Improve Downlink Rates of FDD Massive MIMO Systems by Exploiting CSI Feedback Waiting Phase

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Abstract—**In this paper, we consider a massive multiple-input-multiple-output (MIMO) system, where the base station (BS) is equipped with a large number of antennas while serving a much smaller number of users simultaneously. Though massive MIMO systems can provide significant spectral and energy efficiency via simple signal processing, the required channel state information (CSI) overhead is still a huge challenge, especially for the FDD mode. The basic frame structure of the FDD massive MIMO does not fully exploit the CSI feedback waiting phase since the BS needs to wait some time for the CSI feedback sent by users and then transmit data in downlink with the estimated CSI. The proportion of the CSI feedback waiting phase in the downlink transmission would be high as the MIMO scaling up, which reduces downlink rates for the FDD massive MIMO systems to some extent. In this paper, we propose two novel downlink precoding and transmission (DPT) schemes for FDD systems by exploiting the CSI feedback waiting phase. The corresponding performance comparisons between our proposed DPT methods, the contemporary DPT scheme and the ideal DPT one are also provided based on the COST 2100 outdoor channel model. Numerical results show that one of our proposed DPT schemes can achieve higher downlink rates than the contemporary scheme in relative low-mobility scenarios. The other proposed DPT scheme performs much better and is robust to user mobility.**

Index Terms—**Massive MIMO, CSI feedback, downlink precoding, achievable rates.**

I. INTRODUCTION

In the past two decades, the demand for data traffic is increasing exponentially together with the rapid development in mobile communication systems. Though multiple-input-multiple-output (MIMO) technology has made outstanding contributions to enhance mobile communication networks, it is still difficult to copy with the immense growth of mobile terminals. Recently, massive MIMO—a multi-user MIMO technology where each base station (BS) is equipped with orders of magnitude more antennas [1], has been considered as one of key technologies for the next generation mobile communication system. The use of large arrays of antennas at the BS has many benefits. Theoretically, massive MIMO systems can offer significant spectral efficiency and energy efficiency with simple linear precoding and decoding schemes, such as maximum ratio transmission/combining (MRT/MRC) and zero-forcing (ZF) schemes [2]. Besides, massive MIMO can fight against the small-scale fading of radio channels, simplify signal processing and provide effective power control, etc. [3]-[4].

To fully reap the aforementioned massive MIMO gains, the BS necessitates obtaining accurate channel state information (CSI) for both the time-division-duplex (TDD) mode and the frequency-division-duplex (FDD) mode. Most of the massive MIMO researches consider the TDD system where only the uplink CSI sent by single-antenna user needs to be estimated based on principle of channel reciprocity [3]-[5]. For the TDD mode, the CSI overhead is proportional to the number of users, not to the number of BS antennas. The significant difference between the FDD and the TDD is that channel reciprocity does not hold since the uplink and the downlink channel of the FDD systems adopt different frequency bands. As a result, both the uplink and the downlink CSI are required for the FDD massive MIMO systems. As the number of BS antennas scales up, the CSI overhead will become prohibitively large for the FDD system, which is not the case for the TDD one. Nonetheless, many currently deployed cellular networks operate in FDD mode [6], and FDD systems is generally considered to be more effective for lower transmission delay and higher immunity to system interference [7]. In addition, there are other system imperfections, e.g., pilot contamination, calibration error and hardware impairments, which limit the performance of TDD systems [8]. Thus, it is of great importance to design schemes to mitigate the unfavorable effects of scaling up the number of BS antennas for the FDD massive MIMO systems from the viewpoint of both academia and industry.

To make the massive MIMO systems work in FDD mode with demanding CSI acquisition, quite a few studies have been done to reduce the signaling overhead. Previous researches can be divided into three categories based on different techniques: compressive sensing, temporal correlation and spatial correlation [9]. These works mainly focus on the downlink training techniques [8], [10] and uplink CSI feedback strategies [11], but do not exploit the potential of the CSI feedback waiting phase in the downlink transmission, which is introduced by the uplink CSI feedback. The basic FDD frame structure is shown in Fig. 1, where the BS can only start to transmit downlink data untill it obtains the estimated CSI feedback sent by the users. Specifically, when the downlink pilots training is finished,

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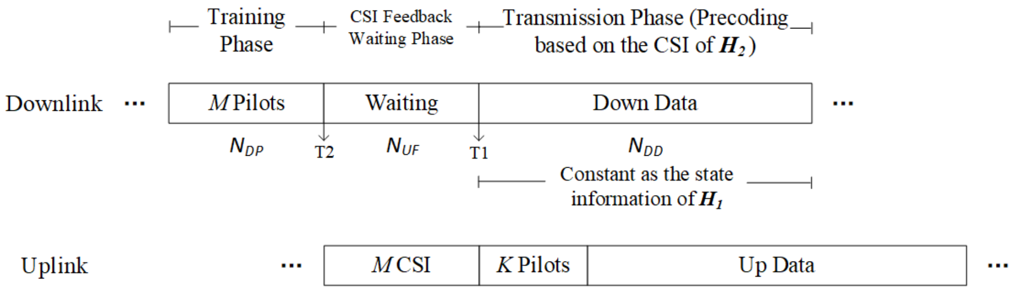


Fig. 1. The basic frame structure for the FDD massive MIMO system where the BS is equipped with M antennas and servers K users.

the BS needs to wait untill the uplink feedback completes so as to get the estimated CSI. The waiting period is called the CSI feedback waiting phase in this paper. As illustrated in Fig. 1, one downlink transmission slot includes training, waiting and data transmission three phases. Recall that the pilot and CSI feedback overhead will get larger when the number of BS antennas increases, which leads to the duration prolongation of the CSI feedback waiting phase accordingly. As a result, the proportion of the CSI feedback waiting phase occupied in the downlink transmission becomes higher, which reduces the downlink rates in FDD massive MIMO systems unavoidably. As far as the authors have known, previous works mainly concentrate on training and feedback techniques. Little attention has been paid to the CSI feedback waiting phase. It is naturally to think of exploiting the CSI feedback waiting phase to enhance the performance of the FDD massive MIMO systems, which is the motivation of this work.

We focus on the downlink precoding and transmission (DPT) schemes with exploiting CSI feedback waiting phase to mitigate the unfavorable effects of CSI overhead for the FDD systems, and investigate the achievable downlink rates of the FDD massive MIMO systems with our proposed DPT schemes. First, we derive the downlink rate expression with ZF precoding. Next, we propose two novel downlink precoding and transmission schemes—DPT Scheme I and DPT Scheme II to fully utilize the idle time of the CSI feedback waiting phase for the FDD mode. Then, we compare the achievable downlink rates of our two proposed schemes with the contemporary DPT one and the ideal DPT over massive MIMO channel generated by the COST 2100 model [12]. Numerical results show that our proposed two schemes always perform better than the contemporary scheme in low-mobility scenarios, and the DPT Scheme II is superior to the DPT Scheme I and the contemporary DPT scheme in the considered scenarios with different velocities. Our research results also provide insights on exploiting the CSI feedback waiting phase efficiently.

The remainder of the paper is organized as follows. In Section II, we describe our system model. In Section III, we specify how to exploit the CSI feedback waiting phase to improve downlink transmission rate, and propose two novel DPT schemes. Section IV gives numerical results, including the comparison with the contemporary and the ideal DPT schemes. Finally, we conclude our work in Section V.

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

II. SYSTEM MODEL

We consider downlink transmission in a single cell FDD massive MIMO system. The BS is equipped with M antennas to serve K single-antenna users. In the downlink, let q_k be the symbol intended for the kth user and the source information vector $\boldsymbol{q} \triangleq [q_1\ q_2\ \ldots\ q_K]^T$ satisfies $E\{\boldsymbol{q}\boldsymbol{q}^H\} = \boldsymbol{I_K}$ where $\boldsymbol{I_K}$ denotes the $K \times K$ identity matrix. Then, the transmitted precoded signal vector $\boldsymbol{x} = \sqrt{\alpha}\boldsymbol{W}\boldsymbol{q}$, where $\boldsymbol{W} \in \mathbb{C}^{M\times K}$ is the precoding matrix and α is a normalization coefficient for satisfying the power constrain $E\{||\boldsymbol{x}||^2\} = 1$. Consequently, the value of α can be calculated as

$$\alpha = \frac{1}{E\{\text{tr}(\boldsymbol{W}\boldsymbol{W}^H)\}}. \tag{1}$$

We employ the ZF precoding where the inter-user interference can be cancelled out at each user [13]. This precoding needs to evaluate the pseudo-inverse of the channel matrix $\boldsymbol{H}$, $\boldsymbol{H} \in \mathbb{C}^{M\times K}$, and the precoding matrix $\boldsymbol{W}$ can be written as

$$\boldsymbol{W} = \boldsymbol{H}^*(\boldsymbol{H}^T\boldsymbol{H}^*)^{-1}. \tag{2}$$

Then, the received signal vector of the K users can be given by

$$\boldsymbol{y} = \sqrt{p_\text{d}}\boldsymbol{H}^T\boldsymbol{x} + \boldsymbol{z}, \tag{3}$$

where $\boldsymbol{y} \triangleq [y_1\ y_2\ \cdots\ y_K]^T$, p_d is the transmit power of the downlink and $\boldsymbol{z} \triangleq [z_1\ z_2\ \cdots\ z_k\ \cdots\ z_K]^T$. We assume that z_k is the additive noise at the kth user and a Gaussian random variable with zero mean and unit variance. Accordingly, the received signal at the kth user is

$$\begin{aligned} y_k &= \sqrt{p_\text{d}}\boldsymbol{h_k}^T\boldsymbol{x} + z_k \\ &= \sqrt{\alpha p_\text{d}}\boldsymbol{h_k}^T\boldsymbol{w_k}q_k + \sqrt{\alpha p_\text{d}}\sum_{k'\neq k}^{K}\boldsymbol{h_k}^T\boldsymbol{w_{k'}}q_{k'} + z_k, \end{aligned} \tag{4}$$

where $\boldsymbol{h_k}$ and $\boldsymbol{w_k}$ are the kth column of the channel matrix $\boldsymbol{H} = [\boldsymbol{h_1}\ \boldsymbol{h_2}\ \cdots\ \boldsymbol{h_k}\ \cdots\ \boldsymbol{h_K}]$ and the kth column of the precoding matrix $\boldsymbol{W} = [\boldsymbol{w_1}\ \boldsymbol{w_2}\ \cdots\ \boldsymbol{w_k}\ \cdots\ \boldsymbol{w_K}]$, respectively. Therefore, the SINR of the kth user is

$$\mathrm{SINR}_k = \frac{\alpha p_d |\boldsymbol{h_k}^T \boldsymbol{w_k}|^2}{\alpha p_d \sum_{k' \neq k}^{K} |\boldsymbol{h_k}^T \boldsymbol{w_{k'}}|^2 + 1}. \tag{5}$$

The achievable sum rate of the downlink FDD massive MIMO system can be calculated as

$$R = \sum_{k=1}^{K} \log_2(1 + SINR_k). \tag{6}$$

Then we can work out the achievable downlink rates via combining (1), (2), (5) and (6). To efficiently compare the performance of our proposed DPT schemes with the contemporary and ideal DPT scheme, we employ the COST 2100 outdoor channel model which is generic, flexible and suitable for multi-user MIMO scenarios to produce channel matrix [12].

III. DOWNLINK PRECODING AND TRANSMISSION SCHEME DESIGNS

A. Contemporary and Ideal DPT Scheme for FDD Mode

For the practical contemporary DPT scheme, the BS transmits N_{DP} downlink pilots to the users for downlink CSI acquisition first. Then, the users send the feedback of downlink CSI to the BS via uplink channel, where the symbol length of the CSI feedback is defined as N_{UF}. During the CSI feedback waiting phase, the BS cannot transmit any downlink data until it receives the downlink CSI. When the feedback completes, the BS just starts to precode and transmit the downlink data, where the symbol length of the downlink data is defined as N_{DD}. We illustrate the contemporary DPT scheme in Fig. 1. Considering that the time varying nature of radio channel between users and BS, channel aging is inevitable. In practical downlink channels, an aging channel evolves continuously with time and can be different during each transmitted symbol [14]. This leads to a mismatch between the true CSI and the estimated one during the training and waiting phase. To simplify the analysis of channel aging, we regard the downlink transmission phase as quasi-static, and the CSI of this phase is constant as the state information of $\boldsymbol{H_1}$, the channel at time T1 that indicates the CSI feedback waiting phase is just finished. On account of channel aging, the obtained CSI estimation of the BS is virtually the state information of $\boldsymbol{H_2}$, the channel at time T2 that indicates the pilot training phase is just finished. So the BS actually employs the state information of $\boldsymbol{H_2}$ to compute the precoding matrix to precode and transmit downlink data in the transmission phase, where the precoding matrix is defined as $\boldsymbol{W_2}$. Thus, the SINR of the kth user in the contemporary DPT scheme is

$$\mathrm{SINR}_{contemporary,k} = \frac{\alpha_{cont} p_d |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{2,k}}|^2}{\alpha_{cont} p_d \sum_{k' \neq k}^{K} |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{2,k'}}|^2 + 1}, \tag{7}$$

$$\alpha_{cont} = \frac{1}{E\{\mathrm{tr}(\boldsymbol{W_2}\boldsymbol{W_2}^H)\}}, \tag{8}$$

where $\boldsymbol{h_{1,k}}$ and $\boldsymbol{w_{2,k}}$ are the kth column of the channel matrix $\boldsymbol{H_1} = [\boldsymbol{h_{1,1}}\ \boldsymbol{h_{1,2}}\ \cdots\ \boldsymbol{h_{1,k}}\ \cdots\ \boldsymbol{h_{1,K}}]$ and the kth column of the precoding matrix $\boldsymbol{W_2} = [\boldsymbol{w_{2,1}}\ \boldsymbol{w_{2,2}}\ \cdots\ \boldsymbol{w_{2,k}}\ \cdots\ \boldsymbol{w_{2,K}}]$, respectively. Note that the BS only transmits data during the transmission phase for the contemporary scheme, so the downlink rate needs to be multiplied by an effective transmission coefficient β_{cont}, which can be written as

$$\beta_{cont} = \frac{N_{DD}}{N_{DP} + N_{UF} + N_{DD}}. \tag{9}$$

Therefore, the achievable rate of the contemporary scheme can be calculated as

$$R_{contemporary} = \beta_{cont} \times \sum_{k=1}^{K} \log_2(1 + SINR_{contemporary,k}). \tag{10}$$

As for the ideal downlink precoding and transmission scheme, the BS is assumed to know the instantaneous CSI during each transmitted symbol even though the channel varies continuously with time. On other words, the ideal DPT can get perfect match between the true CSI and the obtained one. Consequently, the channel aging does not exist in this case. Obviously, it is impossible to implement the ideal DPT in practical FDD systems since no technique can make the BS obtain instantaneous CSI without any delay. We introduce the ideal DPT scheme, where the channel in one transmission slot is invariant and the precoding matrix is evaluated by the constant CSI, for the purpose of comparison in this paper. For simplicity, we regard $\boldsymbol{H_1}$, the channel at time T1 as the invariant channel in one transmission slot. The precoding matrix evaluated by $\boldsymbol{H_1}$ is defined as $\boldsymbol{W_1}$ and the SINR of the kth user is

$$\mathrm{SINR}_{ideal,k} = \frac{\alpha_{ideal} p_d |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{1,k}}|^2}{\alpha_{ideal} p_d \sum_{k' \neq k}^{K} |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{1,k'}}|^2 + 1}, \tag{11}$$

$$\alpha_{ideal} = \frac{1}{E\{\mathrm{tr}(\boldsymbol{W_1}\boldsymbol{W_1}^H)\}}, \tag{12}$$

where $\boldsymbol{w_{1,k}}$ is the kth column of the precoding matrix $\boldsymbol{W_1} = [\boldsymbol{w_{1,1}}\ \boldsymbol{w_{1,2}}\ \cdots\ \boldsymbol{w_{1,k}}\ \cdots\ \boldsymbol{w_{1,K}}]$. We also assume that the BS transmits downlink data to the users in the whole transmission slot without training and waiting phase for the ideal DPT scheme. That is to say, we also do not need to consider the CSI overhead for the ideal DPT scheme. As a result, the effective transmission coefficient β_{ideal} is 1 in this scheme, and the achievable downlink rate of the ideal DPT scheme is

$$R_{ideal} = \sum_{k=1}^{K} \log_2(1 + SINR_{ideal,k}). \tag{13}$$

B. Our Proposed Novel DPT Schemes

Since the BS can not transmit any downlink data in the CSI feedback waiting phase for the contemporary DPT scheme, it is naturally to think of exploiting the CSI feedback waiting phase to design the DPT scheme of FDD systems in a more efficient way. According to [4], we can define the phase duration as the number of OFDM symbols times the tone

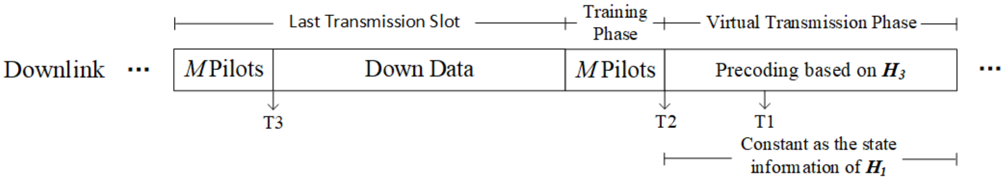


Fig. 2. Illustration of the DPT scheme I.

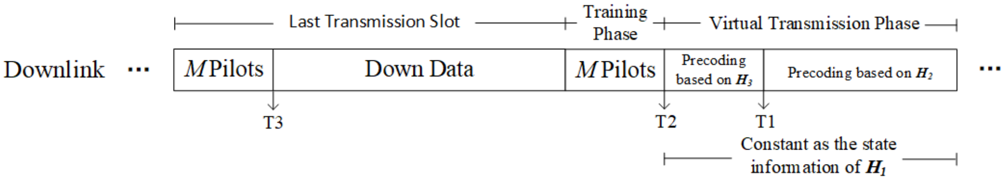


Fig. 3. Illustration of the DPT scheme II.

duration of Nyquist interval, and symbol intervals of different phase are identical. Thus, the duration of different phases only depends on the number of symbols. Recall that the duration of waiting phase is equal to the duration of CSI feedback, so the proportion of the CSI feedback waiting phase occupied in the downlink transmission which is defined as δ can be given by

$$\delta = \frac{N_{UF}}{N_{DP}+N_{UF}+N_{DD}}. \tag{14}$$

Since the amount of CSI feedback needs to be scaled with the number of transmit antennas to control the quantization error, the value of δ can be considerably high when the BS is equipped with large arrays of antennas. To utilize the CSI feedback waiting phase appropriately, we propose two novel DPT schemes for the FDD mode to mitigate the unfavorable effects of large arrays of transmit antennas in the massive MIMO systems.

Based on the basic frame structure shown in Fig. 1, we consider fetching the estimated CSI of last transmission slot to compute ZF precoding matrix, and start to precode and transmit data just after training phase in the present transmission slot. In this case, the BS does not need to wait for the CSI feedback and can transmit data in both the CSI feedback waiting and the transmission phases, not only in the transmission phase suggested in Fig. 1. Meanwhile, The BS can still obtain the estimated CSI when the CSI feedback is finished, which can be used to compute precoding matrix for the next transmission slot. The novel DPT scheme is named as DPT Scheme I and it is depicted in Fig. 2, where the virtual transmission phase includes the CSI feedback waiting phase and the original transmission phase (depicted in Fig. 1). The estimated CSI of the last transmission slot is defined as the state information of $\boldsymbol{H_3}$, the channel at time T3 that indicates the pilot training phase is just finished in the last transmission slot. We assume the virtual transmission phase of this scheme as quasi-static, and CSI of this phase is constant as the state information of $\boldsymbol{H_1}$, the channel at time T1 that indicates the CSI feedback is just finished in the present transmission slot. T2 indicates the time that the pilot training phase is just finished in the present transmission slot. We define the precoding matrix evaluated by $\boldsymbol{H_3}$ as $\boldsymbol{W_3}$. Hence the SINR of the kth user is

$$\text{SINR}_{SchemeI,k} = \frac{\alpha_{sch1} p_d |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{3,k}}|^2}{\alpha_{sch1} p_d \sum_{k'\neq k}^{K} |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{3,k'}}|^2 + 1}, \tag{15}$$

$$\alpha_{sch1} = \frac{1}{E\{\text{tr}(\boldsymbol{W_3}\boldsymbol{W_3}^H)\}}, \tag{16}$$

where $\boldsymbol{w_{3,k}}$ is the kth column of the precoding matrix $\boldsymbol{W_3} = [\boldsymbol{w_{3,1}}\ \boldsymbol{w_{3,2}}\ \cdots\ \boldsymbol{w_{3,k}}\ \cdots\ \boldsymbol{w_{3,K}}]$. The effective transmission coefficient $\beta_{Scheme\ I}$ in DPT scheme I can be written as

$$\beta_{Scheme\ I} = \frac{N_{UF}+N_{DD}}{N_{DP}+N_{UF}+N_{DD}}, \tag{17}$$

and the achievable downlink rate of DPT scheme I can be written as

$$R_{Scheme\ I} = \beta_{Scheme\ I} \times \sum_{k=1}^{K} \log_2(1+SINR_{Scheme\ I,k}). \tag{18}$$

We also propose a modified DPT scheme, which is same as the DPT Scheme I in the CSI feedback waiting phase where both they utilize the estimated CSI of last transmission slot to precode and transmit data. The difference between the two schemes is as follows: for the modified DPT scheme, the BS takes the estimated CSI of current transmission slot for precoding to transmit data in the original transmission phase (depicted in Fig. 1). However, for the DPT Scheme I, the BS still takes the estimated CSI of last transmission slot for precoding in the original transmission phase. We designate the scheme as DPT Scheme II and depict it in Fig. 3, where the virtual transmission phase includes the CSI feedback waiting phase and the original transmission phase. In the virtual transmission phase of the DPT Scheme II, the BS first precodes downlink data based on the state information of $\boldsymbol{H_3}$ from time T2 to time T1, and then precodes data based on the state information of $\boldsymbol{H_2}$. Hence, the SINR of kth user can be roughly calculated as

$$\mathrm{SINR}_{Scheme\ II,k} = \delta \times \frac{\alpha_{sch1} p_d |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{3,k}}|^2}{\alpha_{sch1} p_d \sum_{k' \neq k}^{K} |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{3,k'}}|^2 + 1} + \lambda \times \frac{\alpha_{cont} p_d |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{2,k}}|^2}{\alpha_{cont} p_d \sum_{k' \neq k}^{K} |\boldsymbol{h_{1,k}}^T \boldsymbol{w_{2,k'}}|^2 + 1}, \tag{19}$$

where λ denotes the proportion of the original transmission phase occupied in the downlink transmission, which can be written intuitively as

$$\lambda = \frac{N_{DD}}{N_{DP} + N_{UF} + N_{DD}}. \tag{20}$$

Thus, the achievable downlink rate of the DPT Scheme II is

$$R_{Scheme\ II} = \delta \times R_{Scheme\ I} + \lambda \times R_{contemporary}. \tag{21}$$

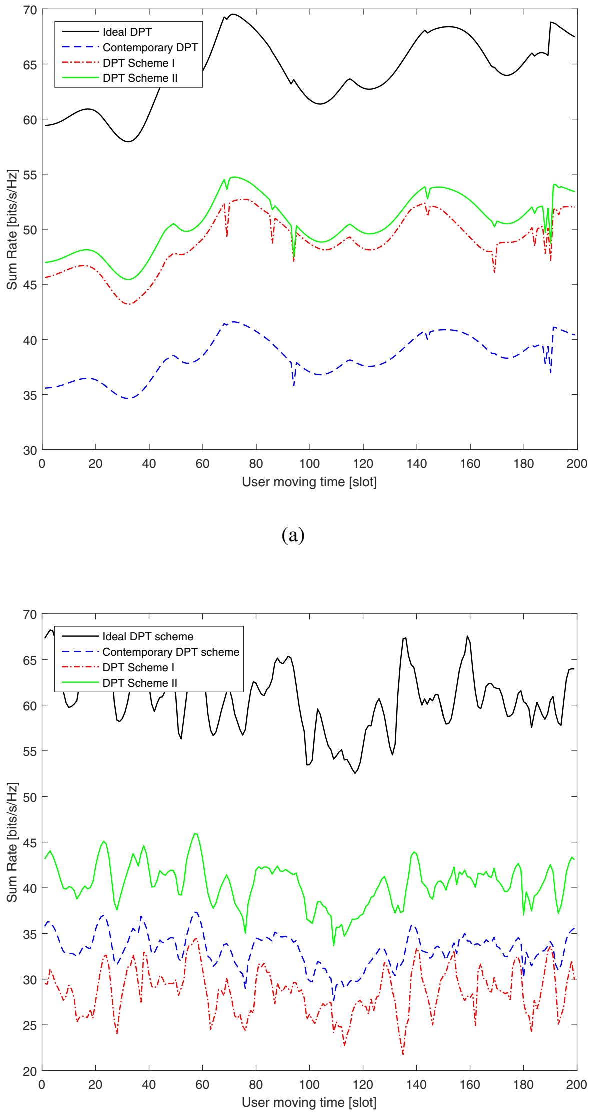
Obviously, λ is equal to the effective transmission coefficient of the contemporary DPT scheme. That is to say, the DPT scheme II combines the DPT scheme I with the contemporary DPT scheme.

IV. NUMERICAL RESULTS

In this section, we present our preliminary numerical results to evaluate our proposed two DPT schemes. We consider a FDD massive MIMO system with $M = 64$, $K = 6$. Then we choose the minimal symbol length for the pilots, and K users are required to send M CSI feedback symbols to the BS over the uplink [4], so $N_{DP} = N_{UF} = M$ symbols. The length of downlink data is 192 symbols, hence the total length of one downlink transmission slot is 320 symbols. For the typical OFDM symbol parameters, the slot duration T_{slot} can be computed as 1.63 ms. The transmit power is 20 dBm. We adopt the COST 2100 outdoor channel model, where the bandwidth $B = 20$ MHz and the central frequency f_c=285 MHz. Also, we set the user speed to be in the range of [0, 40] m/s, which corresponds to the common user mobility including pedestrian and vehicle scenarios. The main simulation parameters are summarized in TABLE 1.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
Number of BS antennas	M=64
Number of users	K=6
Slot duration	T_{slot}=1.63 ms
Transmit power	20 dBm
Total bandwidth	$B = 20$ MHz
Central frequency	f_c=285 MHz
User speed	[0, 40] m/s



(a)

(b)

Fig. 4. Achievable downlink rates of different DPT schemes versus user moving time based on two different scenarios: a) low-mobility scenario; b) high-mobility scenario.

First, we compare the achievable downlink rates of different DPT schemes including the contemporary, the ideal, and our proposed DPT Scheme I, II with respect to the user moving time. We assume that the users start to move at the same time in their given speeds. The two typical diagrams are picked out to illustrate the simulation results in Fig. 4. Fig. 4a illustrates the low-mobility scenario where the velocities of six users are set to [5 5 6 6 8 8] m/s, respectively, and Fig. 4b shows the high-mobility scenario where the velocities of six users are set to [30 30 32 32 34 35] m/s, respectively. Fig. 4 indicates that our proposed two DPT schemes can achieve much higher downlink rates than that of the contemporary DPT scheme in low-mobility scenario with the users moving. However, the DPT Scheme I performs worse in high-mobility scenario though the DPT Scheme II still outperforms the contemporary DPT scheme. The reason behind this is that the channel aging has a small impact on the accuracy of CSI when the channel

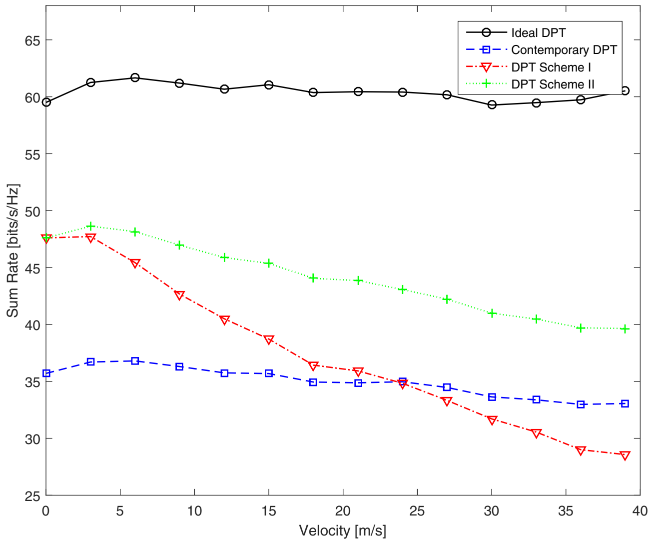


Fig. 5. Achievable downlink rates of different DPT schemes versus user velocity.

varies slowly with low speed. In this case, the achievable gains with exploiting CSI feedback waiting phase outperform the unfavorable effects of channel aging. When the velocity ascends, the impact of channel aging on the accuracy of CSI will dominate the achievable downlink rates.

To demonstrate the impact of user mobility on different DPT schemes more clearly, we illustrate the achievable downlink rates of different DPT schemes with respect to the velocities of users as in Fig. 5. For simplicity, we assume that the velocities of six users are all identical. From Fig. 5, we can see that the proposed DPT Scheme II always outperforms the contemporary DPT scheme and the DPT Scheme I in the whole velocity range. Also, the proposed DPT Scheme I is more attractive than the contemporary DPT in relative low-mobility scenarios. However, as the velocity increases, the performance of the DPT Scheme I gets worse than the contemporary DPT one. Apparently, the DPT Scheme II is more robust to user mobility compared to the DPT Scheme I.

V. CONCLUSION

In this paper, we investigated how to utilize the CSI feedback waiting phase in the FDD massive MIMO systems and proposed two novel downlink precoding and transmission (DPT) schemes, both of which can exploit the CSI feedback waiting phase efficiently. Also, we have studied the achievable downlink rates of the proposed two DPT schemes over the COST 2100 outdoor channel model. Numerical results show that one of our proposed DPT schemes performs better than the contemporary DPT scheme in relative low-mobility scenarios, but gets inefficient when users speed up. The other proposed DPT scheme not only outperforms the former proposed DPT scheme and the contemporary DPT one in terms of achievable downlink rates, but also has stronger robustness to the user mobility. From the standpoint of performance, no doubt that the latter proposed DPT scheme is more recommended. However, the former proposed DPT scheme only needs to evaluate the precoding matrix once in one transmission slot which can reduce computational complexity. In future work, it is necessary to make a trade-off between the DPT performance and computational complexity according to practical application scenarios. Last but not least, we think that the potential for leveraging the CSI feedback waiting phase extends current researches for the massive MIMO systems and can be further exploited for future study.

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