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A Closed-loop Cross-Layer Scheme for Wireless Multiuser Transmissions

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Abstract

To improve transmission efficiency of wireless communication systems, cross-layer design is investigated, which can adapt to the dynamically variable wireless channel characters. In this paper, a novel cross-layer design for multi-user system is proposed to improve system performance. The Beamforming-MIMO cross-layer system is scheduled through combining multilevel adaptive modulation (AM) at physical layer with truncated automatic repeat request (ARQ) protocol at data link layer, and feed backing modulation mode, ARQ request and transmit weight vector from receiver, in order to improve multi-antennas system performance. This paper derives close-form expressions of the system spectral efficiency and the outage probability for wireless multiuser MIMO transmissions. It shows by simulation that, compared to Alamouti's cross-layer system and SISO cross-layer system, this cross-layer system can achieve better performance. And we analyze the impact of the transmit antenna number and mobile user number on the performance.

Keywords- cross-layer design; MIMO; adaptive modulation; automatic repeat request; multi-user scheduling

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1. Introduction

It is well known that multi-antenna systems can offer improvements in spectral efficiency along with diversity benefits (e.g. STBC and BF) over fading channels [1,2]. Space-time block codes (STBC) is a simple form but effective transmit diversity scheme (e.g. Alamouti's scheme, the simplest form of (STBC) by using two transmit antennas); however, STBC are not built for maximizing the SNR [1]. As another spatial diversity technology, beamforming (BF) can achieve high spectral efficiency by adjusting antenna weight to maximize receiving SNR. In [2,3], the combined beamforming and STBC system is proposed. Subsequently, the Alamouti's STBC is coupled with a larger number of transmit antenna via ideal beamforming to achieve higher throughput efficiency, and the full diversity and full code rate can be remained without orthogonality loss. Besides STBC and BF spatial diversity techniques, recent studies hotspot is another diversity technique for multi-user wireless systems, called multi-user diversity [4]. For

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the downlink multi-user scenario, the optimal policy to maximize the total system capacity is the "greedy scheme", that is to say, only one user with the best channel is scheduled to transmit at any time.

In wireless communication networks, adaptive modulation (AM) at the physical layer (PHY) has been studied extensively to enhance system throughout, which can match transmission rate to time-varying channels conditions [5,6]. And an alternative way to mitigate channel fading is to rely on the automatic repeat request (ARQ) protocol at the data link layer (DLL), namely transmitter has to make retransmissions for those packets received by error. Provided that perfect channel state information (CSI) is available at the receiver, the cross-layer design for SISO system (namely, SISO cross-layer scheme) is proposed in [7], and extend to MIMO wireless system in [8], (namely, Alamouti's cross-layer scheme), and the performance is enhanced evidently. However, the two cross-layer schemes can not adjust transmit antenna weights adaptively depending on feedback CSI in order to maximize receiving SNR.

For the sake of better performance gains, we propose the new cross-layer scheme (Beamforming-MIMO) for multi-user system, which combine multi-user scheduling, adaptive MIMO diversity and truncated ARQ through returning modulation mode, ARQ and transmit antenna weights, namely, three-ply feedback, and derive close-form expressions of spectral efficiency and the outage probability for the new cross-layer system. Our numerical results reveal that the new cross-layer scheme outperforms SISO cross-layer scheme and Alamouti's cross-layer scheme. And we investigate the impact of retransmission number and mobile-user number on performance of multi-user system.

The remainder of this paper is organized as follows. Section 2 introduces system models and cross-layer design. We analysis system performance in section 3, provide numerical results in Section 4, and conclude remarks are presented in the last section.

2. System Model

Provided that K mobile users within a cell communicate with the BS, we focus on downlink multi-user system, assuming a MISO wireless channel from the BS with N_T antennas to only the user with greatest SNR in each time, which means that multi-user diversity system can be viewed as a single user system at each time slot. Due to the limited complexity affordable at the mobile device, we assume a single antenna at each mobile user.

Supposing that the $1 \times N_T$ flat fading wireless channel matrix H has i.i.d complex Gaussian random entries elements, and the i th element $h_i \sim CN(0,1)$, where h_i is the channel vector between i th transmit antenna of the BS and receive antenna of the selected user, namely $\mathrm{H} = [h_1 \quad h_2 \quad \cdots \quad h_{N_T}]$. Adaptive modulation is performed using STBC to achieve transmit diversity over the wireless link, and the Alamouti STBC maps each N_f input QAM symbols into N_T orthogonal sequences, and the transmitted signal matrix S can be written as

$$\mathrm{S} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} \tag{1}$$

Where $s_i, i = 1, 2$ represents the modulated data symbol for i th symbol epoch.

For ideal beamforming, the optimal transmit weights vector $\mathrm{W} = \begin{bmatrix} w_1 & w_2 \end{bmatrix}$, can be expressed as

$$\mathrm{W} = \begin{bmatrix} w_1 & w_2 \end{bmatrix} = \frac{1}{\|\mathrm{h}\|_F} \cdot \begin{bmatrix} 0 & h_1^* \\ 0 & h_2^* \\ \vdots & \vdots \\ 0 & h_{N_T}^* \end{bmatrix} \tag{2}$$

Where $\|h\|_F$ is the Frobenius norm, i.e. $\|h\|_F = \sqrt{\sum_{i=1}^{N_T} |h_i|^2}$; and the antenna weight $w_i, i = 1, 2$ is adapted based on estimated CSI at the mobile user [3].

The traditional Alamouti's scheme, allocates the total transmit power equally among the different antennas, and has not optimal power allocation based on practical channel state. Different from the cross-layer scheme in [8] based on Alamouti, the new scheme has channel state information estimation at the mobile user, send optimal transmission weights back to the BS, in order to allocate transmit power optimally to all transmit antennas, and then maximizing the receive SNR. Therefore, keeping strongpoint of Alamouti and beamforming coexistence, the new scheme has optimal power allocation, while still remaining both full diversity and full code rate without orthogonality loss [3].

Dropping the time index for simplicity, the input/output relationship of selected user can be expressed as

$$\mathrm{Y} = \sqrt{P_s}\,\mathrm{H\,W\,S} + \mathrm{E} \tag{3}$$

Where, $\mathrm{Y} = \begin{bmatrix} y_1 & y_2 \end{bmatrix}$, $y_t, t = 1, 2$ is the received signal for t time slot; $\mathrm{E} = \begin{bmatrix} e_1 & e_2 \end{bmatrix}$ is the additive white Guassian noise(AWGN) vector, $e_t \sim CN(0, \sigma^2), t = 1, 2$. Let P_s denote the total transmit power and define the average SNR per receive antenna as $\overline{\gamma} = P_s / \sigma^2$.

At data link layer, ARQ control retransmissions of data packets received by error. Provided perfect channel state information (CSI) is available at the receiver using training-based channel estimation, adaptive modulation mode selector at the receiver choose modulation mode n , and then communicates with transmitter through a feedback channel, adaptive modulation mode controller updates the transmission mode at the transmitter. At the physical layer, we deal with frame by frame transmissions, and the frame structure is referred to [7].

In practice, to minimize delays and buffer sizes, we adopt truncated ARQ protocols, and the maximum number of retransmissions reaches to N_{arq} , which depends to system delay. Due to N_{arq} retransmissions, packet error probability of the packet is decreasing and is identified in limited bound and accepted. However, after N_{arq} retransmission, packet error probability is still large, the packet must be dropped. Let P_{loss} denote the probability of the packet loss, provided in the modulation mode n , let P_{am} denote physical layer packet error probability, the maximum number of transmissions is $\left(N_{arq} + 1\right)$. We obtain $P_{am} \le P_{loss}^{(1/N_{arq}+1)} = P_{phy}$, and packet error rate at the PHY must be no greater than the target probability P_{phy} .

For multi-user system, the greedy algorithm is adopted so that the constellation selection is based on the feedback SNR from the best user. In the automatic modulation design, let N denote the total number of modulation modes available, $N = 8$, the parameters can be referred to [7]. Here we assume constant power transmission, and split the range of the channel SNR into $N+1$ intervals, namely, $\{\gamma_n\}_{n=0}^{N+1}$.When $\gamma \in [\gamma_n, \gamma_{n+1})$, mode n is chosen, when $0 < \gamma < \gamma_1$, no payload bits will be sent. The threshold levels $\{\gamma_n\}_{n=0}^{N+1}$ are set to the required SNR to achieve the target P_{phy}, over a non-fading AWGN channel [5], which leads to the following values

$$Per_n(\gamma) \approx \{ \begin{array}{ccc} 1 & if & 0 < \gamma < \gamma_{pn} \\ a_n \exp(-g_n \gamma) & if & \gamma \geq \gamma_{pn} \end{array} \qquad (4)$$

From (4), we can derive $\gamma_n = -\log(P_{phy} / a_n) / g_n$. And γ denote received SNR, parameters a_n, g_n and γ_{pn} are listed in [7].

3. Performance Analysis

From [3], due to combining the STBC and beamforming, the effective induced channel is equivalent to SISO, and the received SNR γ_{bf}, is Gamma distributed with parameter N_T and mean $N_T\overline{\gamma}$ according to the p.d.f, $p_{\gamma_{bf}}(\gamma)$, given by

$$p_{\gamma_{bf}}(\gamma) = \frac{1}{\Gamma(N_T)} (\frac{1}{\overline{\gamma}}) (\frac{\gamma}{\overline{\gamma}})^{N_T - 1} \exp(-\frac{\gamma}{\overline{\gamma}}) \qquad \gamma > 0 \quad (5)$$

Where, $\Gamma(\cdot)$ is the Gamma function.

For a multi-user system with K mobile users, we use "greedy scheduling strategy" to choose only one mobile user with best channel condition [6]. And define the feedback SNR for the selected best user as $\gamma_{bf}^* := \max_K \gamma_{bf}^k, k \in [1, K]$, where γ_{bf}^k represents the feedback instantaneous SNR for the k th user in a multi-user system. Thus, probability density function (p.d.f.) of γ_{bf}^* can be expressed as $p_{\gamma_{bf}^*}^{\max}(\gamma) = K * p_{\gamma_{bf}}(\gamma) F_{\gamma_{bf}}^{K-1}(\gamma)$, where $p_{\gamma_{bf}}(\gamma)$ represents the p.d.f. of the total received SNR γ_{bf}, as in (5), and $F_{\gamma_{bf}}(\gamma)$ represents their cumulative distribution function (c.d.f). Furthermore, we assume each user has the same expected SNR, i.e., $\overline{\gamma}_{bf}^k = \overline{\gamma}$, $k \in [1, K]$, where $\overline{\gamma}_{bf}^k$ denotes the expected SNR at each receive antenna of the k th user.

To evaluate PER, we first calculate the probability that constellation size $M_n = 2^n$ is chosen, which equals to

$$P_n = \int_{\gamma_n}^{\gamma_{n+1}} p_{\gamma_{bf}^*}^{\max}(\gamma) d\gamma = (1 - \frac{\Gamma(N_T, \gamma_{n+1} / \overline{\gamma})}{\Gamma(N_T)})^K - (1 - \frac{\Gamma(N_T, \gamma_n / \overline{\gamma})}{\Gamma(N_T)})^K \qquad (6)$$

Where $\Gamma(\cdot, \cdot)$ denote the incomplete Gamma function.

Let $\overline{Per_n}$ denotes the average packet error rate for mode n, namely the ratio of the number of incorrectly received packets over those transmitted using mode n, which equals to

$$\overline{Per_n} = \frac{1}{P_n}\int_{\gamma_n}^{\gamma_{n+1}} Per_n \cdot p^{\max}_{\gamma^*_{bf}}(\gamma)d\gamma \tag{7}$$

Where Per_n is in (4).

Using this asymptotic distribution [6], the asymptotic average PER ($\overline{Per_n}$) for multi-user system can be given by

$$\begin{aligned}\overline{Per_n} &= \frac{\sum_{n=1}^{N} R_n B(n)\exp(-BB(n)X_K)}{\sum_{n=1}^{N} R_n \cdot P_n} \\ &\left\{[\Gamma(BB(n)Y_K+1, \exp(-\frac{\gamma_n - X_K}{Y_K}))] \right. \\ &\left. -[\Gamma(BB(n)Y_K+1, \exp(-\frac{\gamma_{n+1} - X_K}{Y_K}))]\right\}\end{aligned} \tag{8}$$

Where $B(n) = a_n(\frac{1}{1+g_n\overline{\gamma}})^{N_T}$, $BB(n) = \frac{g_n}{1+g_n\overline{\gamma}}$, $X_K = F^{-1}_{\gamma_{bf}}(1-\frac{1}{K})$, $Y_K = F^{-1}_{\gamma_{bf}}(1-\frac{1}{K\cdot e}) - X_K$.

$\overline{Per}$ denote the average packet error rate of AM， which equals to

$$\overline{Per} = \frac{\sum_{n=1}^{N} R_n \cdot P_n \cdot \overline{Per_n}}{\sum_{n=1}^{N} R_n \cdot P_n} \tag{9}$$

Considered N_{arq} -ARQ at the data link layer, the average number $\overline{N}(N_{arq})$ is given by [7]: $q = \overline{Per}$

$$\overline{N}(N_{arq}) = 1 + q + \cdots + (q)^{N_{arq}} = \frac{1-(q)^{N_{arq}+1}}{1-(q)} \tag{10}$$

The average spectral efficiency is expressed as

$$SE(N_{arq}) = \frac{\sum_{n=1}^{N} R_n \cdot P_n}{\overline{N}(N_{arq})} \tag{11}$$

And the probability of outage is written as

$$P_{out} = \int_0^{\gamma_1} p^{\max}_{\gamma^*_{bf}}(\gamma)d\gamma \cdot \overline{N}(N_{arq}) = (1 - \frac{\Gamma(N_T, \frac{\gamma_1}{\overline{\gamma}})}{\Gamma(N_T)})^K \cdot \overline{N}(N_{arq}) \tag{12}$$

4. Numerical Results

In this section, we present numerical results for the Beamforming-MIMO cross-layer scheme for multi-user system over Rayleigh flat fading channels. We consider $P_{loss} = 0.0001$, the maximum number of ARQ available is $N_{arq} \in \{0,1,3\}$, mobile user number $K \in \{1,5,10,50,200\}$.

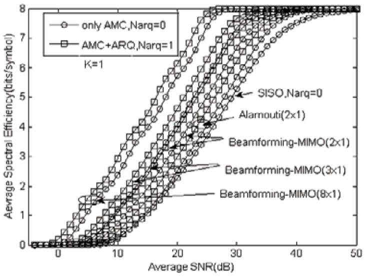

Figure 1. Comparison average spectral efficiency for different schemes

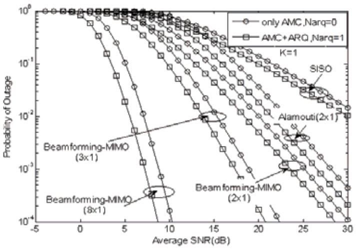

Figure 2. Comparison probability of outage for different schemes

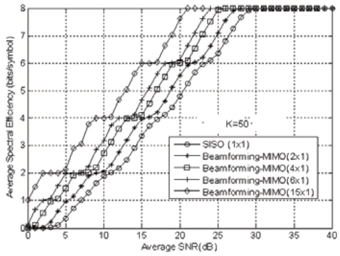

Figure 3. Comparison between the average spectral efficiency for different transmit antennas of the new cross layer system

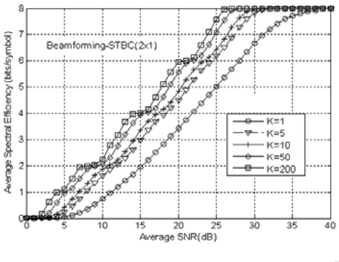

Figure 4. Comparison between the average spectral efficiency for user number $K \in \{1,5,10,50,200\}$ for new cross layer system

For easy to explain, firstly, we illustrate the comparisons between performance of the cross-layer schemes for single -user system in Fig.1 and Fig.2, for the average spectral efficiency and the probability of outage respectively. The two figure show the performance of Alamouti(2x1) cross-layer scheme is higher than the SISO cross-layer scheme, however, lower than the new cross-layer scheme (Beamforming-MIMO(2x1)). It's because of increasing a feedback, i.e. transmission weight vector feedback, which can improve system performance. And increasing the antennas (N_T) and number of ARQ retransmission (N_{arq}) can help increasing the average spectral efficiency and diminishing the probability of outage, as expected.

And Fig.3 and Fig.4 describe the antenna number and mobile user number affects the spectral efficiency of the cross layer systems. With multi-user diversity, the performance of multi-user cross layer system is enhanced.

5. Conclusion

In this paper, we have proposed a novel cross-layer scheme which combines the use of AM at the physical layer with that of multi-user diversity and ARQ retransmission at the data link layer for multi-user MIMO system. Numerical results show that the performance of the new cross-layer scheme exceeds that of Alamouti (2x1) and SISO cross-layer scheme. We derive analytical expressions for the average spectral efficiency and probability of outage of the proposed system, and analyze transmit antenna and number of mobile user on the performance of the multi-user system.

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