Data-aided Weight with Subcarrier Grouping for Adaptive Array Interference Suppression

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Abstract—The effect of additive noise on the channel state information (CSI) quality is a crucial issue in mobile communication systems. The adaptive subcarrier grouping (ASG) for sample matrix inversion (SMI) based minimum mean square error (MMSE) adaptive array has been previously proposed. However, this method needs to know the signal-to-noise ratio (SNR) in advance to set the threshold, perform grouping, and take the average, causing an insufficient number of signal samples. As a result, the ability to eliminate noise is limited. In this paper, we propose a new method based on data-aided weight calculation and the least mean square (LMS) algorithm without SNR information, which increases the number of samples. The decision results and initial weight are obtained by the SMI method with subcarrier grouping, and then the LMS method with subcarrier grouping is applied to reduce the channel estimation error as well as the amount of computation. Simulation results demonstrate that the proposed scheme is an efficient approach to improve Bit Error Rate (BER) performance under various channel conditions.

Index Terms—Noise effect, sample matrix inversion, subcarrier grouping, decision feedback, least mean square.

I. INTRODUCTION

WITh the advent of Internet-of-Things (IoT), mobile data traffic, as well as the number of movable devices and connections, has been rapidly increasing in cellular networks. Increasing transmission rates and realizing huge spectrum capacity are essential for the fifth generation of mobile communications (5G) and beyond [1], [2]. Therefore, millimeter wave (mmWave) is used as the ideal communication technology to solve the above problems [3]. Millimeter wave communication systems exploit the ultra-high frequency (EHF) band for broadband communications where there is still a large amount of available spectrum for communications [4]. However, it suffers from severe propagation loss, causing restricted coverage and a link budget shortfall. The deployment of a massive MIMO-small cell system [5] is one of the promising solutions to reduce the attenuation of radio waves. By setting the phase shifts of all the antenna elements to obtain beamforming gain, the signal to interference plus noise ratio (SINR) can be maximized in massive MIMO. Small cells can manage high traffic demand within the coverage area of macrocells [6], [7]. In the small cells, the propagation environment is dominated by a line of sight (LOS) component for a reliable communication system. Therefore, Rician distribution with LOS and non-LOS (NLOS) components is considered as the channel model in this situation [8].

In general, inter-user-interference (IUI) and additive white Gaussian noise are essential for array antenna. Sample matrix inversion(SMI) [9], [10] is a well-known method for interference suppression adaptive array antennas. SMI utilizes a covariance matrix derived from the pilot symbols and the received signals of each antenna element to calculate desirable weights. Due to the inaccurate channel state information (CSI) caused by the additive noise effect, this method requires a sufficient number of samples to adequately suppress interference [11]. In addition, since the array weights are calculated for each subcarrier in orthogonal frequency division multiplexing (OFDM) systems, it causes not only an insufficient number of samples but also a large amount of computation [12]. Further discussion is needed for the OFDM frame. Common Correlation Matrix (CCM) based SMI algorithm has been proposed to reduce the amount of calculation and enhance weight precision for interference suppression performance. In the CCM method, an adequate number of the time domain signal samples can be available for a well-converged covariance matrix [13], [14]. However, it still has a problem of inaccurate channel estimation and the limitation of working only in an almost frequency-flat fading environment since the weight is common in all subcarriers. For this reason, it cannot work in the heterogeneous deployment of small cells. A more recent work evaluates the effect under the above situation [15]. Reference [15] proposed an adaptive subcarrier grouping (ASG) method. In ASG method, the standard deviations among the adjacent subcarriers are calculated, averaged, and compared with the threshold to determine the grouping. It has good performance even in frequency selectivity channels. However, because of an insufficient number of signal samples under the limited number of pilot symbols, there is a problem of insufficient noise suppression performance and the threshold of the grouping must depend on signal-to-noise ratio (SNR). Therefore, Rician distribution with LOS and non-LOS (NLOS) components is considered as the channel model in this situation [8].

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response $H(f)$ is obtained by Fourier transform of the impulse response as,

$$H(f) = \sum_{l=0}^{N_{FFT}-1} h(l, \tau) \exp \left(-\frac{2\pi f \tau}{N_{FFT}}\right),$$

where $f$ and $N_{FFT}$ denote the frequency component and the number of fast Fourier transform (FFT) points, respectively.

B. Uplink Array Antenna System Model

We suppose uplink transmission where a base station (BS) has $N_r$ elements array antenna and $N_u$ user terminals (UEs) with OFDM like Fig.1.

Throughout this paper, subscripts $c$ and $u$ represent the $c$-th subcarrier and the $u$-th user, respectively. Then, the received pilot signal $X_c \in \mathbb{C}^{N_s \times N_r}$, received data signal $S_c \in \mathbb{C}^{N_s \times N_a}$, and array output $Y_c \in \mathbb{C}^{N_s \times N_a}$ can be expressed as follows.

$$X_c = AH_cP_c + N,$$

$$S_c = AH_cD_c + Z,$$

$$Y_c = W_c^H S_c,$$

where

$$A = [a_1, \ldots, a_u, \ldots, a_{N_u}],$$

$$H_c = \text{diag} (H_1, \ldots, H_{N_u}),$$

$$P_c = [p_1^T, \ldots, p_u^T, \ldots, p_{N_u}^T]^T,$$

$$D_c = [d_1^T, \ldots, d_u^T, \ldots, d_{N_u}^T]^T.$$  

$A \in \mathbb{C}^{N_s \times N_u}$, $H_c \in \mathbb{C}^{N_s \times N_u}$, $P_c \in \mathbb{C}^{N_s \times N_p}$, $D_c \in \mathbb{C}^{N_s \times N_a}$, $N \in \mathbb{C}^{N_s \times N_p}$, $Z \in \mathbb{C}^{N_s \times N_a}$, $W_c \in \mathbb{C}^{N_s \times N_u}$ denote array factor matrix, fading channel matrix, transmitted pilot symbols, transmitted data symbol, additive white Gaussian noise (AWGN) matrices of pilot symbols and data symbols, and weight vector, respectively. The array weight vector can cancel interference components.

C. SMI Algorithm

SMI algorithm is based on a minimum mean square error (MMSE) method for solving the minimum searching problem [9], whose weight can be derived as,

$$E[|e|^2] = E[|P_c - W_c^H X_c|^2].$$

where the pilot symbol $P_c$ is considered as the desired response.
The optimal weight by SMI algorithm is derived as
\[ \Phi_{c} = X_c X_c^H, \]
\[ V_{c} = X_c P_c^H, \]
\[ W_{c} = \Phi_{c}^{-1} V_{c}, \]
where \( \Phi_{c} \in \mathbb{C}^{N_c \times N_c} \) and \( V_{c} \in \mathbb{C}^{N_c \times N_p} \) indicate the covariance matrix and the estimated CSI vector, respectively. However, there is a noise problem in the received signal.

### D. Adaptive Subcarrier Grouping (ASG)

In the above scheme, the effect of noise has not been fully considered when calculating the array weight. By exploiting adaptive grouped subcarriers with correlated frequency responses for averaging, the convergence precision of the covariance matrix can be improved [15]. Frist, subcarriers are chosen for grouping to suppress interference. We define \( m \) as both the number of stages and the end sequence of a group to delimit a group range from the \( c \)-th subcarrier, i.e., the subcarrier sequence corresponding to a group in the \( m \)-th stage is \( (c, \ldots, c + m) \). \( m = 0 \) is initialized as no grouping.

We average the grouped received signal \( X \) and pilot signal \( P \) from subcarrier \( c \) to \( c + m \) to reduce noise, which combines the \((m + 1)\) subcarriers. The grouped received pilot signal matrix and the grouped transmitted pilot signal matrix for averaging is calculated as follows,
\[
\begin{align*}
\overline{X}^{(m)} &= \frac{1}{m + 1} \sum_{k=0}^{m} X_{c+k}, \\
\overline{P}^{(m)} &= \frac{1}{m + 1} \sum_{k=0}^{m} P_{c+k},
\end{align*}
\]
where \( X_{c+k} \in \mathbb{C}^{N_c \times N_p} \) and \( P_{c+k} \in \mathbb{C}^{N_a \times N_p} \) are the \((c + k)\)-th subcarrier of the received pilot signal matrix and transmitted pilot signal matrix. \( \overline{X}^{(m)} \in \mathbb{C}^{N_c \times N_p} \) and \( \overline{P}^{(m)} \in \mathbb{C}^{N_a \times N_p} \) are the averaged received pilot signal and averaged transmitted pilot signal. Then, a standard deviation of the grouped received signal, \( \sigma_{\text{ASG}}^{(m)} \in \mathbb{C}^{N_c \times N_p} \) is calculated as,
\[
\sigma_{\text{ASG}}^{(m)} = \frac{1}{m + 1} \sum_{k=0}^{m} (X_{c+k} - \overline{X}^{(m)})^2,
\]
\[
\sigma_{\text{ASG}}^{(m)} = \frac{1}{N_p N_c} \sum_{j=1}^{N_p} \sum_{i=1}^{N_c} \sigma_{\text{ASG},i,j}^{(m)}/N_p N_r.
\]
\( \sigma_{\text{ASG}}^{(m)} \) represents the dispersion among the grouped subcarriers. Therefore, only frequency-correlated subcarriers are combined by comparing with a threshold value, \( \sigma_{\text{th}}^{\text{ASG}} \), as follows.

If \( \sigma_{\text{ASG}}^{(m)} < \sigma_{\text{th}}^{\text{ASG}} \), grouping operation proceeds to the next stage;
\[ m \leftarrow m + 1. \]

**III. PROPOSAL: SUBCARRIER GROUPING WITH DATA-AIDED WEIGHT**

In the adaptive subcarrier grouping, since setting a threshold too large degrades weight derivation accuracy due to an excess of data symbols having uncorrelated frequency characteristics, setting the appropriate value of \( \sigma_{\text{th}}^{\text{ASG}} \) holds a prominent factor. SNR is considered to be the main factor involved in setting the threshold. Therefore, SNR estimation needs to be applied, such as some comparisons and novel algorithms [16]-[17]. However, if these algorithms are applied, it will increase the complexity of communication. [15] does not consider the computational problem and estimation accuracy. In the proposed method, we not only reduce the noise effect by increasing the number of data-aided samplings but also reduce the computational complexity while ensuring transmission efficiency. At this time, we do not use the additional pilot symbols. Our method is divided into two steps: 1. Deriving decision result of array output by the SMI with subcarrier grouping. 2. Obtaining a more accurate CSI vector aided by feedback decision data and estimating weight by LMS scheme with subcarrier grouping.
A. Initial Weight Calculation

Initial weight is calculated by SMI weight, which uses subcarrier grouping. Different from ASG, the grouping is not established according to the threshold. Each group is directly composed of the same number of subcarriers and the number of subcarriers is \( N_g \). The initial weight \( \tilde{W}_{c+k} (k = 0, \ldots, N_g - 1) \) is calculated from (23) to (27). The range of the group from the \( c \)-th subcarrier is directly delimited as follows, without iteration,

\[
m + 1 = N_g. \tag{28}
\]

The array output for the \( c \)-th subcarrier is written by,

\[
Y_c = \tilde{W}_c^H S_c. \tag{29}
\]

Due to the noise effect, the initial array output contains the errors. It is mapped into the original QAM constellation points and the initial solution \( \tilde{D}_c \) is obtained as follows,

\[
\tilde{D}_c = \mathcal{F}(Y_c), \tag{30}
\]

where \( \mathcal{F}(\cdot) \) represents the decision function. In order to reduce the amount of calculation, \( \tilde{D}_c \) is only determined by the \( M(0 \leq M \leq N_d) \) symbols instead of all. The concept of initial weight estimation for the SMI with subcarrier grouping is shown in Fig. 2. Each group corresponding to a different color contains \( N_g \) subcarriers.

B. Data-aided Weight Calculation

In the data-aided weight calculation scheme, the subcarrier grouping is also used and \( \tilde{D}_c \) can be regarded as an additional pilot signal for signal calculation and combined with the pilot signal as follows,

\[
\tilde{D}_c = [P_c, \tilde{D}_c], \tag{31}
\]

where \( \tilde{D}_c \) is desired response. The desired response in the subcarrier grouping can be derived as,

\[
\mathcal{D} = \frac{1}{N_g} \sum_{k=0}^{N_g-1} \tilde{D}_{c+k}. \tag{32}
\]

where the number of subcarrier grouping for the desired responses is \( N_g \), similar to (19) and (28). Because of the inverse matrix operation, the repeated use of the SMI method results in a significant increase in computation. Therefore, we use the initial weight \( \tilde{W}_c \) and the LMS method to replace SMI.

\[
\tilde{W}_{c+k}(1) = \tilde{W}_{c+k},
\]

\[
\tilde{W}_{c+k}(n + 1) = \tilde{W}_{c+k}(n) + \beta \tilde{X}_{c+k}(\mathcal{D}^H - \tilde{X}_{c+k}^H \tilde{W}_{c+k}(n)), \tag{34}
\]

where \( n \) and \( \beta \) denote the number of iterations and the step size that can control the convergence characteristics of the LMS algorithm, respectively. \( \tilde{W}_{c+k}(n) \in \mathbb{C}^{N_r \times N_g} \) represents the weight at the \( (c + k) \)-th subcarrier in the \( n \)-th step of the LMS algorithm \( (k = 0, \ldots, N_g - 1) \). \( \tilde{X}_{c+k} \in \mathbb{C}^{N_r \times (N_g + M)} \) indicates the signal containing the \( X_c \) and the first \( M \) data symbols of the \( S_c \) with grouping and averaging. Grouping and averaging are performed as (23). In addition, since the initial state of the weight is calculated by the SMI algorithm, the number of iterations required for convergence can be decreased. Consequently, the amount of computation is reduced. It is worth noting that since the convergence rate of LMS without the initial weight is slower than SMI [22] [23], a large number of iterations must be performed to achieve the same satisfactory convergence as SMI. In other words, LMS without the initial weight is more computationally intensive than SMI in order to achieve the same effect. That is why the LMS cannot be used in the initial weight calculation. By repeating the above procedures, the weight error can be minimized. The concept of data-aided weight derivation for the LMS with subcarrier grouping is shown in Fig. 3. Algorithm 1 summarizes the detailed procedure (28)-(34).

IV. COMPUTER SIMULATION

A. Simulation Parameters

We examine the interference suppression performance of the proposed algorithm by a computer simulation. Detailed simulation parameters are listed in Table I. The receiver using \( N_r = 16 \) rectangular array antenna elements attempts to separate out one desired signal from \( N_u = 4 \) incoming signals.

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Algorithm 1 Proposed interference suppression scheme

1: \( \tilde{W}_{c+k} \leftarrow (\Phi_{SG}^{c+k})^{-1} \tilde{V}_{c+k} \)
2: \( Y_c \leftarrow \tilde{W}_c^H S_c \)
3: \( \tilde{D}_c \leftarrow \mathcal{F}(Y_c) \)
4: \( \tilde{D}_c = [P_c, \tilde{D}_c] \)
5: \( \mathcal{D} \leftarrow \frac{1}{N_g} \sum_{k=0}^{N_g-1} \tilde{D}_{c+k} \)
6: \( n \leftarrow 1 \)
7: \( \tilde{W}_{c+k}(n) \leftarrow \tilde{W}_{c+k} \)
8: while \( n > L \) do
9: \( \tilde{W}_{c+k}(n + 1) \leftarrow \text{lms}[\tilde{W}_{c+k}(n), \mathcal{D}] \)
10: \( n \leftarrow n + 1 \)
11: end while
12: *lms[\cdot] denotes the least mean square function
TABLE I
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of receiver antennas $N_r$</td>
<td>16</td>
</tr>
<tr>
<td>Number of signal sources $N_u$</td>
<td>4</td>
</tr>
<tr>
<td>Transmission scheme</td>
<td>OFDM</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>15 kHz</td>
</tr>
<tr>
<td>Symbol duration $T_s$</td>
<td>71.4 µs</td>
</tr>
<tr>
<td>Modulation order</td>
<td>16QAM (w/o FEC)</td>
</tr>
<tr>
<td>Number of pilot symbols $N_p$</td>
<td>4</td>
</tr>
<tr>
<td>Number of data symbols $N_d$</td>
<td>30</td>
</tr>
<tr>
<td>Number of subcarriers $N_c$</td>
<td>128</td>
</tr>
<tr>
<td>Number of FFT points $N_{FFT}$</td>
<td>128</td>
</tr>
<tr>
<td>Angle of desired signal</td>
<td>0°</td>
</tr>
<tr>
<td>Angles of interference signals</td>
<td>30°, −70°, 80°</td>
</tr>
<tr>
<td>Channel model</td>
<td>Rician fading</td>
</tr>
<tr>
<td>Rician $K$ factor</td>
<td>10−10 dB</td>
</tr>
<tr>
<td>Max Doppler frequency $f_d$</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>$(f_d/T_s = 4.0 \times 10^{-5})$</td>
</tr>
</tbody>
</table>

We employ 16QAM modulation to every frame consisting of $N_p = 4$ pilot and $N_d = 30$ data symbols, and each frame is shown in Fig. 4. Moreover, each OFDM symbol is composed of $N_c = 128$ subcarriers. Rician fading with multipath is considered. The bandwidth of the transmission signal is 1.25 MHz, and the OFDM symbol duration is $T_s = 71.4$ µs, then the OFDM symbol rate is about $1/T_s = 14$ kHz. These parameters are almost compatible with a compact cellular system, i.e. LTE system [24].

B. Simulation Results

Figs. 5 and 6 show the BER performance comparison between the conventional SMI, CCM-SMI, adaptive subcarrier grouping [15], and the proposed method. The effect of the conventional and proposed methods is evaluated with different LOS components. Rician $K$ factors, i.e. $K = 10, −10$ dB, present whether the LOS component dominates the channel. When $K = −10$ dB, it approximates Rayleigh fading with no dominant LOS path. In the adaptive subcarrier grouping method, the value of $\sigma_{ASG}$ according to the SNR and shown as follows,

$$\sigma_{ASG} = \sqrt{\frac{10^{-3/10}}{SNR}},$$

(35)

To achieve convergence while reducing the computational complexity, we set $M = 15$, $\beta = 0.6$, $L = 2$, $N_g = 4$ in the proposed method.

The proposed method has better BER performance than other conventional methods at arbitrary $K$ factors. In a large $K = 10$ dB factor, the achievable gain is around 1.5 dB compared to ASG, and 4 dB compared to MMSE-SMI at $10^{-4}$ BER. Furthermore, in a smaller $K = −10$ dB situation, the proposed method also shows the best BER performance, where the achievable gain is around 1 dB compared to MMSE-SMI. However, although CCM-SMI can suppress the noise effect, the BER performance seriously deteriorates and the error floor is observed before $10^{-4}$ or $10^{-2}$ because of frequency selectivity. Therefore, it can only be used in a single-path situation. In addition, it is worth noting that ASG needs the SNR situation to determine the threshold $\sigma_{ASG}$ and make groups for noise rejection. In Figs. 5 and 6, the SNR estimation of ASG is assumed to be absolutely correct without considering the accuracy. If the performance of the SNR estimation method deteriorates, ASG will become ineffective. In addition, the proposed method does not depend on the SNR. It uses the same number of subcarrier groupings and decision feedback to improve BER performance.

C. Computation Complexity

Since a large number of weight calculations require huge memory and hardware resources, it is crucial to minimize the amount of computation with maintaining good performance. The number of complex-valued multiplications is used to evaluate the amount of computation.

Compared with the SMI algorithm, the computation complexity of our proposed scheme can be reduced by 20.4%. It is worth noting that although the decision feedback causes an increase in the amount of computation, several subcarriers can share one weight in the subcarrier grouping and the LMS algorithm is applied, which reduces the amount of computation. The LMS algorithm reuses the weight from the initial
phase as well as replaces matrix inversion that dominates the computational complexity.

V. CONCLUSION

This paper proposed the data-aided weight calculation and LMS method to improve the interference suppression performance of subcarrier grouping-based SMI adaptive array without SNR estimation method. It focuses on increasing data samples to reduce noise, thus maximizing the array weight derivation precision. Simulation results showed that the proposed method attained improved BER performance significantly with maintaining the transmission efficiency, whether LOS is the major factor or not. In addition, it saves computation compared to the conventional calculation of weight derivation for each subcarrier individually. Therefore, our proposed method can be applied as a potential future interference suppression technique for 5G or beyond, where small cells are heterogeneously deployed on the macro cells.

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