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Multiuser MIMO Beamforming for Single Data Stream Transmission in Frequency-Selective Fading Channels

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SUMMARY In this paper, we propose a multiple-input multiple-output (MIMO) beamforming scheme for a multiuser system in frequency-selective fading channels. The maximum signal-to-noise and interference ratio (MSINR) is adopted as a criterion to determine the transmit and receive weight vectors. In order to maximize the output SINR over all users, two algorithms for base station are considered: the first algorithm is based on the receive weight vector optimization and the second algorithm is based on an iterative update of both transmit and receive weight vectors. Based on the result of single user MIMO beamforming, we analyze the interference channels cancellation ability of multiuser MIMO system. The first algorithm is a simple method and the second algorithm is a performative solution. Through computer simulations, it is shown that multiuser communication system is achievable using the proposed methods in frequency-selective fading condition.

key words: *smart antennas, frequency-selective fading, multipath, MIMO, mutiuser systems*

1. Introduction

Demands for broadband wireless access technologies such as mobile internet, multi-media services given by wireless communication systems are rapidly growing during the latest few years. In the effort to deliver high-bit-rates in broadband wireless system, the transmission techniques are required to be able to cope with multipath fading channels. One of the most expected solution is usage of adaptive/smart antennas at either transmitter or receiver [1]–[3]. Because it exploits the significant spatial processing to combat multipath fading, both the bandwidth powerful and performance of system are improved considerably. In recent years, MIMO systems, where array antennas are equipped at both transmitter and receiver sides in configuration with space time signal processing, are used to increase the capacity of system. They utilize techniques of beamforming or space-time coding to improve the high-bit-rates transmission over multipath environments. Several techniques have been succeeded to increase efficiently the capacity and coverage of system by using signal-processing algorithms for flat fading channels [4]–[8]. Unfortunately, they are not easy to deal with frequency-selective fading environments.

Recently, two architectures have been investigated for MIMO system to mitigate the effect of frequency-selective fading channels. The first architecture is transmission of multiple data streams through spatial multiplexing or space-time codes combined with the orthogonal frequency division multiplexing (Spatial multiplexing OFDM and space-time coded OFDM). Spatial multiplexing OFDM can be used to transmit multiple independent data streams simultaneously, where the number of independent streams are limited by the minimum number of antenna elements at both ends thus frequency-selective MIMO channels are transformed into several frequency-flat MIMO sub-channels by OFDM system [9], [10]. The spatial multiplexing OFDM has been proposed to maximize throughput, whereas space-time coded OFDM enable maximum diversity and high coding gains [11]. Besides spatial multiplexing OFDM and space-time coded OFDM, the second architecture, the decision feedback equalization technique, where MIMO systems equipped with tapped delay line (TDL) structure, have been proposed for finding the optimal solution [12]–[14]. However, there are practical difficulties associated with the equalization at several megabits per second with high-speed, compact, and low-cost hardware. In order to mitigate the computing cost, the transmit and receive weight vectors determination has been studied to apply to MIMO frequency-selective fading channels environment for maximizing the SINR that interference channels is effectively cancelled without using the TDL equipment [15]. Thereon, growing number of users and providing high data rates for every single link at the same time have been known as an emerging study approach for multiuser MIMO frequency-selective fading channels [16]–[18].

In this paper, we propose a MIMO beamforming scheme using a single data stream transmission for multiuser systems in frequency-selective multipath channels. It is assumed that the channel state information (CSI) at both transmitter and receiver are known. The transmit weight vector for each user and the receive weight vector at base station (BS) corresponding to each user are calculated using two proposed algorithms to maximize SINR for all receivers and every single link at the same time. Deriving MIMO beamforming for a single user system from [15], we analyze a maximum number of interference channels which could be eleminated in multiuser system.

This paper is organized as follows. In Sect. 2, we introduce the propagation model of the broadband MIMO channel for multiuser system using transmission of a single data stream. The procedure to update the transmit and receive weight vectors based on the MSINR criterion and two algorithms for frequency-selective fading channels are de-

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scribed in Sect. 3. The analysis of interferences cancellation ability of the proposed method is discussed in Sect. 4. In Sect. 5, simulations results illustrating the proposed methods are presented. Finally, Sect. 6 concludes our study.

2. Propagation Model of MIMO Channel

Standard notations are used in this paper. Bold letters denote vectors and matrices. Other notation is as follows.

$(\cdot)^*$ Conjugate
$(\cdot)^T$ Transpose
$(\cdot)^H$ Conjugate transpose
$\mathbf{I}$ Identity matrix
$<(\cdot)>$ Ensemble average
$||(\cdot)||$ Euclid-norm of vector $(\cdot)$

Suppose there are Q users communicating with a BS. The ith user has a linear array antenna with M_i elements, where $i = 1, ..., Q$. BS has an adaptive antenna with N elements. A general MIMO beamforming for a single data stream transmission for a multiuser system under frequency-selective fading channels is shown in Fig. 1.

For wireless broadband systems, the MIMO propagation channel can be modeled as

$$\mathbf{H}_i(\tau) = \sum_{l=0}^{L_i-1} \mathbf{A}_i^{(l)} \delta(\tau - l\triangle\tau) \tag{1}$$

$$\mathbf{A}_i^{(l)} = \begin{pmatrix} a_{11,i}^{(l)} & a_{12,i}^{(l)} & \cdots & a_{1M,i}^{(l)} \\ a_{21,i}^{(l)} & a_{22,i}^{(l)} & \cdots & a_{2M,i}^{(l)} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1,i}^{(l)} & a_{N2,i}^{(l)} & \cdots & a_{NM,i}^{(l)} \end{pmatrix} \tag{2}$$

where $\mathbf{A}_i^{(0)}$ is the channel information of the preceding wave of the ith user, which we regard as the desired wave in this paper, while $\mathbf{A}_i^{(l)}$, $l = 1, ..., L_i - 1$, is the lth delayed channel information of the preceding channel of the ith user, which we consider as interference channels. The notation $a_{nm,i}^{(l)}$ means the lth interference channel response between the mth transmit antenna of the ith user and nth receive antenna of the BS. $\triangle\tau$ is the unit delay time, which corresponds to symbol period T_s, of the modulated signal.

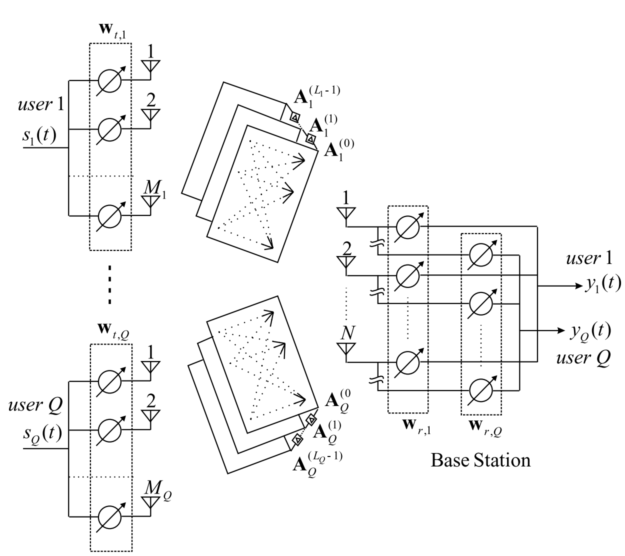

Fig. 1 Broadband MIMO channel and beamforming configuration for a multi-user system.

3. Transmit and Receive Weight Vectors Optimizations

3.1 The Transmit and Receive Weight Vectors

The outputs of array elements are linearly combined with weight vector to give the received signal. Thus the received signal for the ith user at the BS is expressed as

$$y_i(t) = \sum_{j=1}^{Q} \sum_{l=0}^{L_j-1} \mathbf{w}_{r,i}^H \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} s_j(t - l\Delta\tau) + \mathbf{w}_{r,i}^H \mathbf{n}(t) \tag{3}$$

where $s_j(t)$ is the transmit data of the jth user, and $\mathbf{n} = [n_1, n_2, ..., n_N]^T$ is the additive white gaussian noise (AWGN) vector. The beamforming transmit and receive weight vectors $\mathbf{w}_{t,i}$ and $\mathbf{w}_{r,i}$ for the ith user are defined as

$$\mathbf{w}_{t,i} = [w_{t1,i}, w_{t2,i}, \cdots, w_{tM,i}]^T \tag{4}$$

$$\mathbf{w}_{r,i} = [w_{r1,i}, w_{r2,i}, \cdots, w_{rN,i}]^T \tag{5}$$

Assume that the source signals are mutually uncorrelated with zero-mean and unit variance, thereby

$$\langle s_i^*(t - l\Delta\tau) s_i(t - k\Delta\tau)\rangle = 0 \quad \text{for} \quad l \neq k \tag{6}$$

$$\langle s_i^*(t) s_j(t)\rangle = 0 \quad \text{for} \quad i \neq j \tag{7}$$

Let us define $P_{S,i}$, P_N and $1/\gamma_i$, representing the signal power, noise power and power ratio of the signal to noise for the ith user:

$$\langle |s_i|^2 \rangle = P_{S,i} \tag{8}$$

$$\langle |n_1|^2 \rangle = \langle |n_2|^2 \rangle \cdots = \langle |n_N|^2 \rangle = P_N \tag{9}$$

$$1/\gamma_i \equiv P_{S,i}/P_N \tag{10}$$

The output SINR at the output of BS for the ith user is given by

$$\Gamma(\mathbf{w}_{t,i}, \mathbf{w}_{r,i}) = \frac{\mathbf{w}_{r,i}^H \mathbf{A}_i^{(o)} \mathbf{w}_{t,i} \mathbf{w}_{t,i}^H (\mathbf{A}_i^{(o)})^H \mathbf{w}_{r,i}}{R_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i}} \tag{11}$$

where R_{inf} is the sum of interference channels of the preceding channels of the ith user and interference channels caused by other users.

$$R_{inf} = \sum_{l=1}^{L_i-1} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(l)} \mathbf{w}_{t,i} \mathbf{w}_{t,i}^H (\mathbf{A}_i^{(l)})^H \mathbf{w}_{r,i} + \sum_{j=1, j\neq i}^{Q} \sum_{l=0}^{L_j-1} \mathbf{w}_{r,i}^H \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} \mathbf{w}_{t,j}^H (\mathbf{A}_j^{(l)})^H \mathbf{w}_{r,i} \tag{12}$$

We employ the MSINR method to determine the optimal transmit and receive weight vectors, for which single user case is described in detail in [15]. By extending the method to multiuser case, the receive and transmit weight vectors determination for the ith user is summarized in the following.

Receive weight vector determination: Assume that all the transmit weight vectors ($\mathbf{w}_{t,j}, j = 1, ..., Q$) are given, and an optional condition of $\mathbf{w}_{r,i}^H \mathbf{w}_{r,i} = 1$ to keep the total noise power constant. The steering vector of the desired signal is $\mathbf{A}_i^{(0)} \mathbf{w}_{t,i}$ and based on the MSINR method, the receive weight vector at BS for the ith user is given by

$$\mathbf{w}_{r,i}^{(opt)} = \mathbf{R}_{nr,i}^{-1} \mathbf{A}_i^{(0)} \mathbf{w}_{t,i} / \|\mathbf{R}_{nr,i}^{-1} \mathbf{A}_i^{(0)} \mathbf{w}_{t,i}\| \tag{13}$$

where $\mathbf{R}_{nr,i}$ is a covariance matrix, which includes total information of interference channels of the ith user and interference channels caused by other users, given by

$$\mathbf{R}_{nr,i} \equiv \sum_{l=1}^{L_i-1} \mathbf{A}_i^{(l)} \mathbf{w}_{t,i} \mathbf{w}_{t,i}^H (\mathbf{A}_i^{(l)})^H + \sum_{j=1, j\neq i}^{Q} \sum_{l=0}^{L_j-1} \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} \mathbf{w}_{t,j}^H (\mathbf{A}_j^{(l)})^H + \gamma_i \mathbf{I} \tag{14}$$

Transmit weight vector determination: Assume that the receive weight vector $\mathbf{w}_{r,i}$ and all the transmit weight vectors excluding $\mathbf{w}_{t,i}$ are given, we determine the optimal transmit weight vector satisfying the condition $\mathbf{w}_{t,i}^H \mathbf{w}_{t,i}=1$. Based on the method of Lagrange multiplier, the optimal transmit weight vector for the ith user is given by

$$\mathbf{w}_{t,i}^{(opt)} = \mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(o)})^H \mathbf{w}_{r,i} / \|\mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(o)})^H \mathbf{w}_{r,i}\| \tag{15}$$

where $\mathbf{R}_{nt,i}$ is a covariance matrix, which includes total information of interference channels of the ith user and interference channels caused by other users, given by

$$\mathbf{R}_{nt,i} \equiv \sum_{l=1}^{L_i-1} (\mathbf{A}_i^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(l)} + \sum_{j=1, j\neq i}^{Q} \sum_{l=0}^{L_j-1} \mathbf{w}_{t,j}^H (\mathbf{A}_j^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} \mathbf{I} + \gamma_i \mathbf{I} \tag{16}$$

The detailed transmit weight vector determination is seen in the Appendix.

We conclude that by giving the transmit weight vector of the ith user and fixing all the transmit weight vectors of the rest of users, the optimal receive weight vector at BS for the ith user is calculated by Eq. (13). Similarly, the optimal transmit weight vector for the ith user is calculated through Eq. (15) by giving the receive weight vector at the BS for the ith user and all the transmit weight vectors excluding $\mathbf{w}_{t,i}$.

3.2 Proposed Algorithms for Optimization

In this section, we propose two algorithms along the lines of optimization principles, which described in the previous section. Block diagram of algorithm A and algorithm B are shown in Fig. 2 and Fig. 3, respectively. For simplicity, it is assumed that there are two users communicating with a BS and selection of the initial weight vectors $\mathbf{w}_{t,1}(k), \mathbf{w}_{t,2}(k)$ for $k = 0$, where k is iteration index for optimization, are determined from MIMO flat fading channel environments as follows.

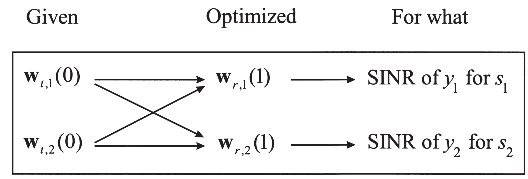

Fig. 2 Block diagram of the maximizing SINR by means of receiver-side weight vector optimization. (Q = 2) [Algorithm A]

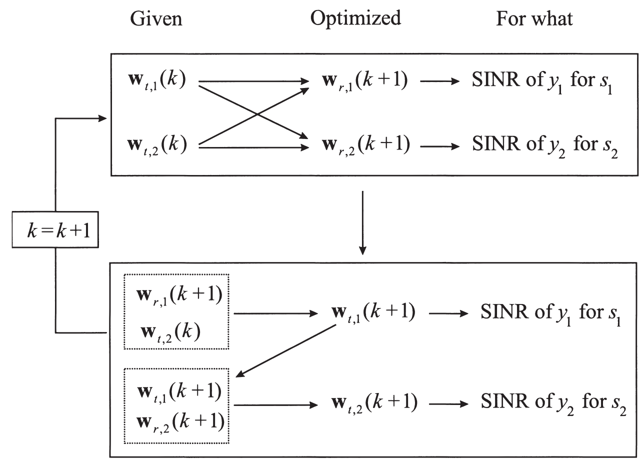

Fig. 3 Block diagram of the maximizing SINR based on iterative update of weight vectors at BS. (Q = 2) [Algorithm B]

$$\mathbf{w}_{t,i}(0) = \mathbf{e}_{t,i_{max}} \tag{17}$$

The vector $\mathbf{e}_{t,i_{max}}$ is the eigenvector corresponding to the largest eigenvalue $\lambda_{i_{max}}$ for the correlation matrix $(\mathbf{A}_i^{(o)})^H \mathbf{A}_i^{(o)}$ [19].

Algorithm A: *Maximizing SINR by receive weight vector optimization only*

Calculate the receive weight vectors $\mathbf{w}_{r,1}(1), \mathbf{w}_{r,2}(1)$ using the given transmit weight vectors $\mathbf{w}_{t,1}(0), \mathbf{w}_{t,2}(0)$ based on Eq. (13) for maximizing SINR corresponding to each user.

In this case, the transmit weight vector obtained from Eq. (17) is a premise to determine the optimal receive weight vector for maximizing SINR. Thus the only degree of freedom (DOF) of BS, namely $N - 1$, is consumed for cancellation of interference waves in desired signal and all other multipath waves in interfering signals. Although a number of DOF is consumed, the algorithm itself is very simple and seems practical.

Algorithm B: *Maximizing SINR based on iterative update of both ends weight vectors*

1) Calculate the receive weight vectors $\mathbf{w}_{r,1}(k + 1), \mathbf{w}_{r,2}(k + 1)$ with the given transmit weight vectors

$\mathbf{w}_{t,1}(k), \mathbf{w}_{t,2}(k)$ based on Eq. (13) for maximizing SINR corresponding to each user.

2) Calculate the transmit weight vectors $\mathbf{w}_{t,1}(k+1), \mathbf{w}_{t,2}(k+1)$ by the updated receive weight and previous transmitted weight vectors $\mathbf{w}_{r,1}(k+1), \mathbf{w}_{t,2}(k)$ and $\mathbf{w}_{r,2}(k+1), \mathbf{w}_{t,1}(k+1)$, respectively, based on Eq. (15) for maximizing SINR corresponding to each user.

3) Go to step 1 and repeat the iteration until a certain condition for termination is satisfied.

4) Send the optimal transmit weight vector obtained at BS to mobile stations. Using this transmit weight vector at each user side, the SINR is maximized for each user.

The maximum SINR is given in Eq. (11) where $\mathbf{w}_{t,i}$ and $\mathbf{w}_{r,i}$ are replaced by $\mathbf{w}_{t,i}^{(opt)}$ and $\mathbf{w}_{r,i}^{(opt)}$, respectively. Although both the algorithm A and B maximize SINR, the algorithm A is a scheme which optimizes the weight vector of receiver side only while the algorithm B is an algorithm which optimizes the weight vector of both transmitter and receiver at BS. Thus, condition is different even if it is the same propagation environment, the performance (namely, obtained maximum SINR) of the algorithm B is better. The detailed analysis of this algorithm is carried out in the next section from the view point of DOF.

4. Analysis of Interference Cancellation Ability of the Proposed Method

In this section, we investigate the interference channels cancellation ability of the proposed MIMO beamforming method in a single data stream transmission for multiuser system. In general, an M-element array, where the optimal beamformer without using the tapped delay lines, has effectively cancelled $M-1$ independent waves, namely, interference waves [20]. It seems correct for the Single-Input Multiple-Output (SIMO) or Multiple-Input Single-Output (MISO) system but the MIMO system. Actually, the interference channels cancellation of MIMO system has been larger than both SIMO and MISO systems, $(M-1)+(N-1)$ is maximum number of interference channels cancellation ability, which is proved from $M \times N$ MIMO system with respect to a single user system [15]. However, for multiuser system, not only interference channel of the preceding channel from the desired user, but also interference channels from other users should be cancelled. For instance, channel model for two users is shown in Fig. 4, where the preceding channel impulses of the first user is regarded as the desired preceding path and all other multipath waves are interferences.

Let's consider that the number of antennas for all users is 1 each. Since BS with N antennas is able to cancel $N-1$ undesired users, the BS can accommodate N users at most ($Q \leq N$). Next, the case where the number of each user is more than two transmit antennas is considered. Even in this case since the DOF of user's antennas is used to control the weight vector for the user for maximizing its SINR, it

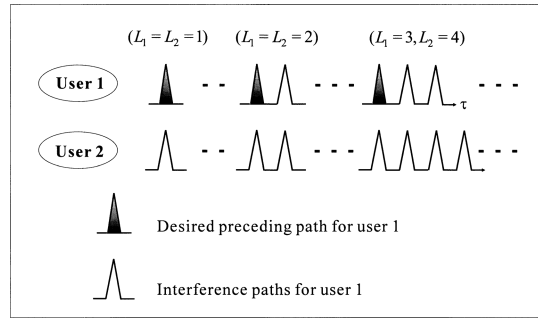

Fig. 4 Examples of the channel impulse response.

is not used to remove interference channels of the desired user. Therefore, condition ($Q \leq N$) is still satisfied for MIMO systems with our proposed scheme. However, when the DOF of transmitter antennas is utilized, not only the receive weight vector is updated in order to exploit the DOF of BS to cancel the undesired users but also the transmit weight vector is updated to produce the DOF of desired user for canceling its own interference channels. They are alternately updated to eliminate much more interference channels. We summarize now the conditions to find a total number of interference channels cancellation as follows.

- A maximum number of users Q is less than or equal to BS array antenna N ($Q \leq N$).
- The DOF of BS, $N-1$, could be used to cancel interference channels of any users.
- If the DOF of BS is larger than a total interference channels of all the undesired users, the DOF remainder of BS might be useful for the desired user to cancel more interference channels themselves.
- The DOF of desired user, $M_i - 1$, could be used to cancel its own iterference channels $\{\mathbf{A}_i^{(l)}; l = 1, ..., L_i - 1\}$.
- The DOF remainder of each user cannot cancel interference channels of other users. In other words, BS can only utilize its own DOF remainder to cancel interference channels of users.

For algorithm A, the condition for interferences cancellation for ith user in multiuser system is found through an inequality, which set up based on the above conditions and is given by

$$N - 1 \geq L_U + (L_i - 1) \qquad \text{for algorithm A} \tag{18}$$

where L_U is a total number of interference channels of all the undesired users, and is given by

$$L_U = \sum_{j=1, j\neq i}^{Q} L_j \tag{19}$$

Based on the update of transmit and receive weight vectors, the BS exploits its DOF to cancel interference channels of all the undesired users and the DOF of desired user is used to cancel interference channels themselves. Therefore, a total number of interference channels cancellation for ith user in multiuser system for algorithm B is found through an inequality in the following.

$$N - 1 \geq L_U + L_D \qquad \text{for algorithm B} \tag{20}$$

where L_D is the remainder of interference channels of the desired user after using its DOF to cancel interference channels themselves, and is given by.

$$L_D = \max\{(L_i - 1) - (M_i - 1), 0\} \tag{21}$$

In the following, the effectiveness of above inequalities (18) and (20) are clearly confirmed by the computer simulation.

5. Simulation

5.1 Simulation Conditions

In this section, to demonstrate the performance of the proposed algorithms, computer simulations are carried out for a two-user case. We assume that the components of the channel state matrix are independent identically distributed (i.i.d) with complex Gaussian distribution, with the uniform power delay profile (model 1) and the exponential power delay profile (model 2) [21], respectively, given by

$$p_i(\tau) = \sum_{l=0}^{L_i-1} \delta(\tau - lT_s) \quad \text{(model 1)} \tag{22}$$

$$p_i(\tau) = \frac{P_{R,i}}{\sigma_{\tau,i}} \sum_{l=0}^{L_i-1} e^{-\frac{\tau}{\sigma_{\tau,i}}} \delta(\tau - lT_s) \quad \text{(model 2)} \tag{23}$$

where T_s is the symbol period of the transmitted signal, and $P_{R,i}$ is the average power of multipath waves and $\sigma_{\tau,i}$ is the delay spread of the ith user channel.

For model 1, each impulse $a_{nm,i}^{(l)}$ is generated by the i.i.d. process while keeping $< |a_{nm,i}^{(l)}|^2 >= 1$ for $n = 1 \sim N, m = 1 \sim M_i$ and $l = 0 \sim L_i - 1$. Figure 5(a) shows the assumed channel considered in uniform power delay profile.

Although the uniform power delay profile is effective for the examination of the working mechanism of the proposed scheme, it is not realistic in indoor and outdoor propagation environments. Therefore, the exponential delay power profile will be used in order to evaluate the quantitative characteristics [21]. Figure 5(b) shows the assumed channel considered in exponential power delay profile. For both profiles, the amplitude of each impulse follows independent complex Gaussian distribution where the average power follows Eq. (22) or (23).

The simulation is performed in the context of a BPSK (Binary Phase Shift Keying) modulation scheme and the noise has been considered to be additive white Gaussian.

The output SINR is calculated via the cross-correlation coefficient ρ_i for the ith user given by

$$\rho_i = \frac{E[y_i(t)s_i^*(t)]}{\sqrt{E[|y_i(t)|^2]E[|s_i(t)|^2]}} \tag{24}$$

The output SINR calculation at the BS for the ith user is finally given by

$$\text{SINR}_{out,i} = \frac{|\rho_i|^2}{1 - |\rho_i|^2} \tag{25}$$

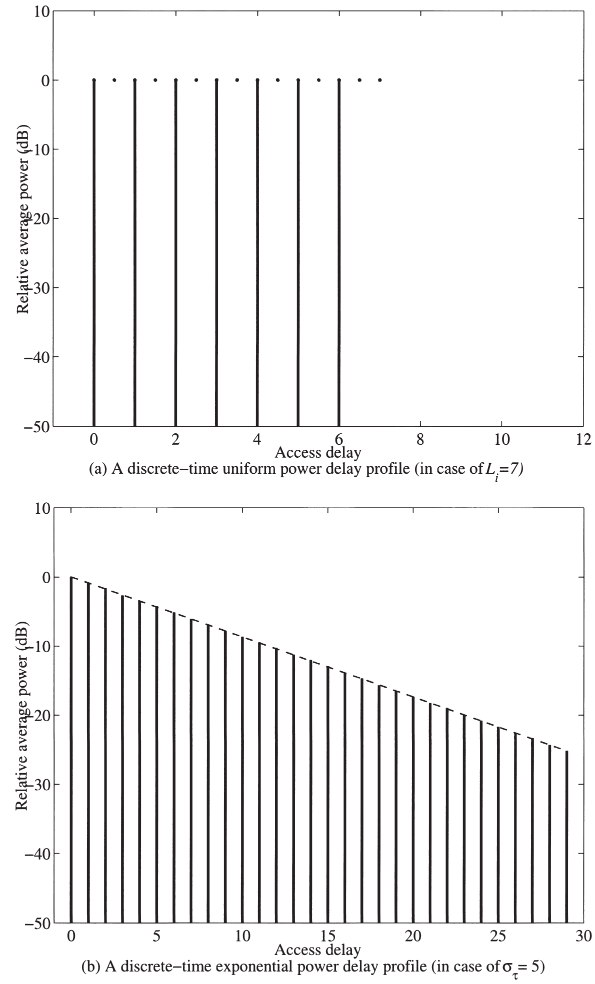

Fig. 5 Assumption of power delay profiles: (a) A discrete-time uniform power delay profile; (b) A discrete-time exponential power delay profile.

5.2 Results

First, we performed a two-user MIMO system simulation in multipath frequency-selective fading channels environment using model 1 that shows the convergence characteristics of system over interference channels by using the algorithm B. The number of antenna elements of BS and each user are equal to 4. In order to make clear interference channels cancellation limit, we set the input SNR = $P_{S,i}/P_N$ = 40 dB. The reference source signal of each user is used in BS to detect the desired signal. The simulation result is shown in Fig. 6.

Although the propagation environment of user 1 and 2 has the same statistical characteristic, instantaneous environment given by random number is different. Then the transmit weight vector of user 1 and 2 is optimized at BS with respect to its received signal. Thus, since the statistical characteristic of propagation environment and antennas number of two users are the same, the two convergence characteristics are similar. After 100 times trials by changing the propagation conditions keeping the given statistical property

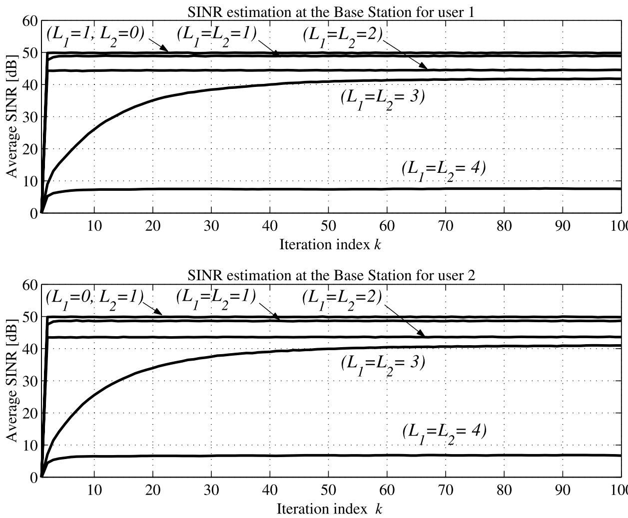

Fig. 6 Convergence characteristics of 4×4 MIMO system for two users using model 1. (upper: for user 1, lower: for user 2)

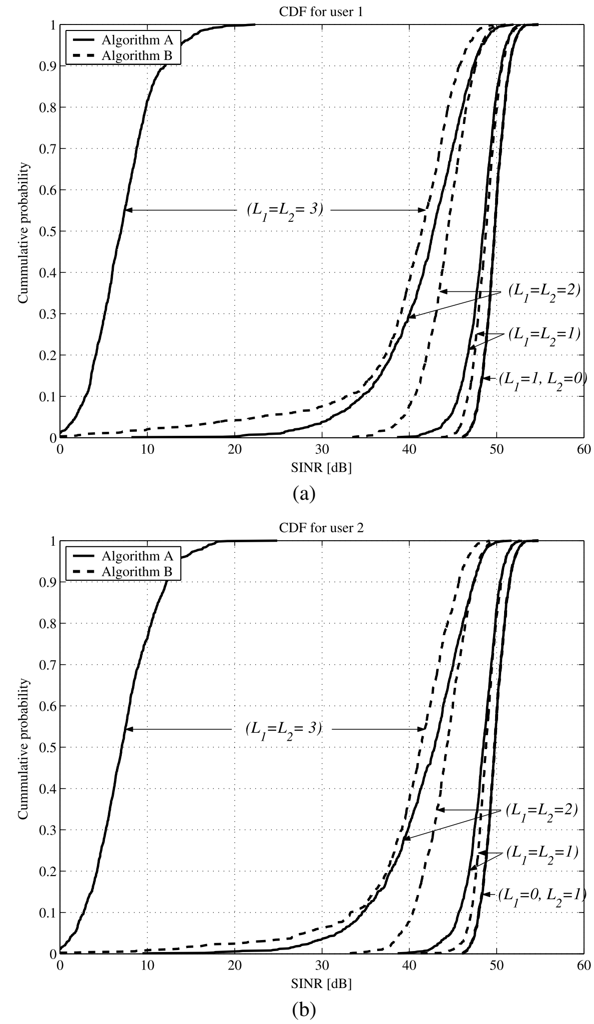

Fig. 7 Distribution function of SINR for two users 4×4 MIMO system: (a) CDF for user 1; (b) CDF for user 2.

constant, it can be identified that the system cancels a total number of 5 interference channels (namely, $L_1 = L_2 = 3$) for both user 1 and user 2. Since the increase in interferences leads to the matrix be full rank so that the increase in interference channels leads to longer convergence time. It is seen that $k = 80$ is a point having sufficient convergence characteristic of system to overcome 5 interference channels.

Next, for comparison of two proposed algorithms, we carried out a two-user 4×4 MIMO system simulation using model 1 that yields the cumulative distribution function (CDF) of SINR. The simulation of CDF shows that the proposed multiuser MIMO beamforming system cancels a number of interference channels effectively. The simulation result is shown in Fig. 7.

As can be seen from the CDF for user 1 in Fig. 7(a), user 1 and user 2 are considered to be the desired and undesired user. Let's consider the case of ($L_1 = L_2 = 2$) with the transmit and receive antennas ($M_1 = M_2 = N = 4$), for instance. By substituting those values into inequalities (18) and (20), we have ($3 \geq L_U + 1$) for the algorithm A and ($3 \geq L_U + 0$) for the algorithm B. As a result, $L_U = 2, 3$ for the algorithm A and B, respectively, which verified by the result of simulation. Moreover, the L_U obtained from inequalities (18) and (20) also imply that the algorithm A cannot remove for ($L_1 = 2, L_2 \geq 3$) while the algorithm B cancels effectively for ($L_1 = 4, L_2 = 3$). The performance characteristics obtained by using the algorithm B is better than algorithm A since DOF of the desired user is effectively utilized to cancel many copies of its preceding channel.

Similarly, Fig. 8 compares two proposed algorithms for a two-user MIMO system using model 1 where the number of antenna elements of each user is equal to 6 while the number of antenna elements of BS is 4.

As shown in Fig. 8, when user 1 and user 2 are considered as the desired and undesired users, respectively, the system has an ability to cancel less than or equal 5 waves of 7 total interference channels. On the contrary, when user 2 and user 1 are considered as the desired and undesired users, respectively, the system has an ability to cancel effectively the total interference channels. They also agree very well with the relation given by inequalities (18) and (20). The algorithm B eliminates considerably the number of interference channels compared to the algorithm A.

Successively, we performed several two-user MIMO system simulations using model 1 to verify the relation of inequalities (18) and (20), which given in Table 1. Herein, M_1, L_1 and M_2, L_2 are the number of antennas and i.i.d channels of user 1 and user 2. N is the number of antennas of BS. O and X denote the possibility of interference channels cancellation satisfied and unsatisfied with inequalities (18) and (20), by judging whether the median value of SINR is larger than 30 dB (O) or not (X). The computer simulations for the algorithm A and algorithm B are in good agreement with the results estimated from relation of inequalities (18) and (20), respectively. It is also observed that the algorithm B improves the performance of system when the preceding

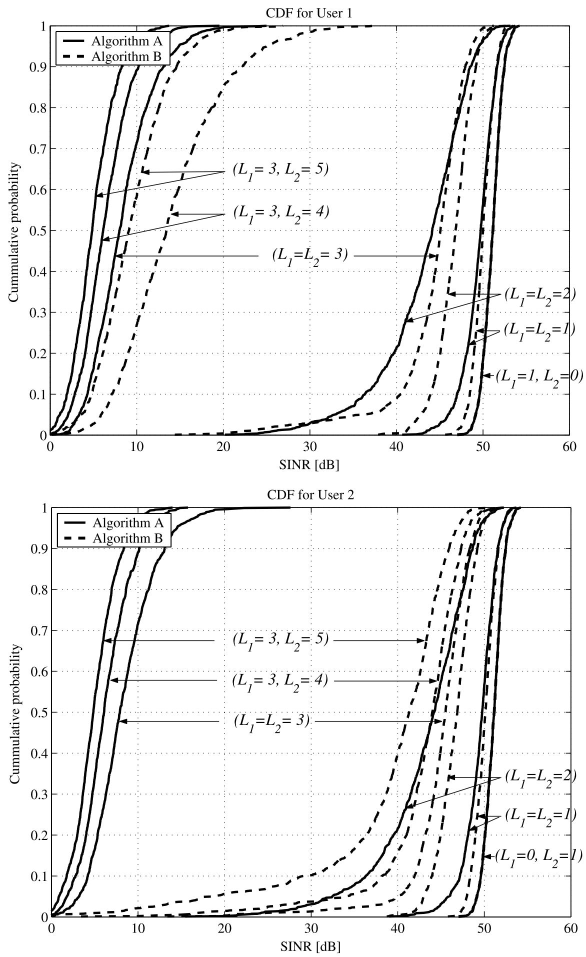

Fig. 8 Distribution function of SINR for two users 6×4 MIMO system.

Table 1 Interference channels cancellation ability of i.i.d channels of user 1 and user 2, respectively.

M_1	M_2	N	L_1	L_2	Algorithm	Desired User			
						1		2	
						Simulated	Estimated	Simulated	Estimated
2	2	4	2	2	A	O	O	O	O
					B	O	O	O	O
2	2	4	2	3	A	X	X	X	X
					B	O	O	O	O
4	4	4	2	4	A	X	X	X	X
					B	X	X	O	O
4	4	4	3	3	A	X	X	X	X
					B	O	O	O	O
6	6	4	3	5	A	X	X	X	X
					B	X	X	O	O
6	6	4	4	4	A	X	X	X	X
					B	X	X	X	X
4	4	6	4	2	A	O	O	O	O
					B	O	O	O	O
4	4	6	6	3	A	X	X	X	X
					B	O	O	X	X

O: Total interference channels cancellation is satisfied with inequalities (18), (20) or confirmed by simulation result viewing the SINR at 40dB and 50% of CDF.
X: Total interference channels cancellation is not satisfied with inequalities (18), (20) or verified by simulation result viewing the SINR at 40dB and 50% of CDF.

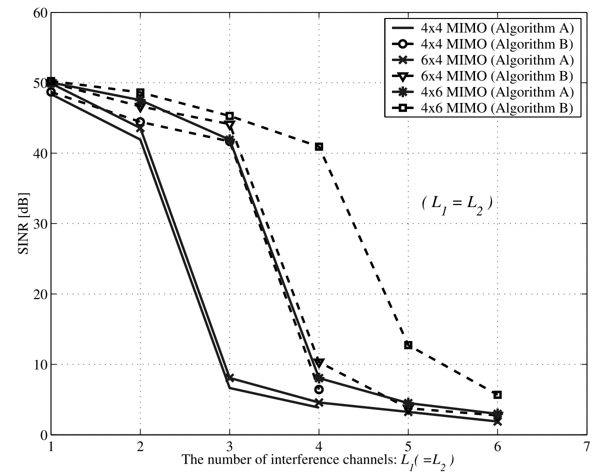

Fig. 9 Median value of SINR as a function of L_1 in case of $L_1 = L_2$.

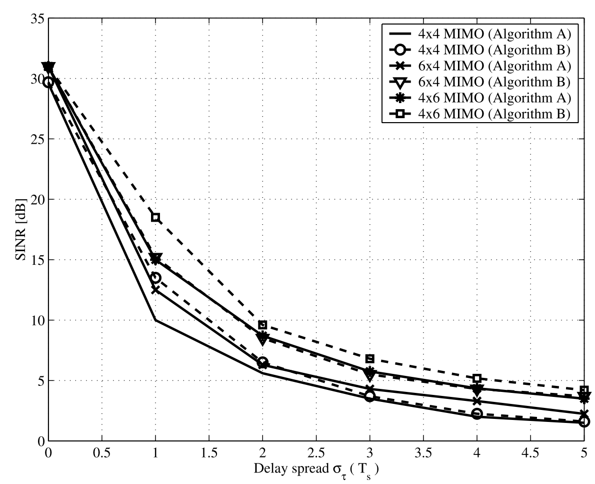

Fig. 10 Average SINR of MIMO system as a function of the delay spread σ_τ.

channel of the desired user has a lot of its own interference channels.

Figure 9 shows the SINRs viewing at 50 percent of the CDF versus the total number of interference and delayed channels of the 4×4, 4×6, and 6×4 MIMO systems. As can be seen in Fig. 9, the total number of interference channels cancelled by exploiting the DOF of both the BS and users of the algorithm B is larger than that of the algorithm A. Since the DOF of the transmit antennas for each user is used to cancel its own interference channels, it is not available to eliminate interference channels of any other users. However, the DOF of the receive antennas for BS has capable to cancel interference channels for all users if the number of interference channels are within the DOF. Therefore, the increasing the number of antennas of BS is better than that of mobile stations to suppress interference channels.

We are now going to show how our proposed schemes apply to multiuser MIMO system in frequency-selective fading channels using model 2 for the delay spread of multipath waves over one symbol period. We performed a simulation for two-user in the cases of 4×4, 4×6, and 6×4 MIMO systems with the input SNR = 20 dB and delay spread σ_τ ranging from 0 to $5T_s$. The simulation result is shown in Fig. 10. It is shown that the performance of system obtained by using the algorithm B is better than the algorithm A and the increase in number of antennas at BS improves the SINR compared to the increase in number of antennas at the desired user.

6. Conclusion

In this paper, we have proposed multiuser MIMO beamforming system for a single data stream transmission. The proposed algorithms are applied for a multi-user system in frequency-selective fading channels without using the tapped delay line. The algorithm A, which is characterized by simple scheme, showed good performance for propagation channel when the preceding channel of the desired user has few its own interference channels, while the algorithm B, which is more sophisticated scheme, shown better performance for canceling not only interference channels caused by other users but also more interference channels as shown in Fig. 9. The improvement of SINR by the proposed algorithms allows that either the more interference channels can be suppressed or more users can be supported in multiuser MIMO systems where a maximum cancellation number of interference channels must satisfy with inequalities Eqs. (18) and (20).

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Appendix: Transmit Weight Vector Determination

In the appendix, we will explain the transmit weight vector determination.

Starting from Eq. (11), we rewrite the output SINR for the ith user expression as

$$\Gamma(\mathbf{w}_{t,i};\mathbf{w}_{r,j}(j=1,...,Q,j\neq i)) = \frac{\mathbf{w}_{t,i}^H\mathbf{A}_i^{(o)}\mathbf{w}_{r,i}\mathbf{w}_{r,i}^H(\mathbf{A}_i^{(o)})^H\mathbf{w}_{t,i}}{\tilde{R}_{inf}+\gamma_i\mathbf{w}_{r,i}^H\mathbf{w}_{r,i}} \quad (A\cdot 1)$$

where

$$\tilde{R}_{inf} = \sum_{l=1}^{L_i-1}\mathbf{w}_{t,i}^H\mathbf{A}_i^{(l)}\mathbf{w}_{r,i}\mathbf{w}_{r,i}^H(\mathbf{A}_i^{(l)})^H\mathbf{w}_{t,i} + \sum_{j=1,j\neq i}^{Q}\sum_{l=0}^{L_j-1}\mathbf{w}_{t,i}^H\mathbf{A}_j^{(l)}\mathbf{w}_{r,j}\mathbf{w}_{r,j}^H(\mathbf{A}_j^{(l)})^H\mathbf{w}_{t,i} \quad (A\cdot 2)$$

We use the Lagrange multiplier method under condition of $\mathbf{w}_{t,i}^H\mathbf{w}_{t,i}=1$. Specifically

$$\phi_i = \Gamma(\mathbf{w}_{t,i};\mathbf{w}_{r,j},(j=1,...,Q,j\neq i)) + \lambda_i(1-\mathbf{w}_{t,i}^H\mathbf{w}_{t,i}) \quad (A\cdot 3)$$

where λ_i represents the Lagrange multiplier.

Taking the derivative of Eq. (A·3) with respect to $\mathbf{w}_{t,i}$ and setting it to zero.

$$\frac{\partial \phi_i}{\partial \mathbf{w}_{t,i}} = \frac{\partial \Gamma(\mathbf{w}_{t,i}; \mathbf{w}_{r,j}, (j = 1, ..., Q, j \neq i))}{\partial \mathbf{w}_{t,i}} + \frac{\lambda_i (1 - \mathbf{w}_{t,i}^H \mathbf{w}_{t,i})}{\partial \mathbf{w}_{t,i}} = 0 \quad (A\cdot 4)$$

And as a consequence, we have

$$\frac{[(\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(0)} \mathbf{w}_{t,i}][\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i}]}{(\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i})^2} - \frac{\sum_{l=1}^{L_i} (\mathbf{A}_i^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(l)} \mathbf{w}_{t,i}}{(\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i})^2} \times (\mathbf{w}_{t,i}^H (\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(0)} \mathbf{w}_{t,i}) - \lambda_i \mathbf{w}_{t,i} = 0 \quad (A\cdot 5)$$

In order to calculate the value of λ_i, Eq. (A·5) is multiplied by weight vector $\mathbf{w}_{t,i}^H$ with the condition $||\mathbf{w}_{t,i}|| = 1$, then we have

$$\lambda_i = \frac{\mathbf{w}_{t,i}^H (\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(0)} \mathbf{w}_{t,i}}{(\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i})^2} \times \sum_{j=1, j\neq i}^{Q} \sum_{l=0}^{L_j} \mathbf{w}_{t,j}^H (\mathbf{A}_j^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i} \quad (A\cdot 6)$$

Substituting Eq. (A·6) into Eq. (A·5), and since $\mathbf{w}_{r,i}^H \mathbf{A}_i^{(0)} \mathbf{w}_{t,i}$ is a scalar, we have

$$\mathbf{w}_{t,i} = \frac{\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i}}{\mathbf{w}_{t,i}^H (\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i}} \times \mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i} \quad (A\cdot 7)$$

where $\mathbf{R}_{nt,i}$ is defined in the Sect. 3, and is given by

$$\mathbf{R}_{nt,i} \equiv \sum_{l=1}^{L_i - 1} (\mathbf{A}_i^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_i^{(l)} + \sum_{j=1, j\neq i}^{Q} \sum_{l=0}^{L_j - 1} \mathbf{w}_{t,j}^H (\mathbf{A}_j^{(l)})^H \mathbf{w}_{r,i} \mathbf{w}_{r,i}^H \mathbf{A}_j^{(l)} \mathbf{w}_{t,j} \mathbf{I} + \gamma_i \mathbf{I} \quad (A\cdot 8)$$

Let us define

$$\xi = \frac{\tilde{R}_{inf} + \gamma_i \mathbf{w}_{r,i}^H \mathbf{w}_{r,i}}{\mathbf{w}_{t,i}^H \mathbf{A}_i^{(0)} \mathbf{w}_{r,i}} \quad (A\cdot 9)$$

The Eq. (A·7) is given by

$$\mathbf{w}_{t,i} = \xi \times \mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(0)})^H \mathbf{w}_{r,i} \quad (A\cdot 10)$$

Without detailed calculation of ξ, the optimal transmit weight vector for the ith user can be normalized and given by

$$\mathbf{w}_{t,i}^{(opt)} = \frac{\mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(o)})^H \mathbf{w}_{r,i}}{||\mathbf{R}_{nt,i}^{-1} (\mathbf{A}_i^{(o)})^H \mathbf{w}_{r,i}||} \quad (A\cdot 11)$$

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