Pilot Design for Inter-Cell Interference Mitigation in MIMO OFDM Systems

Guixia Kang, *Member, IEEE,* Philipp Hasselbach, Yu Yang, Ping Zhang, and Anja Klein

***Abstract*— In this letter, the design of pilots aiming at mitigating the inter-cell interference in MIMO OFDM systems is addressed. It is shown that if an ideal channel between interferer and receiver is assumed, pilots resulting in a variation coefficient of zero, and therefore best performance on system level, can be designed. The properties of these pilots are described, and numerical calculations as well as simulation results are presented to verify the theoretical analysis.**

***Index Terms*— Pilot design, inter-cell interference, MIMO, OFDM.**

I. INTRODUCTION

RECENTLY, wireless communication systems are developing from the third generation (3G) into the beyond 3G or fourth generation (4G). In order to support more users and to maximize the profit of investments, the overall spectral efficiency of the systems has to be increased. Channel knowledge, i.e., channel transfer functions (CTFs) or channel impulse responses (CIRs), influences the spectral efficiency of the system by considering its application in data detection as well as some transmission techniques [1]. In multiple access systems, intra-cell as well as inter-cell multiple access interference (MAI) occur [2], which limit the performance of pilot-aided channel estimation.

Joint channel estimation (JCE) [3] [4] is a pilot-aided multi-user channel estimation technique, capable of canceling intra-cell MAI and inter symbol interference (ISI) simultaneously. In multi-cell environments, however, inter-cell MAI still occurs, which degrades the performance of the estimation on system level.

In this letter, we focus on the pilot design in MIMO OFDM systems in multi-cell environments, which is still an open question in this area. In Section II, the system model and the interference model of the considered multi-cell MIMO OFDM system are described. In Section III, the system performance in the multi-cell environment is evaluated by means of the variation coefficient. Section IV derives the design criterion of pilots for the ideal interference channel case and presents the properties of pilots resulting in a variation coefficient of zero. Then the derived criterion is applied to construct pilots for multi-cell environments. In Section V, numerical calculations as well as simulation results are provided to verify the theoretical analysis. This letter is concluded in the last Section VI.

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G. Kang, Y. Yang, and P. Zhang are with Beijing University of Posts and Telecommunications, Beijing, P.R. China, 100876 (email: gxkang@bupt.edu.cn).

P. Hasselbach and A. Klein are with the Technical University of Darmstadt.

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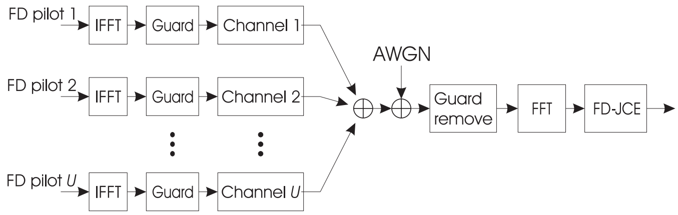

Fig. 1. MIMO OFDM system model.

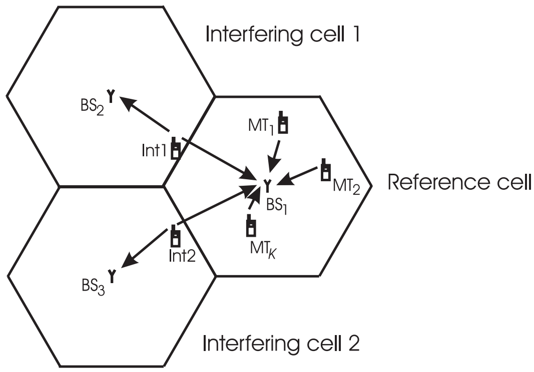

Fig. 2. Application scenario.

II. SYSTEM AND INTERFERENCE MODEL

A MIMO OFDM system model is considered as shown in Fig. 1 [5]. In this system model, it is not distinguished if the training sequences are sent by several users with one antenna per user or if they are sent by different antennas that belong to the same user, or by a mixture of both.

The application scenario is illustrated in Fig. 2 with three neighboring cells, the reference cell and two interfering cells. All cells use the same frequency band, and inter-cell MAI occurs due to the simultaneously active mobile terminals (MTs) in each of the cells. For the reference cell, all MTs from the adjacent cells are interferers. Typically, a few of the interferers are stronger than the others. In this letter, we assume one strong interferer in each of the interfering cells.

It is assumed that the pilots of length N_{F} are transmitted over N_{F} subcarriers and that the maximum multi-path delay is W times of symbol duration and the path number of channel is Q. Applying frequency domain JCE (FD-JCE), the maximum number of CIRs that can be jointly estimated is given by [3] [4]

$$U_{\max} = \frac{N_{\mathrm{F}}}{W}. \tag{1}$$

III. Performance Analysis in Multi-Cell Environments

In this section, the frequency domain variables are distinguished from the time domain variables with a tilde. The variation coefficient is introduced as a measure of the influence of a single interferer on the active users in the reference cell. With the pilot matrix of the considered one strong interferer from one of the interfering cells

$$\underline{\tilde{\mathbf{P}}}_{\mathrm{I}} = \mathrm{diag}\left\{\underline{\tilde{p}}_{\mathrm{I},0} \ \cdots \ \underline{\tilde{p}}_{\mathrm{I},N_{\mathrm{F}}-1}\right\} \tag{2}$$

of dimension $N_{\mathrm{F}} \times N_{\mathrm{F}}$, and the pilot matrix of all pilots applied in the reference cell

$$\underline{\tilde{\mathbf{P}}} = \left[\mathrm{diag}\left\{\underline{\tilde{p}}_0^{(1)} \ \cdots \ \underline{\tilde{p}}_{N_{\mathrm{F}}-1}^{(1)}\right\} \ldots \mathrm{diag}\left\{\underline{\tilde{p}}_0^{(U)} \ \cdots \ \underline{\tilde{p}}_{N_{\mathrm{F}}-1}^{(U)}\right\}\right] \tag{3}$$

of dimension $N_{\mathrm{F}} \times UN_{\mathrm{F}}$, in which $\underline{\tilde{p}}_{\mathrm{n}}^{(u)}$, $u = 1 \ldots U$, $n = 0 \ldots N_{\mathrm{F}} - 1$, indicates the n-th pilot symbol sent over antenna u, the frequency domain receive signal can be expressed as [5]

$$\underline{\tilde{\mathbf{r}}}_{\mathrm{A}} = \underline{\tilde{\mathbf{P}}} \ \underline{\tilde{\mathbf{h}}} + \underline{\tilde{\mathbf{P}}}_{\mathrm{I}} \underline{\tilde{\mathbf{h}}}_{\mathrm{I}}. \tag{4}$$

In (4), $\underline{\tilde{\mathbf{h}}}$ is the total CTF vector of the channels between the U antennas and the receiver and has dimension UN_{F}, and $\underline{\tilde{\mathbf{h}}}_{\mathrm{I}}$ is the CTF vector of the channel between the interferer and the receiver of dimension N_{F}. Noise is not considered in (4), since it is assumed that the interference is much stronger than the noise.

Applying the FD Least Squares JCE (FD-LS-JCE) [3][4] to the receive signal vector $\underline{\tilde{\mathbf{r}}}_{\mathrm{A}}$ of (4), the estimate $\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}}$ of the total CIR vector $\underline{\mathbf{h}}$ can be calculated. The time domain estimation error is given by [3]

$$\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}} = \left(\underline{\tilde{\mathbf{G}}}^{\mathrm{H}} \underline{\tilde{\mathbf{G}}}\right)^{-1} \underline{\tilde{\mathbf{G}}}^{\mathrm{H}} \underline{\tilde{\mathbf{P}}}_{\mathrm{I}} \underline{\tilde{\mathbf{h}}}_{\mathrm{I}} \tag{5}$$

with

$$\underline{\tilde{\mathbf{G}}} = \underline{\tilde{\mathbf{P}}} \ \underline{\tilde{\mathcal{F}}}_{\mathrm{W,tot}}, \tag{6}$$

in which $\underline{\tilde{\mathcal{F}}}_{\mathrm{W,tot}}$ is a blockdiagonal matrix of dimension $UN_{\mathrm{F}} \times UQ$ whose diagonal block is composed of Q columns of a N_{F}-point discrete fourier transform (DFT) matrix [5]. The mean value of the interference power can be expressed as

$$\bar{I} = \frac{1}{UQ}\left(\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right)^{\mathrm{H}}\left(\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right), \tag{7}$$

based on which the mean square deviation of the interference power

$$\sigma_{\mathrm{I}}^2 = \frac{1}{UQ}\sum_{j=1}^{UQ}\left(\left[\left(\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right)\left(\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right)^{\mathrm{H}}\right]_{j,j} - \bar{I}\right)^2 \tag{8}$$

is obtained. The variation coefficient v_{c} is then defined as [5]

$$v_{\mathrm{c}} = \frac{\sqrt{\sigma_{\mathrm{I}}^2}}{\bar{I}}. \tag{9}$$

It is a measure for the fluctuation of the estimation error over all antennas and paths. A system with a smaller variation coefficient will show better performance on system level.

TABLE I
THE VARIATION COEFFICIENT FOR DIFFERENT PILOT SETS.

	$N_{\mathrm{F}} = 441$, $M_{\mathrm{R}} = 4$			$N_{\mathrm{F}} = 275$, $M_{\mathrm{R}} = 7$	
M_{I}	v_{c}	v_{c}(dB)	M_{I}	v_{c}	v_{c}(dB)
17	0	$-\infty$	21	0	$-\infty$
11	154	22	49	0	$-\infty$
67	496	27	62	404	26
130	496	27	117	404	26

IV. Design of Pilots in Multi-Cell Environments

As in the last section, we first consider a single interferer. For best performance on system level, a variation coefficient of zero is desirable. According to (9), the variation coefficient depends on the standard deviation of the interference power, so that a variation coefficient of zero implies a time domain estimation error over UW samples yielding to

$$\left|\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right|_j = \mathrm{const}, \quad j = 0 \ldots UW - 1. \tag{10}$$

We now assume the use of optimum pilots within the reference cell and an ideal channel $\underline{\tilde{\mathbf{h}}}_{\mathrm{I}}$ between the interferer and the receiver. The use of optimum pilots in the reference cell implies [3]

$$\left(\underline{\tilde{\mathbf{G}}}^{\mathrm{H}} \underline{\tilde{\mathbf{G}}}\right)^{-1} = \frac{1}{E_{\mathrm{p}}} \mathbf{I}_{UW}, \tag{11}$$

in which E_{p} is the pilot energy and $\mathbf{I}_{UW}$ is the unity matrix of dimension $UW \times UW$. The ideal channel between the interferer and the receiver means that all N_{F} elements of vector $\underline{\tilde{\mathbf{h}}}_{\mathrm{I}}$ are equal and in the following normalized to one. The elements of (5) can then be derived as

$$\left(\underline{\hat{\mathbf{h}}}_{\mathrm{LS,A}} - \underline{\mathbf{h}}\right)_m = \frac{1}{E_p}\sum_{n=0}^{N_{\mathrm{F}}-1} \underline{\tilde{p}}_n^{(u)*} \underline{\tilde{p}}_{\mathrm{I},n} e^{\jmath \frac{2\pi}{N_{\mathrm{F}}} nk},$$
$$m = 0 \ldots UW - 1, \quad u = m \ \mathrm{div}\ W, \quad k = m \bmod W, \tag{12}$$

where mod is the modulo operation, div is the integer division, and $\underline{\tilde{p}}_{\mathrm{I},n}$ are the interferer's pilot symbols of (2).

Pilots for multi-cell environments can be constructed for example from Constant Amplitude Zero Autocorrelation (CAZAC) codes [6]. Applying different values for parameter M in the CAZAC codes of Chu sequences [7]

$$\underline{\tilde{p}}_n = e^{\jmath \frac{M\pi n(n+\mathrm{mod}(N,2))}{N_{\mathrm{F}}}}, n = 0 \ldots N - 1, \tag{13}$$

it is possible to find sufficient sets of pilots that cause a variation coefficient of zero in multi-cell environments to equip several cells. Substituting (13) with different parameters M_1 and M_2 of two Chu sequences into (12), it can be derived that (10) is fulfilled if and only if $M_1 - M_2$ is prime with N_{F}, which gives the design criteria of pilots of zero variation coefficience in multi-cell environments.

A further discussion is made on the maximum number of pilots with variation coefficience of zero. If N_{F} is prime, the largest number of Chu sequences with different M whose mutual v_c equals to zero is $N_{\mathrm{F}} - 1$. Otherwise, if N_{F} is not prime, $X - 1$ different Chu sequences whose mutual v_c is zero can be obtained, where X is the minimum factor of N_{F} larger than 1.

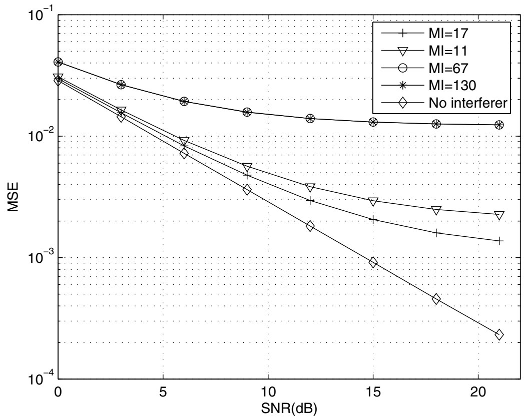

Fig. 3. Mean Square Error (MSE) in the reference cell with different pilot sets in the interference cell (one interferer, $M_{\mathrm{R}} = 4$).

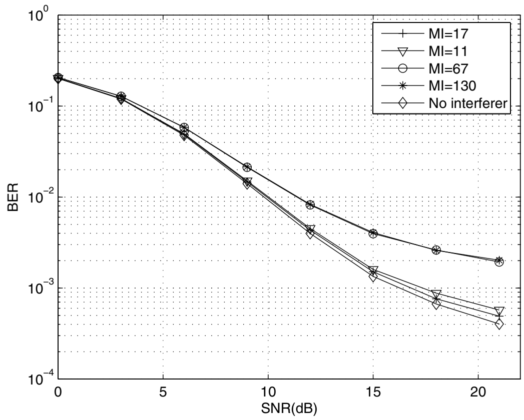

Fig. 4. BER in the reference cell with different pilot sets in the interference cell (one interferer, $M_{\mathrm{R}} = 4$).

V. Numerical Calculations and Simulation Results

In our simulations, the MT velocity is 30km/h, and the channel has six paths whose delays are assumed known. The dual slope pathloss model for the interferer is considered, and the signal-to-interference ratio (SIR) is 8 dB.

We first consider the case that one interferer is active at a time and a system with $N_{\mathrm{F}} = 441$ subcarriers is considered. The pilot length is then 441. $W = 63$ is assumed so that $U_{\max} = 7$ is supported. We then consider the case that two interferers are active at a time and a system with $N_{\mathrm{F}} = 275$ subcarriers is considered. The pilot length is then 275. $W = 55$ is assumed so that $U_{\max} = 5$ is derived.

The variation coefficient v_{c} has been calculated for different sets of pilots. From Table I it is observed that the criterion of $M_1 - M_2$ prime to N_{F} is required for a variation coefficient of zero, where M_{R} and M_{I} indicate the parameters of Chu sequences used in reference cell and interfering cell, respectively. The simulation results from Figs. 3-6 show that the pilot sets with lower variation coefficient achieve better performance on system level in multi-cell environments.

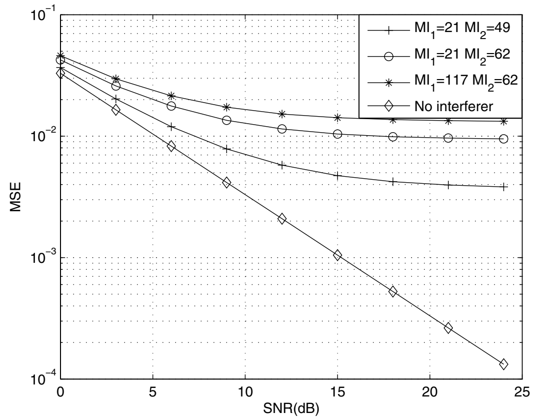

Fig. 5. MSE in the reference cell with different pilot sets in the interference cells (two interferers, $M_{\mathrm{R}} = 7$).

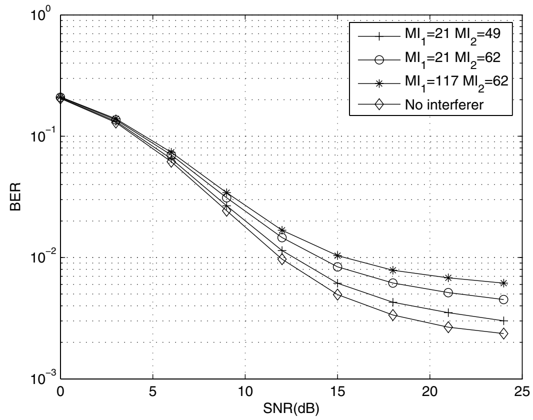

Fig. 6. BER in the reference cell with different pilot sets in the interference cells (two interferers, $M_{\mathrm{R}} = 7$).

VI. Conclusion

The pilots which can mitigate the inter-cell interference in MIMO OFDM systems are derived. The system performance can be optimized when variation coefficient of zero is obtained between the reference cell and the interference cells.

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