

Optimizing a Cooperative Relay Network Using Advanced Power Allocation and Receiver Diversity Technique

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Abstract— Cooperative relaying is a relatively new technique in wireless communication systems that make use of all the nodes present in a wireless sensor network by dynamically sharing their radio resources in a distributed manner. All the nodes present in the periphery of the two communicating nodes will act as relays and forward the information until it reaches the recipient node. By doing this, it achieves a significant diversity gain, which in turn increases the robustness of the communication system. The diversity gain offered by cooperative relay transmission can only be exploited fully if a receiver diversity technique is being employed at the recipient node. Moreover, these cooperative relay networks inherit the power limitation of a traditional wireless sensor network. Therefore, in this paper an effort has been made to optimize a cooperative relay system by addressing these two issues. First, node powers expressions will be derived for a 3-node configuration using fixed gain amplify and forward protocol over a Rayleigh Fading Channel. Second, performance of a 3-node configuration has been further analyzed by using different receiver diversity techniques at the destination node. Simulation results are presented to validate the performance gains when advanced power allocation and receiver diversity is employed in a cooperative relay network.

Keyword— Cooperative relay network, Maximal ratio combining, Moment generating function, Diversity techniques, Rayleigh fading channel, Fixed gain amplify and forward.

I. INTRODUCTION

Over the last few decades, many new techniques have been developed to facilitate the process of wireless communication. These techniques have enhanced the performance of a wireless system in terms of throughput,

coverage, capacity, reliability, etc. One such technique is of spatial diversity, which mitigates the effect of multi-path fading and provides diversity gains.

The technique of relaying in wireless communication emulates a multiple input multiple output (MIMO) system, as it is not feasible to equip a small node with multiple antennas. Cooperative relay transmission achieves spatial diversity, higher rates and increases robustness by using the antennas of the neighboring cooperating nodes [1] [2] and [3]. The source and the cooperating nodes send the same information to the destination node over independently fading paths, thus making a virtual antenna array [4]. At the destination node a diversity gain is achieved as it receives multiples copies of the same information [5]. Among the trusted and proven cooperative relaying techniques, amplify and forward protocol also known as non-regenerative relaying protocol stands out because of its simple execution and low computational cost. The simplicity comes from the fact, as the nodes running this protocol simply amplify the received signal and then forwards it to the destination node without any complex processing [6]. On the contrary, if each wireless node is running complex decoding and encoding for each transmission hop the performance of a wireless system is noticeably hampered. Therefore analysis of the cooperative relay system has been performed employing amplify and forward relaying protocol.

The process of optimizing the cooperative relay system has been divided into two tasks. The first task is to develop an advanced power allocation algorithm as the cooperative communication system inherits the power limitation of a traditional WSN. The power allocation algorithm is required to effectuate the transmission powers of the corresponding nodes. The prime objective is to allocate optimum transmission power to the source and the cooperating relay nodes while maximizing the quality of service at the receiver. The second task is to replace the traditional receiver diversity technique like maximum ratio combining with a more performance oriented technique.

In [7], the power allocation algorithm has been investigated for a cooperative relay network but regenerative relaying protocol has been used with a rician-fading channel.

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In [8], an optimal power allocation OPA technique has been proposed for a cooperative relay network with different network configurations but maximum ratio combining has been employed at the receiver node. In this paper, the powers allocated to the involved nodes have been derived using the moment generation function (MGF) approach and optimization is achieved using the Lagrangian method [9]. Moreover, the sub-optimal receiver diversity technique (MRC) has been replaced with, first equal ratio combining (ERC) and then with enhanced signal-to-noise ratio combining (SNRC).

The remainder of this paper is organized as follows. Section II presents the system model and simulation parameters. In Sections III, the power allocation expressions for the involved nodes have been derived for the 3-node relay network configuration over a Rayleigh channel. In Sections IV, the diversity combining expressions for the receiver nodes have been derived for the corresponding network configuration. The efficiency achieved by the application of the above two proposed techniques is presented in form of performance graphs, in Section V. Section VI, concludes the paper.

II. SYSTEM MODEL

A. Cooperative Relay Network

The network configuration is shown below in Figure 1. The network comprises of three nodes, namely a source node (*S*), destination node (*D*) and a relay node (*R*). Let G_{SD} , G_{SR} , and G_{RD} represent the channel gains for source to destination, source to relay and relay to destination links respectively. The communication channel between the nodes is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian. At all times, each and every communicating node in the network will obey the rules of half duplex transmission. Fixed gain AF protocol has been used as a relaying technique. In the fixed gain AF relaying, the amplifier gain is based on the perfect CSI of the communication link rather than instantaneous knowledge of CSI. In the simulations the system performance has been measured for the end-to-end transmission. Therefore power constraints are applied for the complete transmission cycle instead of intermediate hops.

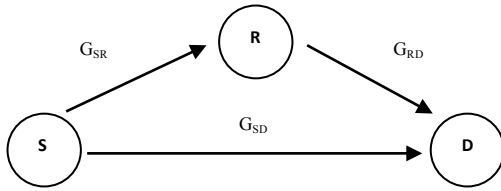


Figure 1. A 3-Node Network Configuration

III. POWER ALLOCATION & DIVERSITY COMBINING

A. Transmission Phase

In the transmission phase, the source node *S* broadcasts data *X* with transmission power P_S to both relay and destination nodes, as shown above in figure 1. The channel gains for the source to relay and from source to destination links are G_{SR} and G_{SD} respectively. The additive white Gaussian noise (AWGN), present at the relay node n_{SR} and destination nodes n_{SD} -

respectively. The signal received at the relay and destination will be expressed as Y_R and Y_D respectively. The expressions are given below for the two received signals

$$Y_D[n] = \sqrt{P_S} G_{SD} \cdot X[n] + n_{SD}[n] \quad (1)$$

$$Y_R[n] = \sqrt{P_S} G_{SR} \cdot X[n] + n_{SR}[n] \quad (2)$$

After that, the relay node amplifies the signal received Y_R and then transmits it to the destination node with the amplifier gain β_R . Now, the transmission power of the relay node, P_R . G_{RD} is the channel gain for relay to destination link and the noise at the destination node, n_{RD} . The modified signal received by the destination Y'_R , sent from the relay node is given below:

$$Y'_R[n] = \beta_R \cdot Y_R[n] \cdot G_{RD} + n_{RD}[n] \quad (3)$$

Here, the fixed amplifier gain β_R is used to accurately tweak the transmission power at the relay to compensate the variations in the relay to destination communication link. The gain is dependent on the channel between the source and relay node [10]. The amplifier gain of the relaying node can provide a maximum improvement, which is defined by the expression below:

$$\beta_R = \sqrt{\frac{P_R}{P_S |G_{SR}|^2 + N_0}} \quad (4)$$

As, the relaying node running AF protocol may also amplify the induced noise so in the next phase receiver diversity combining technique will be used at the receiver node to mitigate this effect.

B. Reception Phase

In the reception phase, the overall performance of the communication system is increased by effectively combining the multiple copies of the transmitted message at the receiver node. Receiver diversity combining particularly targets small scale fading. Therefore, the simulation has been performed using flat Rayleigh fading channel as it is the easiest one to implement and is manageable. Three different signal combining techniques have been employed in the network. With each technique, the objective is to calculate the weights, which compensate for the negative effects of fading. These combining techniques are different in the way they calculate their weight vectors.

1) Maximum Ratio Combining

In maximal ratio combining, the receiver node will perform maximum ratio combining technique on the two received signals. So, the output of the MRC system at the receiver node will be:

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S} G_{SD} \cdot X[n] + n_{SD}[n]) + \alpha_1(\beta_R \cdot Y_R[n] \cdot G_{RD} + n_{RD}[n]) \quad (5)$$

Substituting, equation (2) into (5):

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S} G_{SD} \cdot X[n] + n_{SD}[n]) + \alpha_1(\beta_R \cdot (\beta_R \cdot Y_R[n] \cdot G_{RD} + n_{RD}[n]) \cdot G_{RD} + n_{RD}[n]) \quad (6)$$

In the above expressions, α_0 and α_1 are the weights of the MRC for the communications links between source-relay and between relay-destination. These weights compensate for the effects of channel impairments and are therefore calculated using the expressions given below:

$$\alpha_0 = \frac{\sqrt{P_S} G_{SD}^*}{N_0} \quad (7)$$

$$\alpha_1 = \frac{\sqrt{P_S} \cdot \beta_R \cdot G_{SR}^* \cdot G_{RD}^*}{N_0} \quad (8)$$

2) Advanced SNR Combining

In a traditional signal to noise ratio (SNR) combining technique, the weights are assigned depending on the instantaneous SNR of the communication link, which was used to transmit the signal. The signals coming from the communication link having high SNR will be assigned higher weights and vice versa. In advanced SNR combining instead of taking the instantaneous SNR an estimated factor of SNR is calculated making it a less complex. In this technique, only that signal will be chosen whose SNR is greater than SNR of any other signal by the estimated factor.

$$Y_{ASNRC} = \begin{cases} Y_D[n] & \frac{Y_{SD}}{Y_{RD}} > 10 \\ Y_D[n] + Y_R[n] & 0.1 < \frac{Y_{SD}}{Y_{RD}} < 10 \\ Y_R[n] & \frac{Y_{SD}}{Y_{RD}} < 0.1 \end{cases} \quad (9)$$

C. Optimization Phase

In this phase, the network configuration will be translated into a convex optimization problem, and the next step will be to find the solution of this optimization problem for calculating the optimal transmission powers for the source and all involved cooperating relay nodes.

The SNR for the source-destination link and for the source-relay-destination links are denoted by Γ_0 and Γ_1 respectively.

$$\text{Where,} \quad \Gamma_0 = \frac{\sigma_{SD}^2 \cdot P_S}{N_0} \quad (10)$$

As, the transmission with relay is a multi-hop scenario, the SNR can be calculated by considering it as cascaded single hop transmissions. Therefore, the SNR Γ_1 will be the summation of all individual links.

$$\Gamma_1 = \frac{\sigma_{SD}^2 \cdot P_S}{N_0} + \frac{\sigma_{RD}^2 \cdot P_R}{N_0} \quad (11)$$

The total SNR of the system Γ_T will be:

$$\Gamma_T = \Gamma_0 + \Gamma_1 \quad (12)$$

Substituting equation (10) & (11) into (12):

$$\Gamma_T = \frac{\sigma_{SD}^2 \cdot P_S}{N_0} + \left(\frac{\sigma_{SD}^2 \cdot P_S}{N_0} + \frac{\sigma_{RD}^2 \cdot P_R}{N_0} \right) \quad (13)$$

Here, the bit error probability has been calculated using Moment Generating Function (MGF) approach for QPSK modulation scheme [11]. As, it is known to be an effective tool for performance analysis of any modulation scheme in a fading scenario.

$$P_e = \frac{1}{\pi} \int_0^{\frac{(N-1)\pi}{N}} \prod_{n=0}^{N-1} N_{\gamma_n} \left(\frac{g_{QPSK}}{\sin^2 \theta} \right) d\theta \quad (14)$$

The moment generating function approach computes the bit error probabilities by defining the error probability as an exponential function of γ .

$$N_{\gamma_n} = \int_0^\infty P_{\gamma_n}(\gamma) e^{s\gamma} d\gamma \quad (15)$$

$$N_{\gamma_n} \left(\frac{1}{\sin^2 \theta} \right) = \left(1 + \frac{g_{QPSK}}{\sin^2 \theta} \gamma_n \right)^{-1} \quad (16)$$

$$N_{\gamma_n} \left(\frac{1}{\sin^2 \theta} \right) = \left(1 + \frac{\gamma_n}{\sin^2 \theta} \right)^{-1} \quad (17)$$

Since $(\gamma_n \gg 1)$ equation (17) becomes:

$$N_{\gamma_n} \left(\frac{\gamma_n}{\sin^2 \theta} \right) \cong N_{\gamma_n} \left(\frac{1}{\sin^2 \theta} \right) \quad (18)$$

Substituting the values of γ_0 and γ_1 in equation (18):

$$P_e = \left[\frac{P_S \cdot \sigma_{SD}^2 \cdot \sigma_{SR}^2}{N_0^2} + \frac{P_S \cdot P_R \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2}{N_0^2} \right]^{-1} \quad (19)$$

$$P_e = N_0^2 \left[\frac{1}{P_S \cdot \sigma_{SD}^2 \cdot \sigma_{SR}^2} + \frac{1}{P_S \cdot P_R \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2} \right] \quad (20)$$

Now, as the bit error probability has been formulated for this configuration, the prime objective is to minimize this bit error probability while maintaining the total power constraint [12]. The optimization problem can be expressed as:

$$\text{Minimize } P_e = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \prod_{n=0}^{N-1} N_{\gamma_n} \left(\frac{1}{\sin^2 \theta} \right) d\theta \quad (21)$$

$$\text{Subject to } P_S + P_R \leq P_T$$

Since, the most common method for solving a constrained optimization problem is Lagrange method. Therefore, the above constrained optimization problem will be translated into a Lagrange cost function. The Lagrange cost function comprises of an objective function, constrained function and a Lagrange multiplier as expressed below:

$$J = P_e + \lambda (P_S + P_R - P_T) \quad (22)$$

Substituting equation (21) into (22):

$$J = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \prod_{n=0}^{N-1} N_{\gamma_n} \left(\frac{1}{\sin^2 \theta} \right) d\theta + \lambda (P_S + P_R - P_T) \quad (23)$$

$$J = N_0^2 \left(\frac{1}{P_S^2 \sigma_{SD}^2 \sigma_{SR}^2} + \frac{1}{P_S P_R \sigma_{SD}^2 \sigma_{RD}^2} \right) + \lambda (P_S + P_R - P_T) \quad (24)$$

The next step is to take the partial derivatives of the Lagrange cost function $J(P, \lambda)$, with respect to P_S , P_R and λ . After that these equations will be equated to zero:

$$\frac{\partial J}{\partial P_S} = N_0^2 \left[\frac{-2P_S \cdot \sigma_{SD}^2 \cdot \sigma_{SR}^2}{(P_S^2 \cdot \sigma_{SD}^2 \cdot \sigma_{SR}^2)^2} - \frac{P_R \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2}{(P_S \cdot P_R \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2)^2} \right] + \lambda = 0 \quad (25)$$

$$\frac{\partial J}{\partial P_R} = N_0^2 \left[-\frac{P_S \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2}{(P_S \cdot P_R \cdot \sigma_{SD}^2 \cdot \sigma_{RD}^2)^2} \right] + \lambda = 0 \quad (26)$$

$$\frac{\partial J}{\partial \lambda} = P_S + P_R - P_T = 0 \quad (27)$$

The above expression will be used to calculate the transmission power values of source and all involved relay nodes.

$$P_S = \frac{\sigma_{SR}^2 + \sqrt{A}}{B} P_T \quad (28)$$

$$P_R = \frac{2\sigma_{SR}}{B} P_T \quad (29)$$

Where, in the above equation (28) and equation (29):

$$A = (\sigma_{SR}^2 + 8\sigma_{RD}^2)$$

$$B = (3\sigma_{SR}^2 + \sqrt{A})$$

IV. SIMULATION RESULTS

Figure 2 compares the performance of OPA with that of EPA in terms of ABER for a cooperative network having a single relay node. The results indicate that for any given value of E_b/N_0 the performance of the cooperative system employing OPA is better than the system having EPA as its power allocation technique, also proposed by [13].

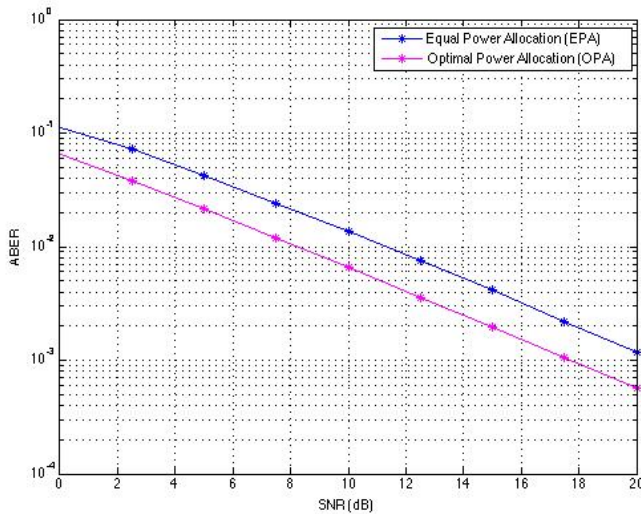


Figure 2. Optimal Power Allocation versus Equal Power Allocation

Table I presents the transmission powers values of the nodes in a 3-node network. These values are calculated using the expressions derived earlier while satisfying the total power constraint of "1". The power values have been calculated for three different scenarios. First, when the relay node is place in between source and destination node.

Second, when the relay node is closer to the destination node. Finally, for the scenario when the relay node is closer to source node. It can be seen clearly that the algorithm allocates different power values based on the link quality between the two communicating nodes at a given time.

TABLE I. OPTIMAL POWER VALUES (3-NODE CONFIGURATION)

Link Quality $\sigma_{SD}^2; \sigma_{SR}^2; \sigma_{RD}^2$	OPA		EPA	
	Source Node	Relay Node	Source Node	Relay Node
(1, 1, 1)	0.6667	0.3333	0.5	0.5
(1, 1, 10)	0.8187	0.1813	0.5	0.5
(1, 10, 1)	0.5472	0.4528	0.5	0.5

In figure 3, performance comparison of the above mentioned receiver diversity combining techniques is presented. The performance curves show that the traditional diversity technique, i.e, MRC is lacking in performance for each values of SNR. The performance gap between the two receiver diversity schemes increases with the increase in value of SNR, as shown by the lower curve. Along with the visible performance increase, ASNRC also does not require the knowledge of channel state information at the receiver node. This in turn reduces the overall complexity of the communicating node.

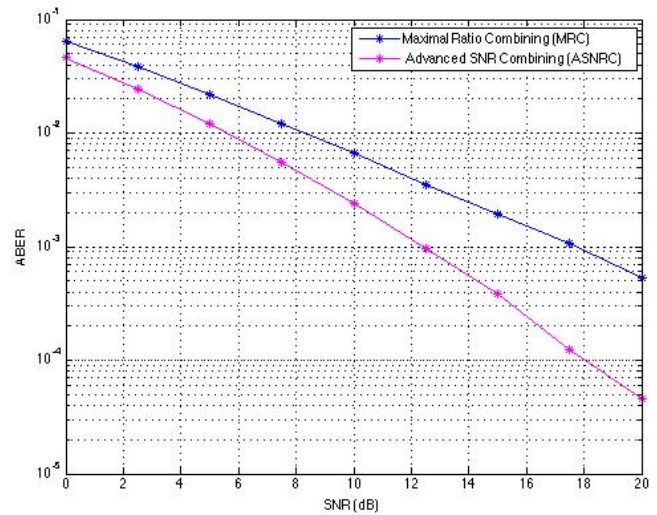


Figure 3. Performance Comparison of MRC and ASNRC

Figure 4, compares the performance of the 3-node cooperative relay system having two different power allocation algorithms and receiver diversity techniques. The first configuration is employing EPA, as its power allocation technique while MRC technique is being used at the receiver node. In the second configuration both of the proposed optimal power allocation and receiver diversity technique are being used. The performance curve of the second configuration outperforms that of the first one for every value of SNR. The performance gaps increases with the increase in the values of SNR.

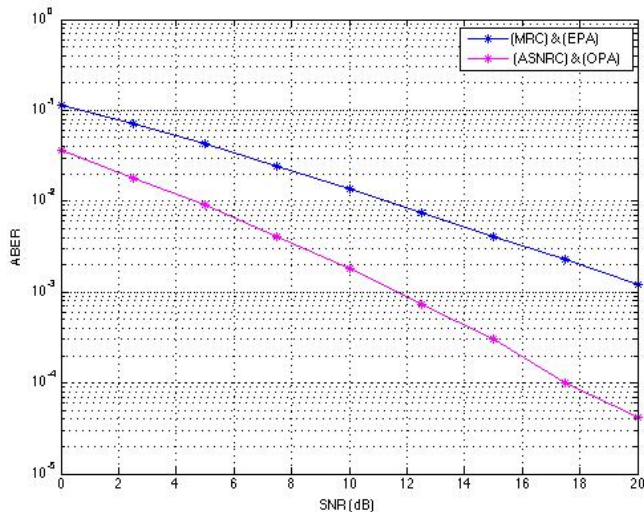


Figure 4. Performance Comparison of Traditional Vs. Proposed Techniques

V. CONCLUSION

In this paper, we have investigated a cooperative relay network employing advanced power allocation and receiver diversity techniques. First, the expressions for different phases in a cooperative communications were derived. After that the expression for the optimal power allocation and the proposed receiver diversity techniques were derived. The results above show clearly that the system performance is enhanced significantly with the use of these techniques. OPA is an ideal candidate for a cooperative network having un-balanced communication links with nodes placed asymmetrically. Where as, EPA performs only well if the nodes are placed symmetrically. It was also shown that if only a rough estimate about the channel quality is available then more advanced techniques like ASNRC could be employed to increase the performance of the system.

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