MIMO-OFDM Channel Estimation with Minimum Differential Feedback for Time-Correlated Rayleigh Block-Fading Channels

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Abstract: In Multi-Input Multi-Output (MIMO) based cognitive radio (CR) systems, with the increasing demand for data rate and reliability in Wireless communicationsand devices, several issues become very important like bandwidth efficiency, quality of service and radio coverage. We first derive the closed-form expression of the minimum differential feedback rate to achieve the maximum erdodic capacity in the presence of channel estimation errors and quantization distortion at the receiver. With the feedback-channel transmission rate constraint, in the periodic feedback system, we further investigate the relationship of the ergodic capacity and the differential feedback interval, First formulate the pilot design as a new optimization problem. Instead ofminimizing the mean-square error (MSE) of the least-squares (LS) channel estimator, we minimize an upper bound which isrelated to this MSE. We then propose an efficient scheme tosolve the optimization problem. This reliability is in the context of the channel estimationin our case. With the MIMO concept we improve the bitrate and BER of theoverall system.Simulation results show that thepilot index sequences obtained by the proposed method exhibitsignificantly better performance than those obtained by existing pilot design methods.

Keywords— Channel state information, MIMO, pilot design, channel estimation, Rayleigh block-fading channels.

I. INTRODUCTION

Channel state information (CSI) feedback from the receiver to the transmitter has been intensively studied with great interest due to its potential benefits to the multiple input multiple output (MIMO) system. CSI can be utilized by a variety of channel adaptive techniques (e.g., water-filling, beamforming, precoding, etc.) at the transmitter to enhance the spectral efficiency as well as the robustness of the system, especially, in the frequency division duplexing (FDD) mode. As the transmission rate of the feedback channel is normally very limited, the infinite feedback of CSI is hard to realize in practice. Therefore, it is important to investigate how to decrease the amount of feedback signalling overhead to meet the uplink feedback channel requirements. As a result, CSI feedback reduction has attracted lots of attention in recent years [1], [2]. Specifically, when the wireless channel experiences time-correlated fading [3], typically represented by a Markov random process [4], the amount of CSI feedback can be largely reduced. In [5], a number of feedback reduction schemes were summarized, considering the lossy compression scheme exploiting the properties of fading process as the best choice. The use of the radio spectrum is regulated by governmental rules. Almost allparts of the radio spectrum are licensed today. The FCC published a thesis in[6] where the spectrum use in the United States is presented in the aim of betterspectrum utilization.On the other hand, studies have shownthat major licensed bands are largely underutilized. This hasinitiated the idea of cognitive radio (CR), where secondaryusers are allowed to utilize the licensed bands without causingharmful interference to the licensed or primary users [7].The CR technology has the potential to significantly increasethe efficiency of the spectrum utilization while maintaining the QoS requirement of the primary users. Multi-Input Multi-Output(MIMO) is the most widelyused technology in current and future wireless communicationsystems. Since OFDM can naturally provide flexibility to fill inspectrum holes over a wide bandwidth, it has been consideredas one of the best candidates for the physical layer of CR systems [8], [9].The channel state information (CSI) is crucial for CR systems [10].

In practice, the CSI can be estimated by usingpilot tones. The selection of pilot tones will significantly affectthe channel estimation performance. For conventional OFDMsystems where all subcarriers can be used for transmission, theissue of pilot design has been well studied [11]. However, thesemethods are not effective for OFDM-based CR systems, sincethe subcarriers used by the primary users cannot be employedby the secondary users. Hence the available subcarriers forthe secondary users may be non-contiguous which brings newchallenges to pilot design.

The simplest pilot design for OFDM-based CR system isto predesign pilot tones for the conventional OFDM systemand then deactivates those tones already used by the primaryusers according to the result of spectrum sensing. At thereceiver, the remaining activated pilot tones are used forchannel estimation. Directly implementing channel estimationbased on such pilot pattern leads to poor performance [12].To obtains satisfactory channel estimation performance, a shift pilot scheme is proposed in [13]. After predesigning pilot tonesand deactivating some of them according to the spectrumsensing result, this scheme selects some activated data subcarriersas the new pilot tones. Specifically, when a pilot toneis deactivated, its nearest activated data subcarrier is then usedas the new pilot tone. The similar idea can be also found in [14], [15]. Although such a scheme outperforms the aforementionedone, it cannot provide satisfactory performance in all cases.This is mainly because the positions of pilot tones are notoptimized.

Instead of minimizing the mean-square error (MSE) of the least-squares (LS) channelestimator itself, we minimize an upper bound which is relatedto this MSE. The MSE and BER are used as measure in judging the performance of each pilotpattern. According to that performance of pilot pattern has beenimplemented in MIMO based CR system. Virtual pilot concept has beenreviewed and implemented in all proposed pilot patterns. The advantages anddisadvantages of virtual pilot concept has been discussed through our simulationresults analysis.. The decision of the best performingpattern is made by observing the MSE and BER obtained from the simulation resultsin the case where no LU is active. The hexagonal pattern shows the lowestMSE and BER compared to the other two patterns. Hence the hexagonal pattern is chosen to be implemented in the CR system. The remainder of this paper is organized as follows. In Section II, we briefly introduce the system model. In Section III, we describe the LS channel estimator. The proposed new pilot design method is described in Section IV. Section V presents simulation results and finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

A. MIMO model with CR system

The MIMO-based CR system under consideration is shownin Fig.1. The pilots are designed according to the result ofthe spectrum sensing. After subcarrier assignment where thesubcarriers occupied by the primary users are deactivated,pilot symbols are inserted and the data are modulated onthe remaining activated subcarriers.We employ the MIMO concept in our simulation platform because it has beenproven that MIMO can achieve a major breakthrough in providing reliable wirelesscommunication links. This reliability is in the context of the channel estimationin our case. With the MIMO concept we improve the bitrate and BER of theoverall system. MIMO is capable of this improvement, because of the property ofmultiple transmission multiple reception. This property is a form of spatial diversity.This diversity is the most effective technique to accomplish reliable communicationover the wireless channel and combating with fading, because it providesthe receiver with multiple copies of the transmitted signal. Those multiple copiesare independently faded. If at least one copy of the transmitted signal is receivedcorrectly, we will have the transmitted signal back. This property improves theBER significantly (low BER) as shown in chapter 6. Beside this, MIMO increases thechannel capacity also, which means more throughputs. There are different ways toexploit multiple antennas at both sides of the communication channel. To improvethe transmission reliability, the transmit antennas should be used such that transmitdiversity is achieved. The transmission rate is comparable to the one obtainedin SISO. To improve the transmission rate, independent signals are transmittedfrom the different transmit antennas. i.e. there is no correlation between the transmittedsignals from the different antennas. In this case the reliability is not muchimproved [10].

$$y_r(t)=\sum_{k=0}^{K-1}\sum_{i=1}^{M}h_{i,r}^{(k)}(t)s_i(t-k)+n_r(t) \qquad (1)$$

Where si(t) is the transmitted signal from antenna i at time t, h(k) i,r(t) is the channel coefficient for the kth path from transmit antenna i to receive antenna r at time t. nr(t) is the Additive White Gaussian Noise. For mobile communications, the channel tap coefficients are random variables. In case the wireless channel varies very slowly, the tap coefficients remain constant for each frame of data. For Rayleigh fading channels, the channel tap coefficients are modeled as complex Gaussian random variables which have zero mean. The different channel taps are assumed to be independent. The average channel gains for different paths are determined from the power Delay profile of the wireless channel. In this work we assume that the channel tap powers decays exponentially. Hence we use the exponential power delay profile. If the MIMO-OFDM system has Nc subcarriers and the fading coefficients are spatially uncorrelated and that the fading coefficients remain constant during one OFDM symbol. Then the transmitted signal over M antennas can be represented by a matrix XOFDM with dimensions NcxM. A symbol transmitted at subcarrier n on transmit antenna is xi (n).

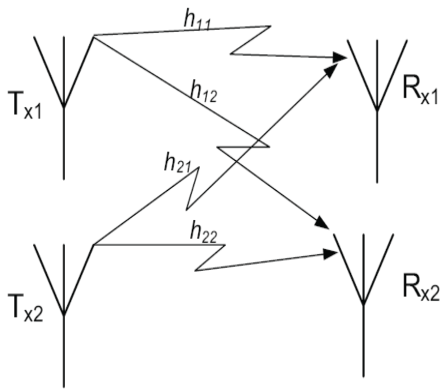

Figure 1 : MIMO setup

At the receiver after applying FFT and removing the cyclic prefix, the resulting signal at the jth receive antenna for the nth subcarrier will be:

$$y_r(n)=\sum_{i=1}^{M}x_i(n)H_{i,r}(n)+n_r(n) \qquad (2)$$

whereHi,r(n) is the channel coefficient from the ith transmit to the rth receive antenna for the nth subcarrier and is given by:

$$H_{i,r}(n)=\sum_{k=0}^{K-1}h_{i,r}^{(k)}e^{-j2\pi nk/N_c} \qquad (3)$$

where we can denote the channel coefficients for the (i, r)th links by:

$$H_{i,r}=\left[H_{i,r}(0)H_{i,r}(1).....H_{i,r}(N_c-1)\right] \quad (4)$$

The vector of K independent fading coefficients of the different taps can be represented by:

$$A_{i,r}=\left[h_{i,r}^{(0)}h_{i,r}^{(1)}........h_{i,r}^{K-1}\right] \qquad (5)$$

Hence we can see that the equivalent channel coefficients are:

$$H_{i,r}=WA_{i,r} \qquad (6)$$

Where W is the FFT matrix. In (6) the fading coefficients for distinct subcarriers are different but dependent. The maximum rank of the (frequency domain) channel matrix is equal to the number of taps K, and is usually low. The time domain signals at the receive antennas can be represented as:

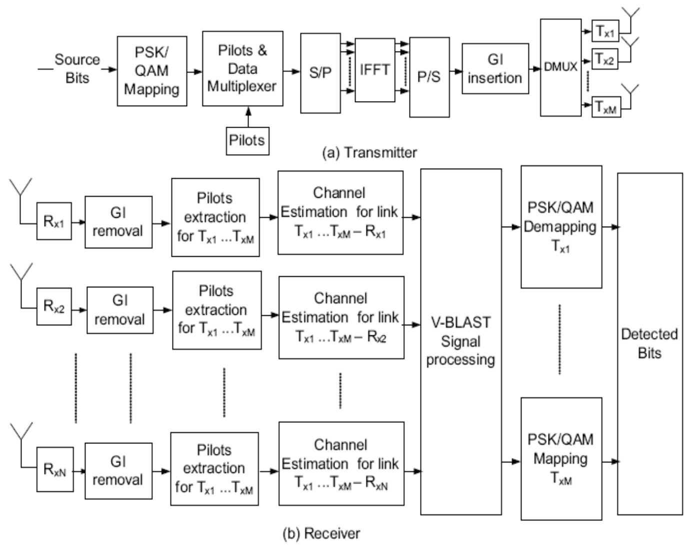

Figure 2 : MIMO System model (a) Transmitter and (b) Receiver

$$y_1=s_1*CIR_{11}+s_2*CIR_{21}+n_1$$
$$y_1=s_1*CIR_{12}+s_2*CIR_{22}+n_2 \qquad (7)$$

Where y_1 and y_2 are the vectors received by receive antennas R_{X1} and R_{X2} respectively. The transmitted signal vectors by transmit antennas T_{X1} and T_{X2} are represented by s_1 and s_2 where all variables are in time domain. CIR_{11}, CIR_{12}, CIR_{21} and CIR_{22} are the channel impulse responses of the different sub-channels, while n1and n2 are the noise vectors (AWGN) with zero mean on the two receive antennas. Those two noise vectors are independent of each other. Putting (3.28) in matrix form gives:

$$\begin{pmatrix}y_1\\ y_2\end{pmatrix}=\begin{pmatrix}CIR_{11} & CIR_{12}\\ CIR_{21} & CIR_{22}\end{pmatrix}\begin{pmatrix}s_1\\ s_2\end{pmatrix}+\begin{pmatrix}n_1\\ n_2\end{pmatrix} \qquad (8)$$

Taking the FFT of the CIR gives the frequency domain channel matrix CTF as:

$$CTF_{2X2}=\begin{pmatrix}CTF_{11} & CTF_{21}\\ CTF_{12} & CTF_{22}\end{pmatrix} \qquad (9)$$

B. The proposed pilot design method

C. Extension to MIMO-OFDM Systems

The proposed pilot design scheme can be readily extended to MIMO systems. In this subsection, we present two extension methods. Let $\mathcal{P}^q=\{p^q{}_0\ldots p^q{}_{P-1}\}$ denote the pilot tone placement at the q-th transmit antenna and assume that $\mathcal{P}^q\cap\mathcal{P}^r=\varnothing$ for $q\neq r$, i.e., pilot tone placements for different transmit antennas are orthogonal. The direct extension of the proposed scheme is to design $\{\mathcal{P}q\}^N{}_{tq=1}$ sequentially, where N_t is the number of transmit antennas. The following Extension Method 1 describes the whole procedure.

1) Initialize $\mathcal{N}^1 = \mathcal{N}$. Set $q = 1$.
2) Obtain $\mathcal{P}^q$ by using Algorithm 2, where $\mathcal{N}$ and G_n are replaced by $\mathcal{N}^q$ and $G_n^q = \sum_{m=0}^{n-1} g\left(p_m^q - p_n^q\right)$, respectively.
3) Let $\mathcal{N}^{q+1} = \mathcal{N} \backslash \cup^q_{i=1} \mathcal{P}^i$. Set $q = q+1$. If $q = N_t+1$, stop, otherwise, return to step 2).

Note that $\mathcal{N}^{N_t} \subset \cdots \subset \mathcal{N}^1$. The above method may lead to "unfairness" among N_t transmit antennas. For example, for the first transmit antenna, pilot tones can be chosen from $|\mathcal{N}^1| = N$ possible subcarriers, while for the last transmit antenna, pilot tones can only be chosen from $|\mathcal{N}^{N_t}| = N - (N_t - 1)$ possible subcarriers. In some cases, the last designed pilot placement may cause much worse performance than the first designed one. Since the system performance is an average performance, reducing the performance gap between the best and the worst may improve the final performance. Consequently, we propose Extension Method 2 that can enhance the fairness among N_t transmit antennas. In Extension Method 2, pilot tones of different transmit antennas are designed in turn. Specifically, we first design $\left\{p_0^q, p_1^q\right\}_{q=1}^{N_t}$ (i.e., the first two pilot tones of all transmit antennas) in the order of $\left\{p_0^1, p_1^1\right\}, \ldots\ldots\ldots, \left\{p_0^{N_t}, p_1^{N_t}\right\}$. Then, we design $\left\{p_2^q\right\}_{q=1}^{N_t}$ in the order of $p_2^{N_t}, p_2^{N_t-1}, \ldots., p_2^1$. After that, we design $\left\{p_3^q\right\}_{q=1}^{N_t}$ in the order of $p_3^1, p_3^2, \ldots., p_3^{N_t}$ and so on. In other words, for the q-th pilot tone, if the design order is $p_1^1, p_q^2, \ldots., p_q^{N_t}$, then for the ($q$+1)-th pilot tone, the design order will be $p_{q+1}^{N_t}, p_{q+1}^{N_t-1}, \ldots., p_{q+1}^1$. The whole procedure is summarized as follows.

1) Initialize $\mathcal{N}^1 = \mathcal{N}$. Set $q = 1$ and $n = 1$.
2) Obtain p^q_0 and p^q_1 by solving (15), where $\mathcal{N}$ and G_1 are replaced by $\mathcal{N}^q$ and G^q_1, respectively. Initialize $\left\{p_0^q, p_1^q\right\}$.
3) Set $\mathcal{N}^{q+1} = \mathcal{N}^q \backslash \mathcal{P}^q$ and $q = q + 1$. If $q = N_t + 1$, let $\mathcal{N}^{N_t} = \mathcal{N}^{N_t+1}$ and $q = N_t$, and go to step 4), otherwise, return to step 2).
4) Set $n = n+1$. If $n = P$, stop, otherwise, go to step 5).
5) Obtain p^q_n by solving (16), where G_n is replaced by G^q_n and $\mathcal{N} \backslash \mathcal{P}$ is replaced by $\mathcal{N}^q$. Update $P^q = P^q \bigcup \left\{p_n^q\right\}$.
6) If n is even, set $\mathcal{N}^{q-1} = \mathcal{N}^q \backslash \mathcal{P}^q$ and $q = q - 1$. If $q = 0$, let $\mathcal{N}^1 = \mathcal{N}^0$ and $q = 1$, and return to step 4).
7) If n is odd, set $\mathcal{N}^{q+1} = \mathcal{N}^q \backslash \mathcal{P}^q$ and $q = q + 1$. If $q = N_t+1$, let $\mathcal{N}^{N_t} = \mathcal{N}^{N_t+1}$ and $q = N_t$, and return to step 4).
8) Return to step 5).

III. SIMULATION RESULTS

Figures 3 and 4 show the MSE and BER performance of the above five methods, respectively. The LS channel estimator described in Section III is applied. From the figures it can be seen that Method A has the poorest performance and it is virtually unusable for the MIMO-based CR system.

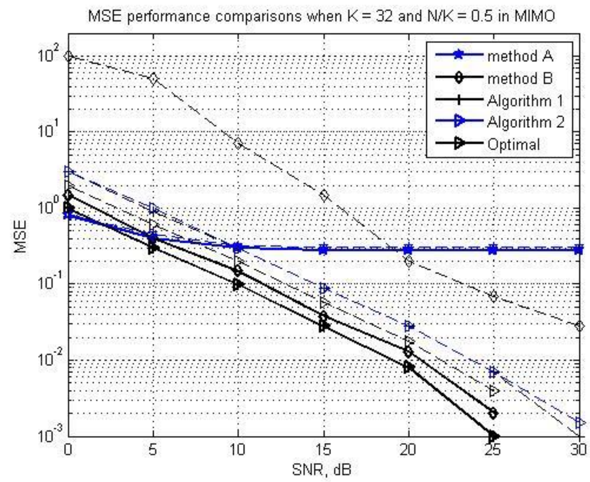

Fig. 3. MSE performance comparisons when $K = 32$ and $N/K = 0.5$.

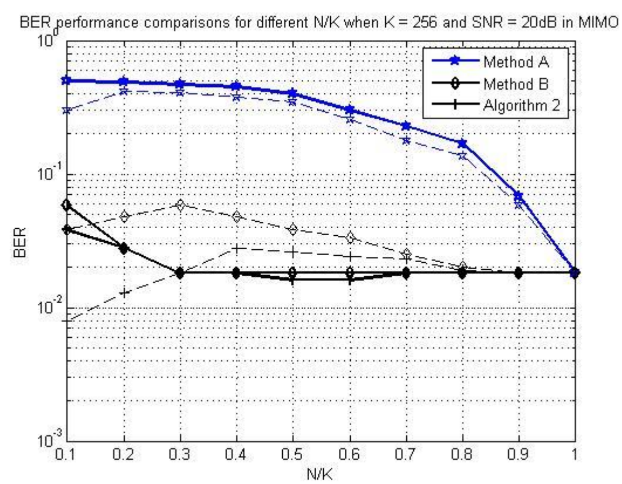

Fig. 4. BER performance comparisons when $K = 32$ and $N/K = 0.5$.

The proposed Algorithms 1 and 2 have almost the same performance in both cases. The proposed algorithms outperform Method B, especially for Case 2. For example, compared with Method B, the proposed algorithms can provide about 10dB gain in SNR for MSE and about 8dB gain in SNR at a BER of 10−2. Moreover, compared with the optimal solution, the proposed algorithms only incur slight performance degradation. We next consider a more practical OFDM-based CR system with K = 256 subcarriers. The channel is assumed to have L = 16 taps. The number of pilot tones is $P = L$ = 16 and the number of contiguous subcarriers in each sub-band for Case 2 is R = 8. The available spectral rate is still chosen as N/K = 0.5. For this scenario, the number of all possible pilot placements is $(N_P) \approx 10^{20}$. Exhaustively searching the desired one from all possible pilot placements is infeasible.

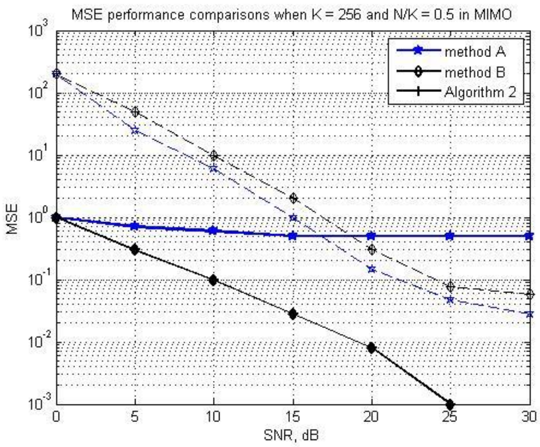

Fig.5.MSE performance comparisons when K = 256 and N/K = 0.5.

Figures 5 and 6 show the MSE and BER performance of the three methods, respectively. It is seen that the proposed algorithm again outperforms the other two methods, especially in Case 2.

In CR systems, the available spectral rate N/K (i.e., the number of activated subcarriers N) varies from time to time. Thus, we evaluate the three methods for different N/K. The BER performance comparisons are shown in Figure 7, where the SNR is set as 20dB. From the figure it can be seen that the proposed algorithm outperforms the other two methods, especially when N/K is small.

Here the channel frequency responses (CFR) at the pilot tones are first estimated and the CFR at the data subcarriers are then obtained by the frequency-domain interpolation. In our simulation, the spline interpolation is used. The results are shown in Figure 8 for $N = 0.5K$.

IV. CONCLUSION

In this paper, a new practical pilot design method for MIMO-based CR systems has been proposed. Using the Gerschgorin disk theorem, we have proposed a new formulation for the pilot placement problem with a simple objective function that involves only real additions. We have also proposed an efficient sequential method to solve the corresponding optimization problem. The performance of this pattern converges at almost 20dB SNR for different filter lengths. Above this SNR value increasing the filter size has no influence any more on improving the performance. The longer the filter size is, the more virtual pilots are utilized in the filtering process, and this will result in accumulation of errors. Simulation results demonstrate that the proposed scheme outperforms two existing ones and more gains in SNR at a given BER can be obtained as the number of activated subcarriers decreases.

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