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Analysis of the Energy Efficiency and Packet Error Rate in Amplify-and-Forward MIMO Cooperative Networks

Manar Al-Kali, Li Yu, Ali Mohammed

Abstract— in this paper, we focus on the energy efficiency issues in cooperative multiple-input multiple-output (MIMO) relay networks. We employ an amplify-and-forward (AF) relay scheme, where a static multiple antennas relay station cooperatively forwards the relaying packets to the destination. Under the assumption of Rayleigh fading channels and time division multiplexing (TDM), we analyze the effect of average received signal-to-noise ratio (SNR) on energy efficiency. We derive the new exact closed form expressions for the packet error rate and energy efficiency in terms of SNR and Q antennas. Subsequently, we validate our analysis by performing Monte Carlo methods. The simulation results demonstrate that the proposed scheme achieves a significantly higher efficiency performance, when compared with the existing relay schemes.

Index Terms— Cooperative networks, diversity techniques, MIMO, Amplify-and-Forward, energy consumption, energy efficiency, packet error rate.

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1 INTRODUCTION

MULIPLE-input multiple-output (MIMO) techniques have been considered as effective solutions to improve data rate and reliability in wireless distributed networks. Furthermore, it has been proven that by combining MIMO with the cooperative diversity techniques via deploying multiple antennas relay(s) can extend the coverage of wireless networks when the direct transmission is very poor and can provide a solution to the energy constraints of the wireless networks [1-6]. Specifically, by exploiting the availability of the perfect channel state information (CSI) in the network, MIMO relying concept has emerged as hot topic in the recent years. For example, partial relay selection scheme was considered in [1] where the source continuously monitors the one hop CSI information and the relay with best source/relay SNR is selected. In [2] the symbol error rate (SER) performance of dual AF-MIMO with best antenna selection was investigated, by benefiting from the full knowledge of the CSI information at both of the source and the relay. While for the energy issues, the hop distance in combination with the number of nodes was optimized in MIMO and multiple-input single-output(MISO) relay systems to improve their energy consumption in [3]-[4]. In [5] transmit power allocation (TPA) strategies based on the criterion of maximum channel capacity are discussed for different MIMO relaying systems where power constraint is imposed on the source and the relay. However, these schemes requires the source to consciously monitors the CSI information, which will increase the overhead and reduce the network life time in resource constrained system.

Despite of the effort that have been done in the MIMO relay networks, all of these works focus on the performance of SER. In this paper, we adopted Packet error rate (PER) as ρ rather than SER because of its definition at the packet level of the hierarchy stack makes it better to handle by the higher layers in the stack. Therefore, we address the energy-efficiency issues in the cooperative MIMO relay networks from the perspective of successful packet transmissions. We consider an amplify-and-forward (AF) relay scheme, where a relay station with Q antennas forwards the packets to the destination nodes rather than [6] where relaying occurs through K number of amplify and forward relays (AP-AF). In this scheme, the relay is allowed to use time division multiplexing (TDM) to permit possible simultaneous transmissions among the nodes. We analyze the effect of signal-to- noise ratio (SNR) and Q antennas on the probability density function (PDF) under Rayleigh fading conditions, and based on it, we derive new closed-form expressions for PER and energy efficiency (η). Furthermore, Monte Carlo methods are employed to support our analysis. Finally, we compare our derived expressions of ρ and η with simulated the scheme of AP-AF in [6]. The numerical results show that the proposed scheme achieves the highest energy efficiency, when compared with the other scheme.

The rest of this paper is organized as follows: We describe the MIMO relay network in Section 2. New closed-form expressions of the PDFs for the direct and cooperative paths are derived in Section 3.1. In Section 3.2, we derive the PER expression from the received SNR at the destination node. The energy efficiency is derived in section 3.3. Monte Carlo simulation and numerical results are given in Section 4. Lastly, Section 5 presents the conclusion.

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2 System Model

The MIMO relay network under the assumption is shown in Figure 1.

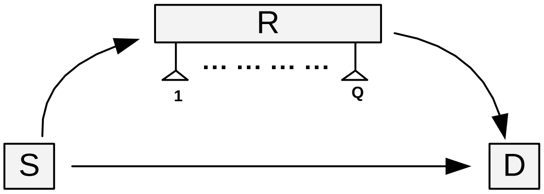

Fig.1 The multiple antenna MIMO relay scheme

The data packets are sent from the source to the destination either directly or cooperatively through a MIMO relay station with Q antennas. The channels are assumed to be independent, identically distributed (i.i.d), half duplex, orthogonal Rayleigh fading channels. To ensure that the source and the relay transmissions occur in consecutive time slots, we assume that the relay utilizes TDM. We assume that the CSI information is acquired at the destination via feedback links.

Let S S, D , and $\sum_{q=1}^{Q} R_q$ denote the source, the destination, and the multiple antenna relay ($1 \le q \le Q$) respectively.

If x is a scalar data symbol sent from the source with zero mean and unit variance, then the received signal at the destination from the source is expressed as:

$$y_{SD} = H_{SD} P_s x + n_{SD} \quad (1)$$

where H_{SD} is the Rayleigh fading coefficient of $S-D$ link, P_s is the average transmit power per symbol at the source, and n_{SD} is the additive white Gaussian noise (*AWGN*) with variance $E[n_{SD}] = N_o$ and $E[.]$ is the expected value.

In the same time slot, the received signal at the relay is combined with maximum ratio combining (*MRC*), according to:

$$y_{SR} = \varepsilon_{SR}(H_{SR} P_s x + n_{SR}) \quad (2)$$

where ε_{sr} is *MRC* the receive weight vector [7], which is expressed as $\varepsilon_{sr} = \frac{H_{SR}^{\dagger}}{\| H_{SR} \|^2}$ with $(^{\dagger})$ and $\| \cdot \|$ denoting the conjugate transpose operation and the vector norm, respectively, H_{SR} is $Q \times 1$ channel vector between S and $\sum_{q=1}^{Q} R_q$ with Rayleigh fading inputs, and n_{SR} is $Q \times 1$ *AWGN* with $E[n_{SR} n_{SR}{}^{\dagger}] = I_Q N_o$

with $I_Q = Q \times Q$ identity matrix.

In the second time slot, the MIMO relay forwards a scaled copy of (2) to the destination with respect to rule of the maximum ratio transmission (MRT) presented in [7]. The obtained signal at the destination from the relay is expressed as:

$$y_{R_i D} = \varepsilon_{RD} \beta P_r H_{RD} y_{SR} + n_D \quad (3)$$

where ε_{rd} is the *MRT* is transmit weight vector [7], which is given by $\varepsilon_{RD} = \frac{H_{RD}^{\dagger}}{\| H_{RD} \|^2}$ H_{RD} is $1 \times Q$ channel vector between $\sum_{q=1}^{Q} R_q$ and D with the Rayleigh fading inputs, P_R is the average transmit power per symbol at the relay, is the scaling $\beta = \frac{1}{\sqrt{P_S \| H_{RD} \|^2}}$ gain in terms of the average SNR of the source/relay channel, and n_D is 1 × Q *AWGN* with $E[n_{RD} n_{RD}{}^{\dagger}] = I_Q N_o$

From (3), the instantaneous end-to-end SNR at the destination obtained from the MIMO relay is given by:

$$w_q = \frac{P_s \frac{\| H_{SR} \|^2}{N_o} . P_r \frac{\| H_{RD} \|^2}{N_o Q}}{\frac{\| H_{SR} \|^2}{N_o} + P_r \frac{\| H_{RD} \|^2}{N_o Q}} = \frac{w_{SR} . w_{RD}}{w_{SR} + w_{RD}} \quad (4)$$

where $w_{SR} = P_S \frac{\| H_{SR} \|^2}{N_o}$ is the instantaneous SNR received from the source to the MIMO relay with PDF $f_{w_{SR}}(w_{SR})$ and $w_{RD} = P_R \frac{\| H_{SR} \|^2}{N_o Q}$ is the instantaneous SNR received from the MIMO relay to the destination with PDF $f_{w_{RD}}(w_{RD})$ (see Appendix A).

The destination combines the two received signals according to the diversity Selection Combining (SC). Finally, the equivalent SNR at the destination is expressed as:

$$D = \max(w_{SD}, w_q) \quad (5)$$

where $w_{SD} = P_s \frac{| H_{SD} |^2}{N_o}$ s the instantaneous SNR from the source to the destination.

From (5), we can express the PDF of D as the PDF intersection of w_{SD} and w_q :

$$f_D(\gamma) = [D = \gamma] = f_{w_{SD}}(\gamma) \cap f_{w_q}(\gamma) \quad (6)$$

where $f_{w_{SD}}(\gamma)$ and $f_{w_q}(\gamma)$ is the PDF of w_{SD} and w_q respectively

Let $\rho_{w_{SD}}$, $\rho_{w_{SR}}$, $\rho_{w_{RD}}$ and ρ_{w_D} denote the average PER of w_{SD} , w_{SR} , w_{RD} and D respectively, which each individual can be given by:

$$\rho = \int_0^{\infty} f(\gamma) p(\gamma) . \gamma \quad (7)$$

where $f(\gamma)$ is the PDF of and $p(\gamma)$ is the instantaneous PER of γ . The PER in the AF MIMO relay with Q transmit/receive antennas is expressed as:

$$\rho_{AF} = \rho_{w_{SD}}(\rho_{w_{SR}} + \rho_{w_{RD}}) - \rho_D \quad (8)$$

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As data packet consists of header, payload, and trailer, we can write η as in [8]:

$$\eta = \frac{L(1-P_e)}{E} \tag{9}$$

In the above, L is the length of packet, ρ is the PER of a transmission scheme , E is the total energy consumption which is given by:

$$E = \frac{L_p P_o}{R_b} \tag{10}$$

where P_o is the total consumed power, L_p is the payload packet length and R_b as the bit rate.

3 Performance Analysis

3.1 Outage Probability

In this section, we present the new closed-form expression for the PDF of D, which it is essential to derive the expressions for both PER in (8) and η in (9). As the channels are assumed to be (i.i.d), (6) can be re-written as:

$$f_D(\gamma) = f_{w_{SD}}(\gamma) f_{w_q}(\gamma) \tag{11}$$

Noting that fading coefficients of the $S-D$ link follow a Rayleigh distribution, the instantaneous received SNR from that link, w_{SD}, follows an exponential distribution with PDF given by:

$$f_{w_{SD}} = \frac{1}{\bar{w}_{SD}} e^{-\frac{\gamma}{\bar{w}_{SD}}} \tag{12}$$

where $\bar{w}_{SD} = \frac{P_S E[|H_{SD}|^2]}{N_o}$ is the average received SNR over $S-D$ link.

Next, we derive a new closed-form expression for the PDF of w_q as given by *proposition 1.*

Proposition 1: For the AF MIMO relaying, the PDF of w_q with Q transmit/receive antennas at the relay is given by:

$$f_{w_q}(\gamma) = 1 - \frac{e^{-\frac{(Q-1)\bar{w}_q}{\bar{w}_{RD}}}}{(Q-1)!\,\bar{w}_{SR}^Q} \times \sum_{q=0}^{Q-1} \frac{\bar{w}_q^q}{q!\,\bar{w}_{RD}^q} \sum_{k=0}^{q} \binom{q}{k} (Q-1)^{q-k} C^k \gamma^{Q-k-1} e^{-\frac{C\bar{w}_q}{\gamma \bar{w}_{RD}} - \gamma \bar{w}_{SR}} \tag{13}$$

where $\bar{w}_{SR} = \frac{P_S E[\|H_{SR}\|^2]}{N_o}$ $\forall q \in [1,\ldots,Q]$ is the average SNR from the source to the MIMO relay, $\bar{w}_{RD} = \frac{P_R E[\|H_{RD}\|^2]}{N_o Q}$ $\forall q \in [Q,\ldots,1]$ is the average SNR from the MIMO relay to the destination, $\bar{w}_q = \frac{Q\bar{w}_{SR}.\bar{w}_{RD}}{\bar{w}_{SR} + \bar{w}_{RD}}$ is the end to end average SNR over the cooperative path, and $C = P_S + P_R$ is the total power consumed from the network.

Proof: See Appendix A

By substituting (12) and (13) into (11) with some algebraic manipulation, we can obtain the new closed-form expression of the PDF for the SNR at the destination valid for an arbitrary Q of antennas:

$$f_D(\gamma) = \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{\gamma}{\bar{w}_{SD}}} - \frac{e^{-\frac{(Q-1)\bar{w}_U}{\bar{\gamma}_{RD}}}}{(Q-1)!\,\bar{w}_{SR}^Q \bar{w}_{SD}} \times \sum_{q=0}^{Q-1} \frac{\bar{w}_U^q}{q!\,\bar{w}_{RD}^q} \sum_{k=0}^{q} \binom{q}{k} (Q-1)^{q-k} C^k \gamma^{Q-k-1} e^{-\frac{C\bar{w}_U}{\gamma \bar{w}_{RD}} - \gamma \bar{w}_1} \tag{14}$$

where $\bar{w}_1 = \frac{\bar{w}_{SR} + \bar{w}_{SD}}{\bar{w}_{SR}.\bar{w}_{SD}}$

3.2 PER Estimation

We estimate the PER expression in (8) by deriving each of its parts relying on the p.d.fs results given in Section III, Appendix A, and the instantaneous PER expression given by [9]:

$$p(\gamma) = 1 - (1 - \frac{1}{2} e^{\frac{\gamma}{2}})^L \tag{15}$$

By using each of (12), (30), and (31) with (15) in the integral (7), we obtain the following new exact closed-form expressions (see Appendix B):

$$\rho_{SD} = 1 - \sum_{M=0}^{L} \binom{L}{M} \left(-\frac{1}{2}\right)^M \frac{2}{M\bar{\gamma}_{SD} + 2} \tag{16}$$

$$\rho_{SR} = \frac{\Gamma(Q)}{(Q-1)!} \left(1 - \sum_{M=0}^{L} \binom{L}{M} \left(-\frac{1}{2}\right)^M \left(\frac{2}{M\bar{\gamma}_{SR} + 2}\right)^Q \right) \tag{17}$$

$$\rho_{RD} = \frac{\Gamma(Q)}{(Q-1)!} \left(1 - \sum_{M=0}^{L} \binom{L}{M} \left(-\frac{1}{2}\right)^M \left(\frac{2}{M\bar{\gamma}_{RD} + 2}\right)^Q \right) \tag{18}$$

where $\Gamma(Q)$ is the Euler's integral of the second kind, which is computed as[15, 8.322]:

$$\Gamma(z) = e^{-\nu z} \prod_{k=1}^{\infty} \frac{e^{\frac{z}{k}}}{1 + \frac{z}{k}} \tag{19}$$

where ν is Euler constant:

$$\nu = \lim_{j \to \infty} \left[\sum_{w=1}^{j-1} \frac{1}{w} - \ln j \right] \tag{20}$$

Then, we derive ρ_D by submitting (14) and (15) into (7) with some algebraic manipulation, and the new expression is given in (21) on the top of this page, where *K:* is the Modified Bessel function of the second kind [[10], 8.44] and $\bar{w}_2 = \bar{w}_1 + \frac{M}{2}$ (see Appendix C)

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We proceed by defining G as the cooperative link strength parameter ($\forall G \in \mathbb{R}, G \geq 1$), which is expressed as follows:

$$G = \frac{\bar{w}_{SR}}{\bar{w}_{SD}} \quad (22)$$

By substituting (16), (17), (18), (21), and (22) into (8), we obtain the new closed-form expression of ρ_{AF} as in (24) on the top of the next page.

The expression in (23) is the analytical representation of the PER for MIMO relay cooperative networks, where it is valid as long as distinct average SNR is obtained from each link, i.e. ($\bar{w}_{RD} = \frac{\bar{w}_{SR}}{Q}$).

3.3 Energy efficiency Estimation

In this section, we utilize the ρ derived in Section IV to estimate η for MIMO relay scheme.

The total limited power in AF MIMO relaying is expressed as[8]:

$$P_{o_{AF}} = P_S(1+\delta)\left[p_{ct} + \sum_{q=1}^{Q} p_{cr}\right](1-\rho_o) + P_R(1+\delta)\left[\sum_{q=1}^{Q} p_{ct} + \sum_{q=1}^{Q+1} p_{cr}\right]\rho_o \quad (24)$$

p_{ct} and p_{cr} are the power consumed in the circuit block of the transmitter and receiver, respectively, δ is the loss factor of the amplified power in the range of $0 \leq \delta \leq 1$ and $\rho_o = \rho_{RD}(1-\rho_{SR})$

By substituting (24) into (10), we get the expression for the energy consumption as:

$$E_{AF} = \frac{L_p\left(P_S(1+\delta)\left[p_{ct} + \sum_{q=1}^{Q} p_{cr}\right](1-\rho_o) + P_R(1+\delta)\left[\sum_{q=1}^{Q} p_{ct} + \sum_{q=1}^{Q+1} p_{cr}\right]\rho_o\right)}{R_b} \quad (25)$$

By submitting (23) and (25) into (9), we obtain the new closed form expression of η in the MIMO relying scheme, which is expressed as:

$$E_{AF} = \frac{L\left(1-\rho_{AF}\right)}{E_{AF}} \quad (26)$$

The expressions obtained are easy-to-compute equations represented by series of standard finite summations, which is simple to simulate by simulating tool such as MATLAB.

4 Numarical Results

In this section, we compare our analysis with the simulating schemes of AP-AF that has been adopted in [6] and illustrate the behavior of the cooperative MIMO relying with respect to the number of antenna Q, by demonstrating their impact on the PER (ϱ) and _. For AP-AF scheme, we note the number of relays participating in the forwarding by K. Our results are evaluated by MATLAB 7.0.1. The normalized noise gain and variance conditions are considered, i.e. ($N_o = E[|H_{SD}|^2] = E[\| H_{SR_q} \|^2] = E[\| H_{RD} \|^2] = 1$) Moreover, the specification of mica2mote [11] is considered in our simulations ($p_{ct} = 10^{-4}, p_{cr} = 5 \times 10^{-5}, L = 80, L_p = 68$, *and* $R_b = 10^5$) Finally, we assume that links over the cooperative scheme are relatively higher, i.e. $G = 2$; hence $\bar{w}_{SR} = 2\bar{w}_{SD}$ and $\bar{w}_{RD} = \frac{2\bar{w}_{SD}}{Q}$.

First, we investigate the reliability of our analytical expression with the help of Monte Carlo simulation method. Figure 2 presents a comparison of η between our derived expression and Monte Carlo simulation for ($Q \leq 3$), and the result obtained confirms the accuracy of our closed-form expression with tolerance less than 1%.

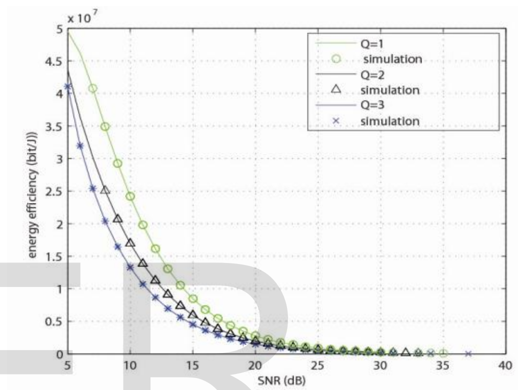

Fig. 2 Comparison between the exact expression of energy efficiency and Monte Carlo simulations

Figure 3 shows the PER of our derived expression and APAF versus the received average SNR $\bar{\gamma}_{SD}$. From the plot, we can observe that our derived expression gives the best ρ among others in low SNR regime; for example, $\rho_{AF} = 0{:}3776$, $\rho_{AF} = 0{:}2654$, $\rho_{AP} = 0{:}5231$ and $\rho_{AP} = 0{:}3885$ for $Q = 3$, $Q = 2$, $K = 3$ and $K = 2$ respectively, in high SNR, we can see that PER increases with the increment of SNR and Q; However, our expression achieves better performance, when compared with the other two.

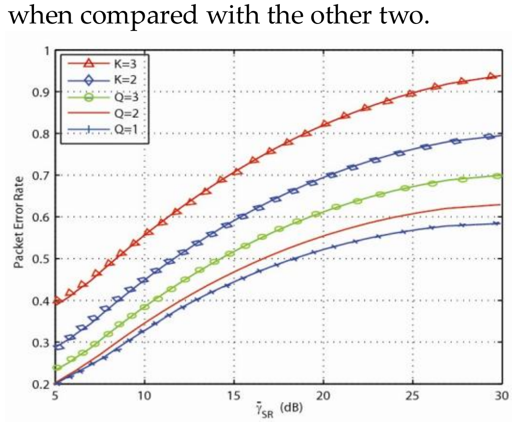

Fig. 3 PER of the exact expression and AP-AF versus γ_{SD}

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$$\rho_D = Q - \sum_{M=0}^{L}\binom{L}{M}\left(\frac{1}{2}\right)^M\left(\frac{2Q}{QM\overline{w}_{SD}+2}+\frac{2e^{-\frac{Q(Q-1)\overline{w}_q}{G\overline{\gamma}_{SD}}}}{(Q-1)!G\overline{w}_{SD}^{Q+!}}\right)\sum_{q=0}^{Q-1}\frac{Q\overline{w}_q^q}{q!G\overline{w}_{SD}}\sum_{k=0}^{q}(Q-1)^{q-k}\left(\sum_{M=0}^{L}\binom{L}{M}\left(-\frac{1}{2}\right)^M\left(\frac{QC\overline{w}_q}{G\overline{w}_{SD}\overline{w}_2}\right)^{\frac{Q-k}{2}}K_{Q-k}\left(2\sqrt{\frac{QC\overline{w}_q\overline{w}_2}{G\overline{w}_{SD}}}\right)\right.$$
$$\left.-\left(\frac{QC\overline{w}_{SD}}{G\overline{w}_{SD}\overline{w}_1}\right)^{\frac{Q-k}{2}}K_{Q-k}\left(2\sqrt{\frac{QC\overline{w}_q\overline{w}_1}{G\overline{w}_{SD}}}\right)\right) \quad (21)$$

$$\rho_{AF} = -Q + \frac{2\Gamma(Q)}{(Q-1)!}\left(1-\sum_{M=0}^{L}\binom{L}{M}\left(-\frac{1}{2}\right)^M\frac{2}{M\overline{\gamma}_{SD}+2}\right)-\frac{\Gamma(Q)}{(Q-1)!}\left(1-\sum_{M=0}^{L}\binom{L}{M}\left(-\frac{1}{2}\right)^M\frac{2}{M\overline{\gamma}_{SD}+2}\right)$$
$$\left(\sum_{M=0}^{L}\binom{L}{M}\left(-\frac{1}{2}\right)^M\left(\left(\frac{2}{MG\overline{\gamma}_{SD}+2}\right)^Q+\left(\frac{2}{MG\overline{\gamma}_{SD}+2Q}\right)^Q\right)\right)+\sum_{M=0}^{L}\binom{L}{M}\left(\frac{1}{2}\right)^M\left(\frac{2Q}{QM\overline{\gamma}_{SD}+2}+\frac{2e^{-\frac{Q(Q-1)\overline{\gamma}_U}{G\overline{\gamma}_{SD}}}}{(Q-1)!G\overline{\gamma}_{SD}^{Q+!}}\right)$$
$$\times\sum_{q=0}^{Q-1}\frac{Q\overline{\gamma}_U^q}{q!G\overline{\gamma}_{SD}}\sum_{k=0}^{q}(Q-1)^{q-k}\left(\sum_{M=0}^{L}\binom{L}{M}\left(-\frac{1}{2}\right)^M\left(\frac{QC\overline{\gamma}_U}{G\overline{\gamma}_{SD}\overline{\gamma}_2}\right)^{\frac{Q-k}{2}}K_{Q-k}\left(2\sqrt{\frac{QC\overline{\gamma}_U\overline{\gamma}_2}{G\overline{\gamma}_{SD}}}\right)-\left(\frac{QC\overline{\gamma}_{SD}}{G\overline{\gamma}_{SD}\overline{\gamma}_1}\right)^{\frac{Q-k}{2}}K_{Q-k}\left(2\sqrt{\frac{QC\overline{\gamma}_U\overline{\gamma}_1}{G\overline{\gamma}_{SD}}}\right)\right) \quad (23)$$

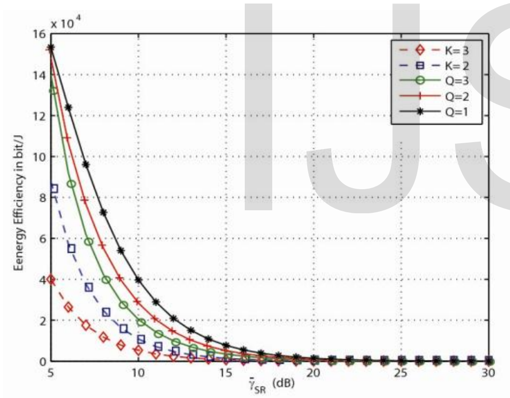

Fig. 4 Energy Efficiency of the exact expression and AP-AF versus γ_{SD}

Figure 4 is the illustration of η of the schemes under the same condition as those given in Figure 3. We can find that our derived expression achieves higher η, when compared with others. This improvement benefits from the diversity order *Q*, which is able to assist in the increment of the received data in the destination. We can also observe that in low SNR regime, η_{AF} achieves its maximum performance, when compared with the other two; for example when $\overline{\gamma}_{SD} = 5{:}8\ dB$ η_{AF} equals 4:7076 × 107 *bit*/*J* for $Q=2,\ Q=3$ respectively.

5 Conclusion

In this study, issues related to η in MIMO cooperative relay networks were investigated. Under Rayleigh fading conditions, we presented a special AF relay scheme, where a static relay station with *Q* antennas cooperatively forwards the relaying packets to the destination node. TDM multiplexing was utilized in the relay to ensure consecutive transmissions through the network. Specifically, we analyzed the impact of the average received SNR on the PDF of the MIMO relay networks. The analysis was utilized to derive new closed-form expressions of PER and η for the multiple antennas MIMO relay networks. The Monte Carlo method was employed to validate our scheme. We compared our scheme with AP-AF low and high-regime SNRs and examined the effect of increasing *Q* antennas on η of our scheme. The simulation showed that the proposed scheme consumes the least energy to complete the transmission and achieves significantly higher efficiency among other relay schemes.

Appendix A

We derive the PDF of w_q (f_{w_q}) in the AF MIMO relaying as follows:

$$f_{w_q}(\gamma) = \frac{\partial}{\partial\gamma}F_{w_q}(\gamma)$$
$$= \frac{\partial}{\partial\gamma}\int_0^\infty F_X(\overline{w}_q(Q-1+\frac{C}{\gamma}))f_Y(\gamma).d\gamma \quad (27)$$

where $FX(x)$ is the cumulative distribution function (CDF) of *X*, which follows a chi-squared distribution with 2*Q* degree of freedom given by:

$$F_X(x) = 1-e^{-\frac{x}{\overline{\gamma}_{SR}}}\sum_{q=0}^{Q-1}\frac{x^q}{q!\overline{\gamma}_{SR}^q} \quad (28)$$

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with a PDF given in:

$$f_X(x) = \frac{e^{-\frac{x}{\bar{\gamma}_{SR}}} x^{Q-1}}{(Q-1)!\bar{\gamma}_{SR}^{Q}} \qquad (29)$$

and $fY(y)$ is the PDF of Y, which also follows a chi-squared distribution with 2Q degree of freedom given by:

$$f_Y(y) = \frac{e^{-\frac{y}{\bar{\gamma}_{RD}}} y^{Q-1}}{(Q-1)!\bar{\gamma}_{RD}^{Q}} \qquad (30)$$

By substituting (29) and (31) into (28) with some algebraic manipulation, we get the expression

Appendix B

The three parts of (8) are evaluated by using (30), (31), (15), and (7):

$$\rho_V = \int_0^{\alpha} \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{\gamma}{\bar{\gamma}_{SD}}} - \int_0^{\infty} \frac{1}{\bar{\gamma}_{SD}} \sum_{M=0}^{L} \binom{L}{M} \left(\frac{1}{2}\right) e^{-\frac{\gamma}{\bar{\gamma}_{SD}} + \frac{\gamma M}{2}} \qquad (31)$$

$$\rho_{SR} = \int_0^{\alpha} \left(\frac{e^{-\frac{x}{\bar{\gamma}_{SR}}} x^{Q-1}}{(Q-1)!\bar{\gamma}_{SR}^{Q}} \right) (1-(1-\frac{1}{2}e^{-\frac{x}{2}})^L).dx \qquad (32)$$

Similarly, ρ_{RD} is estimated:

$$\rho_{RD} = \int_0^{\alpha} \left(\frac{e^{-\frac{y}{\bar{\gamma}_{RD}}} y^{Q-1}}{(Q-1)!\bar{\gamma}_{RD}^{Q}} \right) \cdot (1-(1-\frac{1}{2}e^{-\frac{\gamma}{2}})^L).dx \qquad (33)$$

Solving of the above-mentioned equations using the identity in [15, 3.381.4] yields the expressions (17), (18), and (19).

Appendix C

ρ_D is calculated using (14), (15), and (7) as follows

$$\rho_D = \left(\frac{1}{\bar{\gamma}_{SD}} e^{-\frac{\gamma}{\bar{\gamma}_{SD}}} - \frac{e^{-\frac{(Q-1)\bar{\gamma}_U}{\bar{\gamma}_{RD}}}}{(Q-1)!\bar{\gamma}_{SR}^{Q}\bar{\gamma}_{SD}} \sum_{q=0}^{Q-1} \frac{\bar{\gamma}_U^{q}}{q!\bar{\gamma}_{RD}^{q}} \sum_{k=0}^{q} \binom{q}{k} \right.$$
$$\left. \times (Q-1)^{q-k} C^k \gamma^{Q-k-1} e^{-\frac{C\bar{\gamma}_U}{\gamma\bar{\gamma}_{RD}} - \gamma\bar{\gamma}_1} \right) (1-(1-\frac{1}{2}e^{-\frac{\gamma}{2}})^L).dy \qquad (34)$$

By using the Binomial theorem and the identity in [15, 3.471.9] yields to the expression given in (21).

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