Coherent Relaying in Cooperative MIMO Communication Systems

Yi Zheng, Hani Mehrpouyan, and Steven Blostein
Department of Electrical and Computer Engineering
Queen's University, Kingston, Ontario, K7L3N6, Canada

Abstract

In this paper we propose an enhancement to the Amplify and Forward (AF) protocol. The proposed multi-relay scheme assumes that the source, destination, and each relay have M, N, and 1 antennas, respectively. It is assumed that the source does not have access to the channel state information and takes advantage of uniform spatial multiplexing. Unlike the conventional AF scheme, the proposed scheme allows for each relay to adjust the phase of received signal before applying the AF protocol. Imperfect channel estimation and its effect on the performance of the multi-relay scheme is also investigated. In determining the parameters, conventional optimization schemes cannot be applied due to the non-convex nature of the function. A low complexity method is used to optimize the system that utilizes bisection search. Numerical calculations of capacity and BER simulations demonstrate a significant performance gain over conventional AF.

I. Introduction

Cooperative communication has become a rapidly emerging and important area of research, enabling efficient spectrum usage by resource sharing among multiple nodes in the network. Pioneering contribution can be found in [1]- [2] and results on MIMO broadcast and multiple-access channels have been reported in [3], [4], and [5]. Since future generations of cellular networks are migrating to higher carrier frequencies, MIMO cooperative communications is a potentially attractive method to combat the resulting severe signal attenuation.

In [6], it is shown that a single antenna cooperative system is capable of providing large SNR gains but no multiplexing gain. In [7], a cooperative system with multiple antennas at the source, relay, and destination is proposed, but only one relay is considered. However, the proposed scheme in [7] assumes perfect knowledge of the channel state information (CSI) at the destination and relays which results in significant complexity that overshadows the performance gains. In [8] and [9], various schemes based on AF, Decode and Forward (DF), and a combination of the two (hybrid schemes) are proposed. However, the performance of the proposed non-coherent scheme is limited and only asymptotic results for large numbers of relays are given. In [10] and [11], beamforming schemes are proposed that aim to maximize the capacity of multi-antenna relay systems. Nevertheless, both [10] and [11] require full CSI at the source and relays. The Orthogonal Random Beam Forming (ORBF) scheme, first proposed in [12] and later extended to multiple access channels in [13], only requires partial feedback at the source. However, the requirement of a feedback mechanism adds significant overhead to the operation of the cooperative system. Furthermore, the above studies do not consider the effect of imperfect channel estimation on the overall performance of ORBF. In [14], it is shown that for a single relay system, AF is significantly outperformed by DF due to the amplification of noise at the relay in low SNR region. However, by considering multiple relays, an AF scheme can overcome these shortcomings and reach the same performance as that of DF in median to high SNR region.

We propose a novel low-feedback scheme based on a modification of the AF protocol that circumvents the shortcomings of the AF algorithm and significantly improves the overall system performance. The proposed algorithm first takes advantage of multiple single-antenna relays. Secondly, the phase of the forwarded signal at each relay is adjusted based on the calculated phase group set. The scheme is appropriately named Amplify Phase Shift Forward (APSF). A simple and iterative algorithm based on a bisection search is described that allows for the phase shift required at each relay to be efficiently determined.

II. Channel and System Model

A wireless network consisting of a designated source-destination pair and K relay terminals located randomly and independently is considered (see Figure. 1). The source and destination, equipped with M and N antennas, respectively, are denoted as *S* and *D*. The kth relay employs a single transmit/receive antenna and is denoted by $R_k(k = 1, 2, \cdots, K)$. We assume that there is no direct link between *S* and *D* due to large distance between *S* and *D*. Data is transmitted from source through relays to the destination over two time slots in half-duplex mode. In APSF, the source has M transmit antennas. The Vertical Bell Laboratories Layered Space-Time Architecture (VBLAST) proposed in [15] is employed for the transmission of the signal from the source to the relays in the first time slot. After processing the received signals, the relay terminals simultaneously transmit the processed data to the destination terminal during the second time slot while the source terminal is silent. As in

[9], frequency-flat fading channels are assumed during each transmission block. It is also assumed that all the terminals are perfectly synchronized.

Denote the signal transmitted from the source as **s**. The signal model at the kth relay is given by

$$r_k = \sqrt{\frac{P}{M}}\mathbf{h}_k^T\mathbf{s} + n_k \tag{1}$$

where r_k is the received signal and P is the power available at the source. The vector **s** is the $M \times 1$ transmit signal vector with covariance matrix $\mathbf{I}_M$, n_k is the zero mean unit variance complex additive white Gaussian noise at the kth relay and $\mathbf{h}_k^T$ is the $1 \times M$ channel vector from the source to the kth relay. $\mathbf{h}_k$ can be further expressed as $\mathbf{h}_k = \sqrt{\alpha_k}\tilde{\mathbf{h}}_k$, where the entries of $\tilde{\mathbf{h}}_k$ are independent and identically distributed (i.i.d) complex Gaussian random variables with unit variance, and α_k represents the path loss and independent lognormal shadowing effects, and can be expressed as $\alpha_k = x^{-\gamma}10^{\zeta_k/10}$, where *x* is the distance between the source and relay k. The scalar γ denotes the path loss exponent (set to 4 in this paper). The lognormal shadowing term ζ_k is a random variable drawn from a normal distribution with a mean of 0 dB and a standard deviation δ (dB). In our simulations δ=8dB, which is a value typical in urban cellular environments. We normalized the range between the source and destination so that x is 0.5kM. Throughout, we consider the uplink cellular network, where the source is a subscriber terminal, the destination is the base station, and relays can be fixed as part of the infrastructure or subscriber terminals. In all the protocols to be discussed, we assume that the kth relay has perfect or estimated CSI from the source to the relay and that the destination has full knowledge of perfect or estimated CSI from the source to relay and also from the relay to destination.

III. Relaying Scheme

A. Amplify and Phase Shift Forward

In APSF, the phase adjustment required at each relay can be efficiently calculated at the destination and fed back to the relays since the destination has knowledge of both source-to-relay and relay-to-destination channels. Therefore, APSF requires only the set of phases to be fed back to the relays, minimizing overhead and complexity.

The APSF protocol involves phase shift and amplification:

$$t_k = \sqrt{\eta_k}\frac{r_k}{|r_k|}e^{j\theta_k} = \sqrt{\eta_k}\frac{\sum_{i=1}^{M}\sqrt{\frac{P}{M}}h_{k,i}s_i + n_k}{\sqrt{\sum_{i=1}^{M}\frac{P}{M}|h_{k,i}|^2 + 1}}e^{j\theta_k} \tag{2}$$

where $\sqrt{\eta_k}$ is the power available at the kth relay, and θ_k is the phase shift at the kth relay. In (2), $h_{k,i}$ is the channel from the ith antenna to the kth relay.

B. Determining the Phase Shift

The received signal model at the destination is

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{g}_k t_k + \mathbf{n}_d \tag{3}$$

where the vector $\mathbf{g}_k$ is the channel from kth relay to the destination, which is written as $\mathbf{g}_k = \sqrt{\beta_k}\tilde{\mathbf{g}}_k$, where each entry of $\tilde{\mathbf{g}}_k$ is an i.i.d complex Gaussian random variable with unit variance and β_k contains the same path loss as α_k and independent lognormal shadowing terms with the same deviation as in α_k. The vector $\mathbf{n}_d$ is the $N \times 1$ complex circular additive white Gaussian noise at the destination with identity covariance matrix.

Substituting (2) into (3),

$$\mathbf{y} = \textstyle\sum_{i=1}^{K} \mathbf{g}_i \mathbf{h}_i^T \sqrt{\frac{\frac{P}{M}\eta_i}{\frac{P}{M}|\mathbf{h}_i|^2+1}} e^{j\theta_i} s_i + \sum_{i=1}^{K} \mathbf{g}_i n_i \sqrt{\frac{\eta_i}{\frac{P}{M}|\mathbf{h}_i|^2+1}} e^{j\theta_i} + \mathbf{n}_d \tag{4}$$

Through simple manipulation, (4) is reformulated as:

$$\mathbf{y} = \sum_{i=1}^{K} \mathbf{U}_i s_i + \mathbf{n} \tag{5}$$

where

$$\mathbf{U}_i = \mathbf{g}_i \mathbf{h}_i^T \sqrt{\frac{\frac{P}{M}\eta_i}{\frac{P}{M}|\mathbf{h}_i|^2+1}} e^{j\theta_i}. \tag{6}$$

and

$$\mathbf{n} = \sum_{i=1}^{K} \mathbf{g}_i n_i \sqrt{\frac{\eta_i}{\frac{P}{M}|\mathbf{h}_i|^2+1}} e^{j\theta_i} + \mathbf{n}_d \tag{7}$$

The noise covariance matrix is

$$\mathbf{\Sigma_n} = E[\mathbf{n}\mathbf{n}^H] = \textstyle\sum_{k=1}^{K} \mathbf{g}_k \mathbf{g}_k^H \eta_k \frac{1}{\frac{P}{M}|\mathbf{h}_k|^2+1} + \mathbf{I}_N \tag{8}$$

The capacity of the cooperative system may be calculated via [16]

$$C(\theta_1, \theta_2, \ldots, \theta_K) = \max_{\theta_1,\theta_2,\ldots,\theta_K} \tfrac{1}{2}\log_2\det\left(\mathbf{I} + \left(\textstyle\sum_{l=1}^{K} \mathbf{U}_l\right)\left(\sum_{m=1}^{K} \mathbf{U}_m\right)^H \Sigma_n^{-1}\right) \tag{9}$$

Assume the set of phases $(\theta_1, \ldots, \theta_{k-1}, \theta_{k+1}, \ldots, \theta_K)$ is fixed, after straightforward algebraic manipulation, we arrive at

$$C(\theta_k) = \frac{1}{2}\left(\log_2\det(\Sigma_1) + \max_{\theta_k} \log_2\det\left(\mathbf{I} + \mathbf{A}e^{j\theta_k} + \mathbf{A}^H e^{-j\theta_k}\right)\right) \tag{10}$$

where

$$\Sigma_1 = \mathbf{I} + \left(\mathbf{U}_k \mathbf{U}_k^H + \sum_{m=1, m\neq k}^{K} \sum_{l=1, l\neq k}^{K} \mathbf{U}_m \mathbf{U}_l^H \right) \Sigma_n^{-1} \tag{11}$$

and

$$\mathbf{A} = \left(\frac{\mathbf{U}_k}{e^{j\theta_k}} \sum_{m=1, m\neq k}^{K} \mathbf{U}_m^H \right) \Sigma_n^{-1} \Sigma_1^{-1}. \tag{12}$$

Take first derivative of $C(\theta_k)$ with respect to θ_k, we have

$$\text{Tr} \left[\left(\mathbf{I} + \mathbf{A} e^{j\theta_k} + \mathbf{A}^H e^{-j\theta_k} \right)^{-1} \left(\mathbf{A} e^{j\theta_k} - \mathbf{A}^H e^{-j\theta_k} \right) \right] = 0 \tag{13}$$

1) The case of a single antenna at the receiver: In this case $\mathbf{A}$ in (13) becomes scalar a. From (13) we obtain

$$\theta_{k,1} = \frac{1}{2} \arctan \frac{\Re(\frac{a^*}{a})}{\Im(\frac{a^*}{a})}, \theta_{k,2} = \pi + \frac{1}{2} \arctan \frac{\Re(\frac{a^*}{a})}{\Im(\frac{a^*}{a})} \tag{14}$$

We also have

$$\frac{\partial^2 C}{\partial \theta_k^2} |_{\theta_k = \theta_{k,1}} \frac{\partial^2 C}{\partial \theta_k^2} |_{\theta_k = \theta_{k,2}} < 0. \tag{15}$$

Which implies either, $\theta_{k,1}$ or $\theta_{k,2}$ is a maximize $C(\theta_k)$.

2) The case of multiple antennas at the receiver: The maximization problem with multiple receive antennas at the destination ($N \geq 2$) is very difficult to analyze from (13). Let $\mathbf{B} = \frac{1}{2}\mathbf{I} + \mathbf{A} e^{j\theta}$, from (9) we have

$$\underset{\theta_k}{\text{argmax}}\, C(\theta_k) = \underset{\theta_k}{\text{argmax}} \det \left(\mathbf{B} + \mathbf{B}^H \right) \tag{16}$$

Through simple manipulation, we have $\det(\mathbf{B}^H) = \det(\mathbf{B})^* = \frac{1}{2} \left(1 + a^* e^{-j\theta_k} \right)$ where

$$a = 2\mathbf{h}_k^T \sqrt{\frac{\frac{P}{M}\eta_k}{\frac{P}{M}|\mathbf{h}_k|^2 + 1}} \sum_{m=1, m\neq k}^{K} \mathbf{U}_m^H \Sigma_n^{-1} \Sigma_1^{-1} \mathbf{g}_k \tag{17}$$

As $\det(\mathbf{B})$ and $\det(\mathbf{B}^H)$ are linear combinations of sinusoid functions, they have the property that in one period, there is a unique maximum and a unique minimum. We observe through simulations that $\det \left(\mathbf{B} + \mathbf{B}^H \right)$ also display such a property. However, we can not prove the uniqueness of the maximum. This motivates a bisection search to find θ_k which maximize $C(\theta_k)$.

From (9) it is observed that the system capacity is a function of the phases $\theta_1, \theta_2, \ldots, \theta_K$. Since the $\log$ function is monotonically increasing, maximizing $C(\theta_1, \theta_2, \ldots, \theta_K)$ is equivalent to $\max_{\theta_1, \theta_2, \ldots, \theta_K} \det(\mathbf{\Psi})$, where

$$\mathbf{\Psi} = \mathbf{I} + \left(\sum_{i=1}^{K} \mathbf{U}_i \mathbf{U}_i^H \right) \mathbf{\Sigma}_{\mathbf{n}}^{-1} \tag{18}$$

From (6) we have

$$\mathbf{U}_i\left(\theta_1, \theta_2, \ldots, \theta_K\right) = \mathbf{U}_i\left(\theta_1 + 2m_1\pi, \theta_2 + 2m_2\pi, \ldots, \theta_K + 2m_K\pi\right) \tag{19}$$

where $m_1, m_2, \ldots, m_K$ can be arbitrary integers. From (9) and (19) we have

$$C(\theta_1, \theta_2, \ldots, \theta_K) = C(\theta_1 + 2m_1\pi, \theta_2 + 2m_2\pi, \ldots, \theta_K + 2m_K\pi). \tag{20}$$

In other words, $C(\theta_1, \theta_2, \ldots, \theta_K)$ is a periodic function of $\theta_1, \theta_2, \ldots, \theta_K$ with a period of 2π for the phase of each relay. So the bisection search for θ_k is performed in a 2π period.

Though bisection search can find θ_k which maximize $C(\theta_k)$ when fixing $(\theta_1, \ldots, \theta_{k-1}, \theta_{k+1}, \ldots, \theta_K)$. It is not guaranteed that the iterative bisection search algorithm discussed in Section D will find the global optimum phase set. A plot of the system capacity of a three-relay system with the phase of one of the relays fixed is illustrated in Figure 2 where the capacity in a 4π by 4π radian phase region is represented (system capacity is also 2π-periodic). For each 2π by 2π radian region as depicted in Figure 2, there exists multiple maxima and minima. This illustrates that maximizing (20) is a non-convex problem with possible multiple extremes.

C. Channel Estimation

In the case of imperfect channel estimation the model proposed in [17], [18], [19], [20] is applied to the multi-relay scheme proposed here. When orthogonal training sequences are transmitted from each source transmit antenna or relay, i.e. $\mathbf{b}_i^H \mathbf{b}_j = \delta_{i,j}$ ($\delta_{i,j} = 1$ if $i = j$ and $\delta_{i,j} = 0$ if $i \neq j$), the received signal at the ith received antenna is given by

$$\mathbf{a}_i = \textstyle\sum_{j=1}^{M} \sqrt{\frac{P}{M}} h_{i,j} \mathbf{b}_j + \mathbf{n}_i \tag{21}$$

where $h_{i,j}$ is the channel gain from the jth transmit antenna to the ith receive antenna, and $\mathbf{n}_i$ is the zero mean complex Gaussian noise vector at the ith receive antenna with $E[\mathbf{n}_i \mathbf{n}_i^H] = \sigma^2 \mathbf{I}$. We obtain a noisy version of $h_{i,j}$, $\hat{h}_{i,j}$, simply by computing

$$\hat{h}_{i,j} = \sqrt{\frac{M}{P}} \mathbf{b}_j^H \mathbf{a}_i = h_{i,j} + \sqrt{\frac{M}{P}} \mathbf{b}_j^H \mathbf{n}_i = h_{i,j} + x_{i,j} \tag{22}$$

where x_{ij} is the zero mean complex Gaussian noise with $P[x_{ij} x_{ij}^*] = \sigma_e^2 = M\sigma^2/P$. Note that x_{ij}s are independent of h_{ij} and i.i.d. $\forall i, j$. Based on the above, equations (8) and (6) can be estimated as

$$\hat{\mathbf{\Sigma}}_{\mathbf{n}} = E[\hat{\mathbf{n}}\hat{\mathbf{n}}^H] = \textstyle\sum_{k=1}^{K} E[(\mathbf{g}_k + \mathbf{c}_k)(\mathbf{g}_k + \mathbf{c}_k)^H] \eta_k \frac{\sigma_e^2}{\sum_{i=1}^{M} \frac{P}{M}(|h_{k,i}|^2 + \sigma_e^2) + 1} + \mathbf{I}_N \tag{23}$$

$$\mathbf{U}_i = (\mathbf{g}_i + \mathbf{c}_i)(\mathbf{h}_i + \mathbf{d}_i)^T \sqrt{\frac{\frac{P}{M}\eta_i}{\frac{P}{M}|\mathbf{h}_i|^2 + 1}} e^{j\theta_i}, \tag{24}$$

where $\mathbf{c}_i$ and $\mathbf{d}_i$ are the estimation error vectors for $\mathbf{g}_i$ and $\mathbf{h}_i$, respectively and σ_e^2 is the scaled estimation error variance. Equation (23) can also be re-written as

$$\hat{\mathbf{\Sigma}}_{\mathbf{n}} = \sum_{k=1}^{K} (\mathbf{g}_k \mathbf{g}_k^H + \sigma_e^2 \mathbf{I}_N) \eta_k \frac{1}{\sum_{i=1}^{M} \frac{P}{M}(|h_{k,i}|^2 + \sigma_e^2) + 1} + \mathbf{I}_N. \tag{25}$$

Equation (25) can then be used to determine $\mathbf{\Psi}$ which is employed in the bisection search algorithm described below.

The time average of (22) over T time slots

$$avg(\hat{h}_{i,j,T}) = \frac{\hat{h}_{i,j,1} + \hat{h}_{i,j,2} + \ldots + \hat{h}_{i,j,T}}{T} \tag{26}$$

where $\hat{h}_{i,j,t}$ represents the estimated channel coefficient at time t. Assuming that the channel does not change appreciably in T time slots, (22) can be rewritten as:

$$avg(\hat{h}_{i,j,T}) = h_{i,j} + \bar{x}_{i,j,T} \tag{27}$$

where $\bar{x}_{i,j,T}$ represents the average of $x_{i,j}$ over T time slots. Under this assumption, the variance of $x_{i,j}$ decreases with T. This is clearly represented in the simulation results presented in the next section.

D. *Optimization Scheme*

As pointed out previously in the case of $N > 1$ antennas, $\det(\mathbf{\Psi})$ is neither convex nor concave, and it resemble a sinusoid curve in one period when fixing all phases but one of the set of K phases. This motivates a bisection search algorithm to find the local maxima.

Algorithm:

Step 1. Choose an initial set of randomly generated phases. Denote these phases as $\theta_1^{(1)}, \theta_2^{(1)}, \ldots, \theta_K^{(1)}$.

Step 2. Repeat until calculated system capacity reaches a stopping criterion (the capacity difference from last iteration below a certain threshold). Cycle through each relay phase by fixing all but one of the set of K phases. Determine the phase that maximizes $\det(\mathbf{\Psi})$ (Eq. (18)).

Denote this the set of phases as $\theta_1^{(o)}, \theta_2^{(o)}, \ldots, \theta_K^{(o)}$, where the superscript indicates that a local maximum is reached. It is also clear that the iterative algorithm converges, since first, the capacity of the overall system is upper-bounded because there is a power constraint for the total power at the source, and second, during each iteration of the bisection search algorithm the capacity monotonically increases.

IV. Simulation Results

In Figure 3, we provide numerical capacity results for cooperative system with $M = 2$, $K = 4$, $N = 2$, $\frac{P}{\sigma_n^2}$ in the range of 0dB to 30dB, and $\frac{P_i}{\sigma_n^2} = 10dB$ where i indicates the i^{th} relay, $1 \leq i \leq K$. Figure 3 shows the capacity of the proposed APSF scheme and compares it with the conventional AF and APSF with imperfect CSI. As noted in Figure 3, the capacity gain compared to that of the conventional AF (simply amplifying the received signal at every relay) is considerable. This performance gain is achieved with minimal added feedback and computational complexity. First, the proposed algorithm does not require CSI at the source and only requires the set of phases to be fed back to the relays and secondly, the iterative bisection search algorithm converges exponentially fast to the optimized set of phases. We have observed that convergence occurs after only one or two passs through all the relay phases. However, it should be pointed out that from an implementation point of view, APSF requires added hardware compared to AF at the relays which increases hardware costs and complexity. An analog implementation requires the use of adjustable analog phase shifters (see [21]). Another approach would be through the use of digital signal processors at the relays. Figure 3 also represents the performance of APSF which degrades under imperfect channel estimation, where imperfect channel scenarios with time averaging over $T = 1$ and $T = 5$ time slots are considered.

We further compare the performance of the iterative algorithm to that of exhaustive search. Under the exhaustive search scheme, the phase adjustment, θ, for each relay is quantized into N intervals. Thus, for K relays, there exist N^K points to evaluate. The maximum capacity corresponding to the N^K points is determined and compared to the maximum capacity obtained through the outlined iterative algorithm. For $N = 50$, it was observed that out of 1000 realizations the maximum capacity calculated based on these two schemes match 98% of the time. This is mainly due to the existence of only one maximum or minimum within one period of the capacity expression (9) for 3, 4, or 6 relays in most of the cases (Figure 2 is one of the few scenarios where more than one maximum and minimum exist within a period).

Figure 4 illustrates the capacity of APSF as a function of SNR at the relays. As expected, when the SNR at the relays is increased the capacity increases. However, when the SNRs at the relays is fixed, the capacity gain achieved by increasing the SNR at the source flattens out. This is expected since the noise at the relays is a limiting factor. In conclusion, when the SNR is balanced at both the source and the relay a higher capacity can be achieved.

Figure 5 compares the Average Bit Error Rate (ABER) of the conventional AF, DF, and APSF under perfect and imperfect channel estimation. QPSK modulation combined with VBLAST is used and the frame length is set to 20 bits. It is important to note that as the number of relays is increased the BER performance of APSF tends to significantly improve. This is mainly due to the coherent combining effect of APSF. Figure 6 represents the corresponding capacities of AF and APSF with different numbers of relays which are consistent with the BER results presented in Figure 5.

In [22] we compare the performance results of DF and APSF. Similar to AF, the addition of relays does not improve the BER performance of a multi relay DF system. Therefore, one can deduce that blind addition of relays based on conventional cooperative schemes, septically AF and DF, does not result in performance gain. Furthermore, [22] provides insight on the BER and capacity of multi-hop systems based on AF, DF, and APSF.

V. Conclusion

In this paper, we propose a novel cooperative MIMO scheme based on AF named Amplify Phase Shift Forward (APSF). APSF takes advantage of multiple antennas at the source, multiple antennas at the destination and employs single antenna relays. It has been demonstrated that by adjusting the phase APSF provides significant performance improvement over that of convectional AF. The performance advantage compared to AF is even more significant when the number of relays is four or more. The advantage gain is achieved without requiring any feedback to the source, very little feedback to the relays, and limited additional complexity at the destination.

References

[1] N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 3, pp. 3062–3080, 2004.

[2] A. Dana and B. Hassibi, "On the power efficiency of sensory and ad-hoc wireless networks," *IEEE Trans. Inf. Theory*, vol. 52, no. 3, pp. 2890–2914, 2006.

[3] W. Yu and J. M. Cioffi, "Sum capacity of gaussian vector broadcast channels," *IEEE Trans. Inf. Th.*, vol. 50, no. 9, pp. 1875–1892, 2004.

[4] S. Vishwanath, N. Jindal, and A. Goldsmith, "Duality, achievable rates, and sum-rate capacity of gaussian MIMO broadcast channels," *IEEE Trans. Inf. Th.*, vol. 49, no. 10, pp. 2658–2668, 2003.

[5] D. N. C. Tse, P. Viswanath, and L. Zheng, "Diversity-multiplexing tradeoff in multiple access channels," *IEEE Trans. Inf. Th.*, vol. 50, no. 9, pp. 1859–1874, 2004.

[6] A. Hst-Madsen, "Capacity bounds for cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 6, pp. 1522–1544, 2006.

[7] O. Muoz-Medina, J. Vidal, and A. Agustn, "Linear transceiver design in nonregenerative relays with channel state information," *IEEE Trans. Signal Process.*, vol. 55, pp. 2593–2604, 2007.

[8] Y. Fan and J. Thompson, "MIMO configurations for relay channels: Theory and practice," *IEEE Trans. Wireless Comm.*, vol. 6, pp. 1774–1786, May 2007.

[9] H. Bolcskei, R. U. Nabar, O. Oyman, and A. J. Paulraj, "Capacity scaling laws in MIMO relay networks," *IEEE Trans. Wireless Comm.*, vol. 5, pp. 1433–1444, 2006.

[10] J. Yindi and H. Jafarkhani, "Network beamforming using relays with perfect channel information," *IEEE Acoustics, Speech and Signal Proc.*, vol. 3, pp. 473–476, 2007.

[11] E. Yilmaz, Sunay, and M. Oguz, "Effects of transmit beamforming on the capacity of multi-hop MIMO relay channels," *IEEE Personal, Indoor and Mobile Radio Communications*, pp. 1–5, 2007.

[12] M. Sharif and B. Hassibi, "On the capacity of MIMO broadcast channels with partial side information," *IEEE Trans. Inf. Th.*, vol. 51, no. 9, pp. 506–522, 2005.

[13] K. Zhang and Z. Niu, "Random beamforming with multi-beam selection for MIMO broadcast channels," *IEEE Int. Conf. on Comm.*, vol. 9, pp. 4191–4195, 2006.

[14] A. Avestimehr and D. TSE, "Outage capacity of the fading relay channel in the low snr regime," *IEEE Trans. Inf. Theory*, vol. 53, no. 4, pp. 1401–1415, 2007.

[15] P. Wolniansky, G. Foschini, G. Golden, and R. Valenzuela, "V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel," in *URSI International Symposium on 29 Sept.-2 Oct.*, 1998, pp. 295–300.

[16] A. Goldsmith, N. J. S. Jafar, and S. Vishwanath, "Capacity limits of MIMO channels," vol. 21, no. 5, pp. 684–702, 2003.

[17] S. Serbetli and A. Yener, "MMSE transmitter design for correlated MIMO systems with imperfect channel estimates: Power allocation trade-offs," *IEEE Trans. in Wireless Comm.*, vol. 5, no. 8, pp. 2295–2304, 2006.

[18] T. L. Marzetta, "BLAST training: Estimating channel characteristics for high capacity space-time wireless," *37th Annual Allerton Conference on Communication, Control and Computing*, pp. 958–966, 1999.

[19] B. Hassibi and B. M. Hochwald, "How much training is needed in multiple-antenna wireless links?" *IEEE Trans. in Inform. Th.*, vol. 48, no. 4, pp. 951–963, 2003.

[20] A. Scaglione, "Optimal designs for space-time linear precoders and decoders," *IEEE Trans. in Signal Proc.*, vol. 50, no. 5, pp. 1051–1064, May 2002.

[21] A. Megej and V. F. Fusco, "Low-loss analog phase shifter sing varactor diodes," *Microwave and Optical Technology Letters*, vol. 19, no. 6, pp. 384–386, 1998.

[22] Y. Zheng, H. Mehrpouyan, and S. Blostein, "Amplify phase shift forward relaying in cooperative mimo communications," *Submitted to IEEE Globecom conference*.

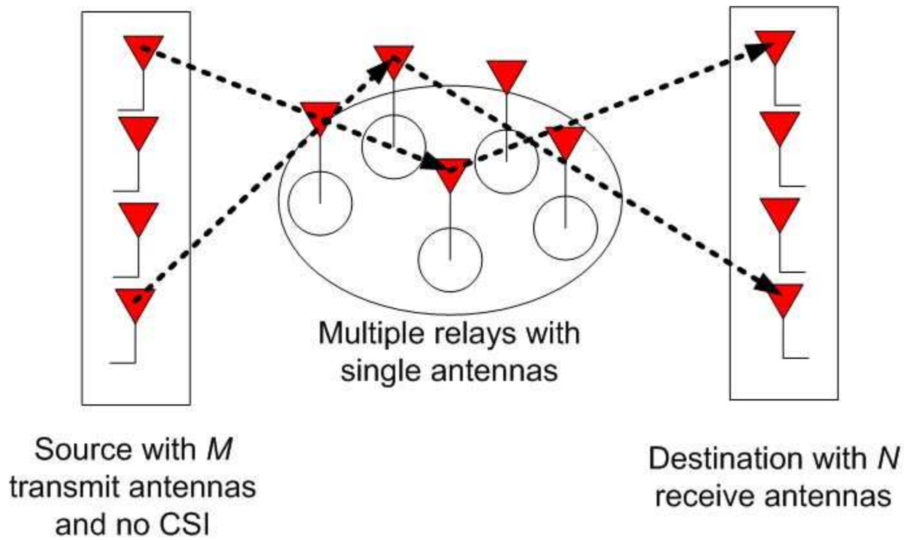

Fig. 1. MIMO wireless relay network setup. The relay terminals each employ one antenna.

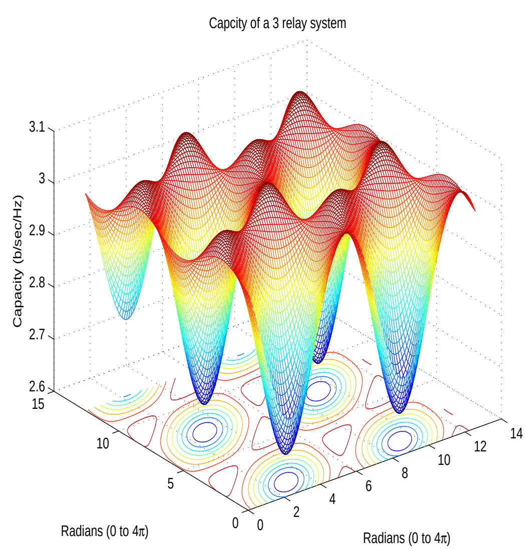

Fig. 2. Capacity plot of a three relay cooperative system demonstrating multiple extrema.

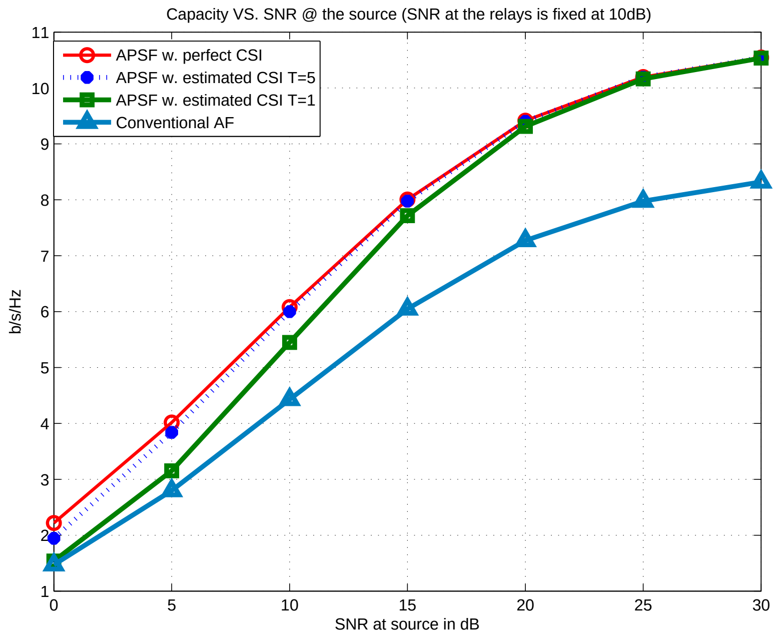

Fig. 3. Comparison of the capacity between systems deploying the conventional AF, proposed APSF, and APSF protocols with imperfect channel estimation performed over 1 and 5 blocks of training data.

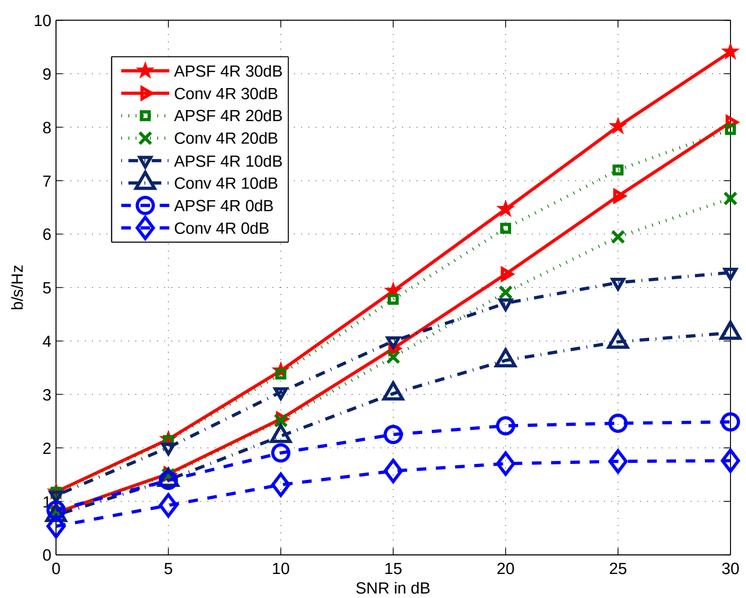

Fig. 4. Comparison of the capacity between AF and APSF deployed in a two-hop cooperative scheme. Different SNRs at relays are investigated in this scenario consisting of 4 single antenna relays, 2 source antennas, and 2 destination antennas.

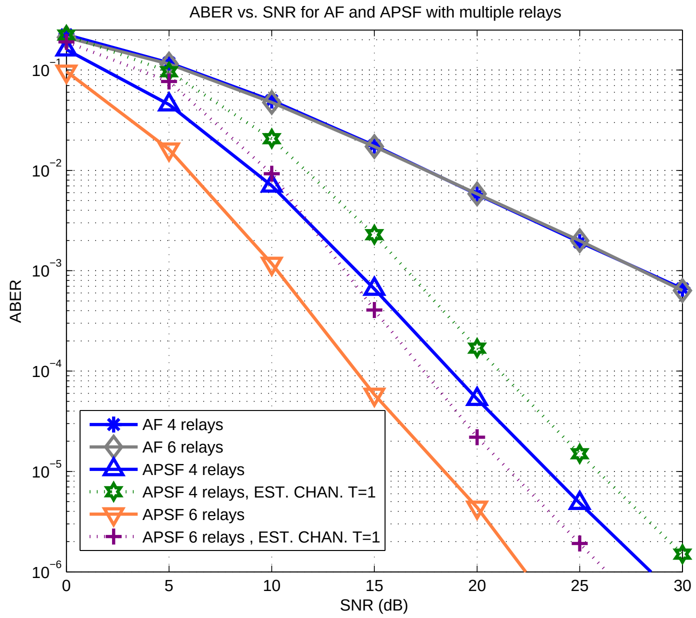

Fig. 5. Comparison of the BER performance for the conventional AF and APSF with 4 and 6 single antenna relays, under the assumption of perfect and imperfect channel estimation. The plots in the case of AF for 4 and 6 relays overlap since there is almost no BER gain due to addition of more relays in the case of AF.

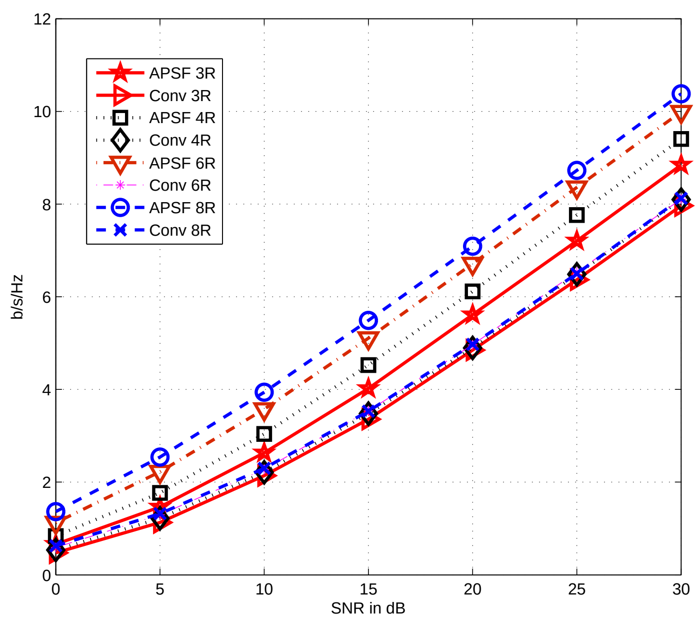

Fig. 6. Comparison of the capacity between the conventional AF, and APSF, with 3, 4, 6, and 8 relays (The AF capacity for 3, 4, and 6 relays overlap).