustness of our proposed scheme by increasing ρ_e to decrease the channel estimation error, which is demonstrated by the right shift of breakaway point. Note that the breakaway point is indicated by the arrow in Fig. 4a-c.

V. Conclusion

In this paper, we investigated how often wireless channels should be estimated in massive MIMO with channel aging. We first proposed a novel channel estimation scheme for TDD massive MIMO systems to effectively exploit the redundancy among actual user coherence times based on the temporal channel correlation. Then we derived closed-form expressions for achievable spectral efficiency under channel estimation and aging, and formulated a combinatorial optimization problem for determining the optimal time interval of CSI estimation in the proposed scheme. Numerical results demonstrate the great performance gains obtained by our proposed estimation scheme as compared to the conventional one, and the proposed scheme can be applied in practice to some extent even without perfect CSI. In the future, we can extend this work to multi-cell massive MIMO systems and packet-based transmissions, and use channel prediction techniques to improve the proposed estimation scheme. It is also interesting to study how the number of BS antennas affect the proposed scheme.

References

[1] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, and F. Tufvesson, "Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.

[2] W. Yu, T. Wang, and S. Wang, "Multi-Label Learning Based Antenna Selection in Massive MIMO Systems," *IEEE Trans. Veh. Tech.*, vol. 70, no. 7, pp. 7255–7260, Jun. 2021.

[3] E. Bjornson, E. G. Larsson, and T. L. Marzetta, "Massive MIMO: ten myths and one critical question," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 114–123, Feb. 2016.

[4] Z. Kuai and S. Wang, "Thompson Sampling-Based Antenna Selection With Partial CSI for TDD Massive MIMO Systems," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7533–7546, Dec. 2020.

[5] Z. Tao, T. Wang, and S. Wang, "Improve Downlink Rates of FDD Massive MIMO Systems by Exploiting CSI Feedback Waiting Phase," in *Proc. IEEE Globecom'19*, Waikoloa, HI, 2019.

[6] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for Next Generation Wireless Systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[7] T. L. Marzetta, "Massive MIMO: An Introduction," *Bell Labs Tech. J.*, vol. 20, no. 20, pp. 11–22, Mar. 2015.

[8] J. Yuan, H. Q. Ngo, and M. Matthaiou, "Machine Learning-Based Channel Prediction in Massive MIMO With Channel Aging," *IEEE Trans. Wireless Commun.*, vol. 19, no. 5, pp. 2960–2973, May 2020.

[9] T. X. Vu, T. A. Vu, S. Chatzinotas, and B. Ottersten, "Spectral-Efficient Model for Multiuser Massive MIMO: Exploiting User Velocity," in *Proc. IEEE ICC'17*, Paris, France, 2017.

[10] S. E. Hajri, M. Assaad, and M. Larrañaga, "Enhancing massive MIMO: A new approach for Uplink training based on heterogeneous coherence times," in *Proc. IEEE ICT'18*, Saint-Malo, France, 2018.

[11] E. Björnson, E. G. Larsson, and M. Debbah, "Massive MIMO for Maximal Spectral Efficiency: How Many Users and Pilots Should Be Allocated?" *IEEE Trans. Wireless Commun.*, vol. 15, no. 2, pp. 1293–1308, Feb. 2016.

[12] S. Noh, M. D. Zoltowski, Y. Sung, and D. J. Love, "Pilot Beam Pattern Design for Channel Estimation in Massive MIMO Systems," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 787–801, May 2014.

[13] S. Bazzi and W. Xu, "Downlink Training Sequence Design for FDD Multiuser Massive MIMO Systems," *IEEE Trans. Signal Process.*, vol. 65, no. 18, pp. 4732–4744, Sept. 2017.

[14] Y. Han, W. Shin, and J. Lee, "Projection-Based Differential Feedback for FDD Massive MIMO Systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 202–212, Jan. 2017.

[15] R. Deng, Z. Jiang, S. Zhou, and Z. Niu, "Intermittent CSI Update for Massive MIMO Systems With Heterogeneous User Mobility," *IEEE Trans. Commun.*, vol. 67, no. 7, pp. 4811–4824, July 2019.

[16] L. Liu, C. Oestges, J. Poutanen, K. Haneda, P. Vainikainen, F. Quitin, F. Tufvesson, and P. De Doncker, "The COST 2100 MIMO channel model," *IEEE Wireless Commun.*, vol. 19, no. 6, pp. 92–99, Dec. 2012.

[17] K. T. Truong and R. W. Heath, "Effects of Channel Aging in Massive MIMO Systems," *J. Commun. Netw.*, vol. 15, no. 4, pp. 338–351, Aug. 2013.

[18] B. Hassibi and B. M. Hochwald, "How Much Training is Needed in Multiple-Antenna Wireless Links?" *IEEE Trans. Inf. Theory*, vol. 49, no. 4, pp. 951–963, Apr. 2003.

[19] N. Jindal, "MIMO Broadcast Channels With Finite-Rate Feedback," *IEEE Trans. Inf. Theory*, vol. 52, no. 11, pp. 5045–5060, Nov. 2006.