The potential approaches to achieve channel reciprocity in FDD system with frequency correction algorithms

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***Abstract*—Channel reciprocity is an inherit feature of time division duplex (TDD) system, which is widely used to get uplink (UL)/downlink (DL) channel knowledge from DL/UL channel measurements without additional feedback. While in frequency division duplex (FDD) system, the transmitter usually obtains the DL channel state information (CSI) through a variety of feedback strategies in order to enhance the system performance. However, the impacts of feedback overhead and delay on Multiple-Input-Multiple-Output (MIMO) performance can't be ignored. The paper focuses on the potential approaches to realize FDD channel reciprocity so as to reduce the feedback channel overhead. Compared with TDD system, UL and DL are allocated by different frequencies in FDD system thus the frequency correction is needed to achieve channel reciprocity. The paper presents the performance analysis and comparison of typical frequency correction algorithms, especially the algorithms based on the long-term statistical channel characteristics, which mainly include the channel covariance matrix, the channel space-time correlation, and the direction of arrival (DoA). The potential application scenario for each approach is presented as conclusion.**

Keywords-receprocity; FDD; frequency correction; DOA; covariance matrix; Spatio-Temporal Correlation

I. INTRODUCTION

A Multiple-Input-Multiple-Output (MIMO) system is equipped with antenna arrays at both transmitter and receiver. MIMO technology has attracted substantial attention in wireless communications, because it can achieve higher spectral efficiency and link reliability or diversity. MIMO has been adopted as a fundamental technique both for single-user and multi-user in IMT-Advanced. In the downlink, the system performance can be significantly enhanced through the use of scheduling, beam-forming and power allocation techniques. To achieve beam-forming, the Base Station (BS) transmitter must be informed with the channel state information (CSI) of the DL. This has motivated the proposal of many approaches to provide the channel state information at the transmitter (CSIT) more efficiently.

There are roughly two categories to provide CSIT depending upon the chosen duplex scheme for the wireless network. In the case of TDD system, it is proposed to obtain CSIT by using the reciprocity of the UL and DL channels, in order to avoid the resource consume brought by feedback channel. However, in FDD system, UL and DL are allocated with different frequencies and hence the channel realizations can be safely assumed independent of each other. Therefore, a dedicated feedback is used, in which the user conveys the information of the estimated DL channel back to the BS, due to the lack of the channel reciprocity. Moreover, there are also many strategies proposed on how to use a limited feedback channel efficiently while providing the BS with exploitable CSIT. Recently, several interesting strategies have attracted attention to the channel reciprocity in FDD system.

Since UL and DL are allocated by different frequencies in FDD system, the frequency correction is needed to achieve channel reciprocity. In [1], the base station (BS) reuses the spatial (angular) information derived during UL reception, but a prerequisite for this algorithm is that the spatial channel characteristics at the UL and DL frequencies are similar. Different channel sounding campaigns is processed in [2]-[5] to discuss whether the DL channel information can be obtained by the UL channel information in FDD system, but the conclusions seem to be contradictory. Therefore, further discussion through the estimation and calculation of the field measurement is presented in [6], which proves that the UL and DL channel spatial information is relevant, and the UL channel spatial information can be used for DL beam-forming. Similarly, in [7], when the UL and DL frequency interval is set to be 200MHz of FDD system, which means that the UL and DL channel fading are not related, the DOAs of them are roughly the same. Reference [8]-[10] introduce the methods that DL covariance matrix is transformed by the use of UL channel covariance matrix. In addition, 3GPP proposals [11]-[17] have also made a discussion among various companies. It is shown in [11] that DL covariance matrix can be generated utilizing UL covariance matrix at BS, and the transformation matrix is provided. In [18], both beam-forming and MU-MIMO results for a FDD system with actual field measurements at 3.5GHz are provided. The estimation of both temporal and spatial DL correlation using UL correlation is investigated in [20], but is not considered in a joint way. Therefore, an improved algorithm is presented in [21], which the conversion from UL to DL is treated jointly on the temporal and the spatial correlation.

In this paper, we present the performance analysis and comparison of typical frequency correction algorithms, especially the algorithms based on the long-term statistical channel characteristics, which mainly include the channel covariance matrix, the channel space-time correlation, and the direction of arrival (DoA).

II. CHANNEL MODEL

The channel model is critical for the simulation of using channel reciprocity in FDD system. We consider the channel models according to the geometry of array.

Suppose that both the transmit and receive arrays are uniform linear array (ULA) and there are k scatters (within one cluster) between the transmitter and receiver, one physical MIMO channel model for this cluster is

$$\mathrm{H} = \sum_{k=1}^{K} \beta_k \mathrm{a}_R(\phi_{R,k}) \mathrm{a}_T^H(\phi_{T,k}) \qquad (1)$$

Where β_k is the path gain for the *k*th scatter, $\phi_{T,k}$ and $\phi_{T,k}$ are AOD and AOA, respectively.

Fig 1 shows the diagram of equidistant linear antenna for receiving the signal. It is assumed that the electromagnetic wave transmits through a long distance. When it reaches the space antenna array, the reached wave can be regarded as a plane wave. The same assumption can also be employed by the transmitting signal.

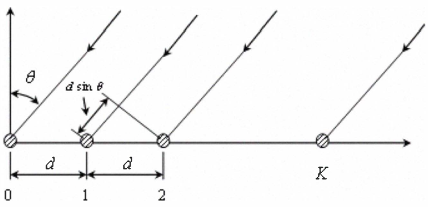

Figure 1. uniform linear array (ULA) receiving signal diagram

Array response vectors at both sides are described as:

$$\mathrm{a}_T(\phi_{T,k}) = \begin{bmatrix} 1 \\ \exp(-j2\pi\theta_{T,k}) \\ \vdots \\ \exp(-j2\pi(M-1)\theta_{T,k}) \end{bmatrix} \qquad (2)$$

$$\mathrm{a}_R(\phi_{R,k}) = \begin{bmatrix} 1 \\ \exp(-j2\pi\theta_{R,k}) \\ \vdots \\ \exp(-j2\pi(N-1)\theta_{R,k}) \end{bmatrix} \qquad (3)$$

Where $\theta_{T,k} = d_t \sin(\phi_{T,k}) / \lambda$ and $\theta_{R,k} = d_r \sin(\phi_{R,k}) / \lambda$, the wavelength is λ, d_t and d_r are respectively the distance between the transmit and receive array.

The equation (1) can be written as matrix form:

$$\mathrm{H} = \mathrm{A}_R \mathrm{H}_P \mathrm{A}_T^H \qquad (4)$$

Where $\mathrm{A}_R = [\mathrm{a}_R(\phi_{R,1}),...,\mathrm{a}_R(\phi_{R,K})]$ is M by K matrix, $\mathrm{A}_T = [\mathrm{a}_T(\phi_{T,1}),...,\mathrm{a}_T(\phi_{T,K})]$ is N by K matrix, and $\mathrm{H}_p = diag(\beta_1,...,\beta_K)$ is diagonal matrix.

III. ANALYSIS OF FREQUENCY CORRECTION ALGORITHM

Since UL and DL are allocated by different frequencies in FDD system, the frequency correction is needed to achieve channel reciprocity. This section analyses all kinds of algorithms based on different long-term statistical characteristics.

A. *Frequency Correction Based on DOA*

Recently, several contributions have discussed whether the DL channel state information can be obtained by the UL channel state information in FDD system[1]-[5]. Reference [6] summarized the potential ways of the above documents, and provided a more comprehensive analysis. Assume the UL channel frequency with 1935MHz and the DL channel frequency with 2125MHz, the difference of the dominant UL and DL DOA is obtained as

$$\varphi_{dom,diff}(f_{UL}, f_{DL}) = \varphi_{dom}(f_{UL}) - \varphi_{dom}(f_{DL}) \qquad (5)$$

Though a great deal of measurements, the probability of the DOA difference is

$$\mathrm{P}\{\varphi_{dom,diff} \in (-0.5^\circ, 0.5^\circ)\} = 0.18$$
$$\mathrm{P}\{\varphi_{dom,diff} \in (-1.5^\circ, 1.5^\circ)\} = 0.46$$
$$\mathrm{P}\{\varphi_{dom,diff} \in (-2.5^\circ, 2.5^\circ)\} = 0.62$$
$$\mathrm{P}\{\varphi_{dom,diff} \in (-4.5^\circ, 4.5^\circ)\} = 0.81$$

Where $\mathrm{P}\{\bullet\}$ indicates the probability of the values. In general, the dominant DOAs in UL and DL show only a minor deviation. Therefore, the utilization of the dominant DOA estimated during UL reception for DL beam-forming purpose is reasonable.

The system performance between the non-equal gain beam-forming and beam-forming using UL DOA through channel reciprocity is compared in [14]. The DL covariance matrix utilized from UL channel DOA can be described as

$$\mathbf{R}_{DL} = p\mathbf{a}_{DL}(\theta_{\max})\mathbf{a}_{DL}^H(\theta_{\max}) \qquad (6)$$

Where $\theta_{\max}$ is the UL DOA. This algorithm is proposed based on the similitude of DOA between the UL and DL channel. Compared with non-equal gain beam-forming, the algorithm makes a small loss in the system performance. But in MU-MIMO applications, performance loss will be increased, since DOA loses the important spatial information.

In addition, the accurate estimate of DOA from the UL data is the key to this algorithm.

B. Frequency Correction Based on Covariance Matrix

The methods for the UL to DL information transformation based on the covariance matrix were provided in [8]-[19], which further realize the frequency correction. In FDD system, the typical algorithms for UL to DL information transformation are based on the channel long-term information (e.g. covariance matrix), because the long-term statistic covariance matrix changes much more slowly than the coherence time and bandwidth of the channel. Therefore, a covariance matrix is valid on both UL and DL frequency bands. Even though the duplex distances are large, we can use the frequency correction techniques to improve the accuracy.

In [8], UL to DL covariance matrix transformation techniques based on Minimum Mean Square Error (MMSE) is introduced. And then, Minimum Variance Distortion-less Response (MVDR) filter is presented in [9], in order to obtain DL covariance matrix based on UL covariance matrix. The transformation process is shown as Fig 2. .

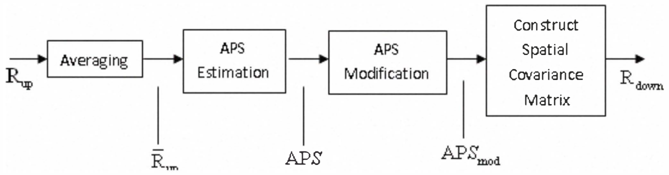

Figure 2. UL to DL Covariance Matrix Transformation

Due to the effects of the angular spread and multi-paths, there are errors between the presumed and the actual UL steering vectors. Reference [10] has proposed a scheme to correct the errors, and in comparison, the system performance is enhanced. And this method is further discussed in [12], considering the impacts of the antennas on the channel reciprocity. The main issues included the impact of the antenna response on DL covariance matrix, and the affect of correlation between antennas on the measurement of UL covariance matrix. In addition, reference [12] proposed an algorithm to obtain DL covariance matrix from UL covariance matrix by frequency transformation matrix.

Assuming a uniform linear array (ULA), UL/DL covariance matrix at the base station (BS) can be shown as

$$\boldsymbol{R} = \int_{\vartheta} p(\phi)\boldsymbol{a}(\phi)\boldsymbol{a}^H(\phi)\,d\phi \qquad (7)$$

where $p(\phi)$ is the ray power density at direction of arrival/departure angle ϕ , and $\boldsymbol{a}(\phi)$ is the antenna array response (steering vector). In the condition of ULA, the antenna array response in the UL and DL of direction ϕ is obtained as

$$\mathrm{a}_{UL}(\phi) = [1, \exp(-j2\pi\frac{d}{\lambda}\frac{f_{UL}}{f_0}\sin(\phi)), \cdots, \exp(-j2\pi\frac{d}{\lambda}\frac{f_{UL}}{f_0}(M-1)\sin(\phi))]^H$$

and

$$\mathrm{a}_{DL}(\phi) = [1, \exp(-j2\pi\frac{d}{\lambda}\frac{f_{DL}}{f_0}\sin(\phi)), \cdots, \exp(-j2\pi\frac{d}{\lambda}\frac{f_{DL}}{f_0}(M-1)\sin(\phi))]^H \qquad (8)$$

where d is the antenna separation [in meters], λ is the wavelength of the carrier [in meters], and M the number of array antennas. The ULA is designed for the carrier frequency f_0 , f_{DL} and f_{UL} are the DL and UL carrier frequencies respectively.

If the frequency duplex is large, in order to estimate DL channel covariance matrix accurately, a frequency transformation matrix is introduced as

$$\mathrm{a}_{DL}(\phi) = \mathrm{T}(\phi)\mathrm{a}_{UL}(\phi) \qquad (9)$$

and the diagonal transformation matrix is

$$\mathrm{T}(\phi) = diag(1, e^{-j2\pi\frac{d}{\lambda}\frac{f_{UL}-f_{DL}}{f_0}\sin(\phi)}, \cdots, e^{-j2\pi\frac{d}{\lambda}\frac{f_{UL}-f_{DL}}{f_0}(M-1)\sin(\phi))}) \qquad (10)$$

Then downlink covariance estimate can be obtained as

$$\widehat{\mathrm{R}}_{DL} = \mathrm{T}(\phi)\mathrm{R}_{UL}\mathrm{T}^H(\phi) \qquad (11)$$

By estimating the dominating DOA in the UL, for example, $\phi_{\max}$, we can improve the estimate of $\widehat{\mathrm{R}}_{DL}$.

In [19], it's assumed that the uniform circular array (UCA) for UL and DL, the same algorithm is used to obtain (11).

C. Frequency Correction Based on Spatio-Temporal Correlation

In general, space-time pre-processing at the base station, such as beam-forming or channel pre-coding, can profit from the knowledge of the DL spatio-temporal correlation properties. Compared with methods above considering the spatial correlation only, reference [20] investigates the estimation of both temporal and spatial DL correlation using an UL correlation estimate. However, the frequency transformation is not considered in a joint way. On the basis of [20], reference [21] presented an improved algorithm, in which the conversion of UL to DL correlation is treated jointly for the temporal and the spatial correlation. The results show that the correlation between UL and DL is related to the ratio between UL and DL carrier frequency. Consequently, the DL correlation can gain easily from the UL correlation.

Assuming the transmitter with n_T antennas and the receiver with 1 antenna, with S discrete scatters surrounding the mobile user, the channel impulse response can be obtained as

$$h(n) = \sum_{s=1}^{S} \alpha_s \exp\{j(2\pi f_{D,s} nT_{sl} + \varphi_s)\} a(\theta_s) \qquad (12)$$

Where T_{sl} is the time slot duration, α_s is the signal amplitude, θ_s is the angle of arrival as seen from the base station, $f_{D,s}$ is the Doppler shift and φ_s a random phase shift of the S$^{\text{th}}$ scatter, respectively. The vector $a(\theta_s)$ is the steering vector of a uniform linear array (ULA).

The spatio-temporal correlation matrix is defined as follows

$$R(m) = E\{h(n)h^H(m+n)\} \qquad (13)$$

Where the (i,j) element of the matrix R is

$$r([i-j],n)=[R(n)]_{i,j}=\sum_{s=1}|\alpha_s|^2\exp\{j(2\pi[\frac{D_{ie}}{\lambda}(i-j)\sin\theta_s-f_{D,s}n_{sl}]\}\qquad(14)$$

It can be seen that the correlation depends on the carrier frequency. Assume the UL frequency f_u and the DL frequency f_l, then the UL correlation function can be given as

$$r_u(m,n)=\sum_{s=1}^{S}|\alpha_s|^2\exp\{j(2\pi[\frac{D_{ie}}{\lambda_u}m\sin\theta_s-f_{D,s,u}nT_{sl}]\}\qquad(15)$$

Similarly, DL correlation function $r_d(m,n)$ can be gained, with $\lambda_u=\frac{c_0}{f_u}$ $f_{D,s,u}=v_0f_u/c_0\cos\beta_s$, UL and DL correlation can be seen to depend on each other via

$$r_d(m,n)=r_u(m\cdot k_g,n\cdot k_g)\qquad(16)$$

Where $k_g=\frac{f_d}{f_u}$ is the relative duplex gap.

In addition, a fast calculation algorithm based on Fourier coefficient is also proposed in [21].

IV. SIMULATION RESULTS

Due to the duplex frequency distances between UL and DL in FDD systems, the UL and DL covariance matrix are different. In the simulation, the impact of covariance matrix mismatch is investigated and the related simulations are provided by taking the adaptive codebook as an example. In addition, the effects brought by the antenna correlation are also analyzed. The simulation parameters are listed in TABLE I.

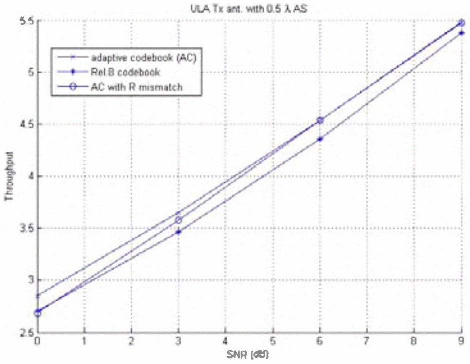

Figure 3. Performance comparison of ULA with 0.5λ AS

TABLE I. SIMULATION PARAMETER

Parameter	Assumption
Channel model	SCM UMa
Carrier Frequency	DL: 2.85 GHz, UL: 2.51 GHz
Number of Subcarriers	512
Bandwidth	5M
UE Speed (km/h)	3
Pre-coding type	Subbands (5PRB) and Wideband
Feedback type	2 Subbands or Wideband feedback
Antenna configuration	4x2 0.5 and 4 wavelength antenna spacing at eNodeB 0.5 wavelength antenna spacing ULA or cross polarized antennas at UE
Polarization antenna	ULA and Cross polarized
RS density	DL: 6 CRS/antenna/PRB UL: 30 SRS/antenna/subband/5ms
Channel estimation	Ideal
CQI estimation	Ideal
Receiver	MRC/MMSE
Baseline codebook	Rel.8 codebook
MIMO mode	SU-MIMO with Rank-1 transmission

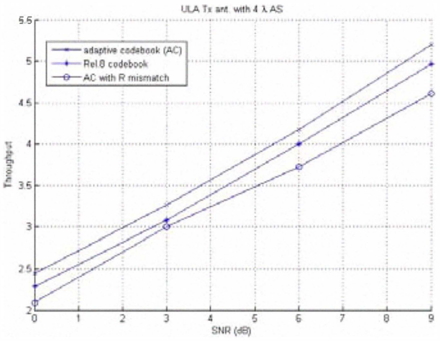

Figure 4. Performance comparison of ULA with 4λ AS

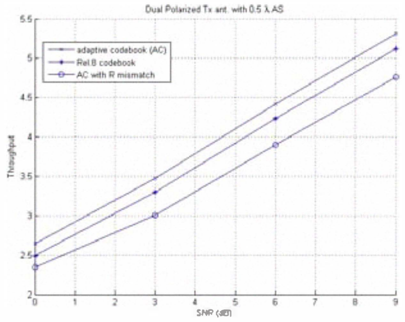

Figure 5. Performance comparison of dual-polarized antenna array with 0.5λ AS

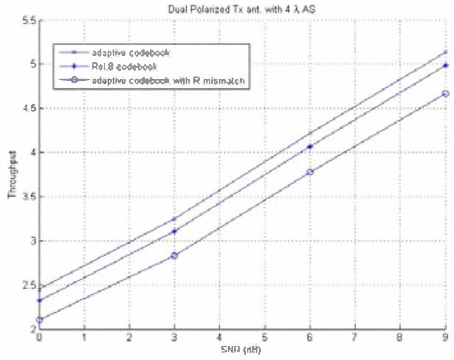

Figure 6. Performance comparison of dual-polarized antenna array with 4λ AS

The performance comparison based on ULA with 0.5λ antenna spacing is shown in Fig 3. As shown in the result, UL transmission based DL covariance estimation works quite well. The impact of R mismatch is very limited and can be negligible.

Performances with ULA with 4λ and dual-polarized antenna array are evaluated , which were shown in Fig.5, Fig6 and Fig.7. Even though the channel of ULA with 4λ is still relatively correlated, the performance degradation however becomes quite significant. When dual-polarized antenna array is assumed, the performance degradation becomes even severer.

As can be seen from the simulation, compared with the traditional feedback form, using the channel reciprocity to estimate DL covariance matrix based on UL covariance matrix has a performance loss inevitably, which is due to a variety of factors, such as the antennas correlation. When the correlation is poor, it is not appropriate to use channel reciprocity. Certainly, there are maybe other factors, for instance frequency duplex distance, antenna configuration propagation scenarios, and so on. However, the channel reciprocity does have advantages in reducing the system overhead, it can be inferred that as long as we design a practical system, in which a certain loss conditions can be accept but also accept a certain loss conditions, it can be considered to apply FDD channel reciprocity.

V. CONCLUSION

The paper presents the performance analysis and comparison of typical frequency correction algorithms, especially the algorithms based on the long-term statistical channel characteristics, which mainly include the channel covariance matrix, the channel space-time correlation, and the direction of arrival (DoA). Due to the duplex frequency distances between UL and DL in FDD systems, to achieve a DL beam-former from UL channel state information, we usually focus on the parameters or statistics of the propagation channel that remain almost the same between UL and DL. The performance of frequency correction algorithm based on DoA strongly relied on the accuracy of DOA estimation using UL signal, and may not be adopted for the scenarios with angular spreading and distributed scatter. However, the algorithm based on the transformation from UL channel information to DL channel information, does not make any assumption about spatial distribution of scatters, and it can transpose second order statistics of the channel from UL to DL frequency. Moreover, the performance of this algorithm is affected by the antenna array topology, the appropriate antenna array can enhance system performance. The algorithm based on the Spatio-Temporal correlation considered both the spatial channel characteristics and the time characteristics. However, it is computationally exhaustive.

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