Research on anti-pilot contamination in massive MIMO

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Abstract. In order for the pre-coding technology to suppress the influence of pilot contamination, a hybrid pre-coding scheme is proposed in this paper by combining a full digital pre-coding technology and an analog beamforming in the context of current massive MIMO. Simulation results show that the proposed pre-coding scheme effectively suppresses the pilot contamination while reducing the system structure complexity and ensuring the system’s basic performance, which is of great significance in practical communication applications.

1. Introduction

The technology of multiple-input multiple-output (MIMO) (also called large-scale MIMO) was first proposed by Thomas L. Marzetta [1]. In their scheme, the number of antennas configured in a base communication station was small (usually no more than eight), resulting in a low spatial freedom. This situation was unable to meet the exploding demand for mobile communications in the 5G market [2]. Unlike the traditional MIMO technology, the Massive MIMO (also called large-scale MIMO) is superior in both architecture and overall performance [3]. One is that Massive MIMO replaces multiple antennas in traditional MIMO with a much larger antenna array. Second, the Massive MIMO system uses a smaller hardware device with lower power consumption to reduce the complexity of the hardware, which is a great innovation and breakthrough for the traditional MIMO technology. In addition, the Massive MIMO system uses the Time Division Duplexing (TDD) system to replace the joint use of TDD and Frequency Division Duplex (FDD) systems in the traditional MIMO system [4]. The advantages of the Massive MIMO are three aspects. First, the cellular system can serve multiple users at the same time; second, the data transmission rate of the system can be greatly improved; at last, the spatial diversity and multiplexing can be sufficiently utilized. In conclusion, the large-scale MIMO system not only inherits but also maximizes all the performance of the traditional MIMO system. However, the same orthogonal pilot sequence in different quarters makes the base communication station unable to effectively differentiate different signals with the same pilot sequence [5].

At present, there is a common sense that the pilot contamination cannot be completely eliminated [6]. Therefore, how to reduce the pilot contamination has become a hot research focus. In order to suppress the influence of pilot contamination, a hybrid pre-coding scheme is proposed in this paper by combining a full digital pre-coding and an analog beamforming in the context of current massive MIMO. The simulation results show that the proposed scheme can reduce the system structure complexity and effectively suppress the pilot contamination on the premise of ensuring the basic performance of the system, which is of great significance in practical communication applications.
2. Related work and problem statement

There are three main methods to reduce the pilot contamination [7], including designing a reasonable pre-coding scheme, improving the channel estimation and using an appropriate pilot allocation strategy.

The principle of a pre-coding scheme is to design a desirable pre-coding matrix [8], by which the channel state information is estimated in the case of pilot contamination, so as to reduce the influence of pilot contamination. Common pre-coding schemes include maximum ratio transmission (MRT) pre-coding, zero forced pre-coding and full digital pre-coding. The advantage of the MRT pre-coding is that the number of the base station antennas is large enough to get an optimal performance, but the system requirements are high. The advantage of zero forced pre-coding lies in its low complexity and good practicability, but it ignores the influence of noise amplification. A full digital pre-coding can achieve an optimal performance in the case of a good channel status, but the implementation is complex and costly.

When a signal is transmitted in a wireless channel, its amplitude and phase change randomly, so that the information contained in the transmitted signal cannot be accurately obtained. A channel estimation algorithm first estimates the impulse response of the channel [9], by which the random changes experienced by the signal can be estimated. At present, common improved channel estimation algorithms include the least square estimation (LSE) algorithm and the least mean square error estimation (LMSE) algorithm. The LSE algorithm is characterized with a simple structure, a small amount of computation but a poor accuracy and the ease of power loss. The LMSE algorithm has a small mean square error and a strong capability of suppressing pilot contamination, but with a huge complexity and computation.

A pilot allocation strategy reduces the influence of pilot contamination on the system by using a specific allocation method and reducing the overlap of the same or non-orthogonal pilots in the system [10]. At present, common pilot allocation strategies include the maximal posterior coordinative pilot allocation strategy, pilot power control strategy and pilot offset strategy. The maximal posterior coordinative pilot allocation strategy has little negative influence on the system, but it has a high complexity and noise sensitivity. The pilot power control strategy improves the system’s performance while optimizing the power output, but it is not suitable for large-scale systems. The pilot offset strategy improves the system’s performance in the case of complete overlap of pilots, but it is not applicable to relatively large-scale systems.

Comparing the above-mentioned three pilot contamination suppressing strategies, one can conclude as follows. The improved channel estimation algorithm has a high spectral efficiency but with a high computational complexity. The pre-coding matrix can effectively reduce the dependence on the receiver algorithm, hence only a linear pre-coding is considered [11]. The pilot allocation strategy has a great improvement in system’s capacity and transmission rate, but there exist some harmful noise interferences, limiting the degree of pilot contamination suppression. In summary, each scheme has its own advantages and disadvantages. For the Massive MIMO system, when the processing capacity in the user terminal is limited, only a single one of the above strategies cannot meet the requirements of cost reduction due to the increasing number of antennas.

3. Proposed pilot contamination suppressing scheme in massive MIMO

In the Massive MIMO system, using a full digital pre-coding alone can lead to high hardware complexity and high cost. The power loss becomes very large when applying an analog beamforming alone. Therefore, a hybrid pre-coding technology which combines a full-digital pre-coding technology with an analog beamforming is a reasonable choice.

The hybrid pre-coding technology proposed in this paper combines both the analog and digital pre-coding technologies. In the first step, the signal is digitally preprocessed in the baseband, and then goes through a few radio frequency (RF) chains. In the second step, the signal is processed by the phase shifter. In the third step, the mixed pre-coding matrix is obtained by the analog pre-coding. The general process of the whole scheme is shown in Figure 1.
In view of the poor performance of partially connected systems, a fully connected system is adopted. Generally, the singular value decomposition (SVD) algorithm is used to iterate the system RF link continuously. The column with the largest residual inner product is selected from the codebook, and the residual inner product of pre-coding matrix is calculated according to the column, and then normalized. After a sufficient number of iterations, the complete recoded matrix is obtained. In our hybrid pre-coding scheme, SVD is replaced by Orthogonal Matching Pursuit (OMP) algorithm. The simulation results show that the proposed OMP hybrid pre-coding scheme not only keeps the satisfactory performance, but also reduces the hardware complexity.

![Figure 1. System configuration.](image)

The data stream generated by the mixed pre-coding is very large, which puts a great pressure on the transmission and reception of the system. The use of a small amount of RF chain and phase shifter can not only achieve the same transmission effect, but also make the system more concise and reduce energy consumption.

According to the above requirements, a fully connected hybrid pre-coding system model is proposed, as shown in Figure 2.

![Figure 2. The proposed fully connected mixed pre-coding system model.](image)

After the RF amplification and pre-coding, the transmission signal can be expressed as

$$x = F_{RF} F_{BB} s$$  \hspace{1cm} (1)
where $x \in \mathbb{R}^{N_t}$ is the transmission signal after the RF amplification and pre-coding, $s \in \mathbb{R}^{N_s}$ is the initial transmission signal, $F_{RF} \in \mathbb{R}^{N_t \times N_{RF}}$ is the RF matrix, and $F_{BB} \in \mathbb{R}^{N_s \times N_s}$ is the digital baseband pre-coding matrix.

The processed signal $r$ can be expressed as

$$r = \sqrt{p_d} H x + n$$

(2)

where $H$ is the channel matrix, $p_d$ is the transmission power, and $n$ is the system noise.

After signal detection, the received signal $y$ can be expressed as

$$y = W_{RF}^H W_{RF}^H r$$

(3)

with $W_{RF}$ being the analog beam shaping technology, $W_{BB}$ the digital receiver matrix, and the superscript $H$ the transpose of a matrix.

By combining Formulas (2) and (3), the system's spectral efficiency can be calculated, as

$$R_{\text{sum}} = \log_2 \left( I_{N_s} + \frac{p_d}{N_s} R_{\text{eq}}^{-1} W_{RF}^H H F_{RF} F_{BB}^H F_{RF}^H W_{RF} W_{BB} \right)$$

(4)

In the Massive MIMO system, the number of antennas is very large, resulting in an increasing hardware complexity and high cost. Using the hybrid pre-coding technology will greatly reduce the hardware complexity. It uses an analog beam shaping technology at both the sending and receiving ends, so that an RF chain can be connected with multiple antennas through a phase shifter, which greatly reduces the hardware complexity and the cost of the system. In terms of computation load of the hybrid pre-coding algorithm, both of the sending and receiving ends need to iterate through the OMP algorithm to generate the encoding and decoding matrices, while the full digital pre-coding only needs to decompose the channel matrix through SVD. Therefore, the hybrid pre-coding algorithm needs a longer time of computation. The complexity of SVD is relatively low in theory, but the implementation of SVD is relatively complex, therefore generally, SVD is only used in the case of obtaining the ideal value.

In summary, the OMP hybrid pre-coding algorithm can achieve almost the same effect as the all-digital pre-coding technology with lower hardware complexity and cost, which indicates that the hybrid pre-coding technology is more practical for commercial use.

4. Simulation and analysis
Simulations are conducted for testing the proposed mixed pre-coding model. The number of antennas at the receiving end is set to $N_r = 16$ and then 64, the number of antennas at the sending end is set to $N_t = 64$ and then 256, the number of data streams transmitted is set to $N_s = 4$, the corresponding numbers of radio frequency links are $N_{RF}$ and $N_{RF}^*$, respectively. The number of multipath channels is set as $N = 16$. The number of RF links are set to 4. The software environment is MATLAB. The full digital pre-coding algorithm with SVD and the OMP mixed pre-coding algorithm are simulated to observe and analyze the performance of spectral efficiency with respect to signal-to-noise ratios (SNR) in the cases of two arrangements of antennas.

4.1. OMP mixed pre-coding implementation
1. Generation of receiving matrix

```matlab
% Generation of a standard normally distributed matrix
G1 = randn(1, L) + j*randn(1, L);
for i = 1:Nr; % rank of the matrix
    for t = 1:L;
        Fr(i, t) = exp(j*pi*(i - 1)*sin(A(1, t))) / sqrt(Nr);
    end
end
for i = 1:Nt;
    for t = 1:L;
        Ft(i, t) = exp(j*pi*(i - 1)*sin(B(1, t))) / sqrt(Nt);
    end
end
```
2. Calculation of RF and baseband pre-coding matrices

\begin{verbatim}
for i = 1:NtRF;
    U1 = ADFT' * Fres;
    Q1 = diag(U1*U1');
    [Value, k] = max(Q1);
    FRF = [FRF ADFT(:, k)];
    FBB = inv(FRF'*FRF)*FRF'*Fopt;
    Fres = (Fopt - FRF*FBB)/(norm(Fopt - FRF*FBB,'fro'));
end
\end{verbatim}

3. Calculation of spectral efficiency according to (4)

\begin{verbatim}
Q11 = FRF*FBB;
FBB = (sqrt(Ns)*FBB) / norm(Q11, 'fro');
Wmmse = sqrt(Nt)* inv(FBB'*FRF'*H'*H*FRF*FBB + Ns*eye(Ns)/SNR)*FBB'*FRF'*H';
M1(testcount, times) = log2(abs(det(eye(Ns) + (pinv(Wmmse')*H*FRF*FBB*FBB'*...
                        FRF'*H*Wmmse*SNR/Ns))));
\end{verbatim}

4.2. Analyses of results

The mixed pre-coding system and the sparse channel model described above are adopted in this simulation. MATLAB software is used to simulate OMP hybrid pre-coding algorithm, and the spectrum efficiency curves with respect to SNR of this pre-coding technology are obtained under the condition of different number of transceiver antennas.

Figure 3 shows the spectral efficiency comparison with respect to the signal-to-noise ratio in the cases of two arrangements of transceiver antennas. When $N_t$ and $N_r$ are 64 and 16, respectively, the spectral efficiency value is 4 bps/Hz, when $N_t$ and $N_r$ are 256 and 64, respectively, the spectral efficiency value reaches 13 bps/Hz. From Figure 3, it can be concluded that increasing the number of transceiver antennas will increase the spectral efficiency by means of the proposed OMP mixed pre-coding.

![Figure 3. Spectral efficiency comparison of OMP mixed pre-coding scheme.](image)

Figure 4 shows the spectral efficiency values with respect to signal-to-noise ratios when the SVD full-digital pre-coding is utilized. From Figure 4, it can be seen that with the increase of antennas, the spectral efficiency of the OMP mixed pre-coding scheme will approach gradually that of the SVD full-digital pre-coding scheme.
By comparing the results from Figure 3 and Figure 4, it can be concluded that the proposed OMP mixed pre-coding scheme performs comparatively with the full-digital pre-coding at a much lower hardware complexity and cost.

5. Conclusions
In this paper, in the context of Massive MIMO system, a new OMP mixed pre-coding scheme combining the full-digital pre-coding and the analog beamforming technology is proposed. Finally, through the simulation of relevant algorithms, it is verified that the scheme can achieve the expected use effect. Simulation results prove that the performance of the proposed OMP mixed pre-coding scheme is comparable with the full-digital pre-coding while at a much lower hardware complexity and cost.

![Figure 4. Spectral efficiency comparison of SVD full-digital pre-coding scheme.](image)

The hybrid pre-coding design is mainly based on how to design a low-complexity algorithm to obtain the pre-coding matrix, how to break the hardware constraints in the hybrid architecture and how to reduce the hardware complexity. In the future, it is worth designing the low-complexity algorithms and considering how to design the most effective RF plan or find other alternative methods for replacing RF chains.

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