Performance Analysis of Power Allocation and Relay Location in a Cooperative Relay Network

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***Abstract*— Transmission using cooperative relays is a new paradigm in wireless communication. The cooperating relays facilitate the process of communication by performing the operations like data transmission and data processing in a distributed manner. In this wireless system every node is an active element and can act as a relay node. So when a group of these cooperating nodes are involved in a communication stream, a virtual multiple input multiple output (MIMO) system is formed which provides the networks with additional benefits of spectral efficiency and error reduction. Since this system is based on the traditional wireless sensor network (WSN) in which each node has a limited power and computational resource. Therefore, energy efficiency achieved by employing cooperating relays is not sufficient enough. Some extra measures need to be taken to decrease the power consumption of the network. This paper is an effort in this direction, as a power efficient allocation algorithm has been proposed which allocates transmission power optimally to the source node and the involved relay nodes. In the first part of the paper mathematical expressions have been derived for various phases in a cooperative relay transmission. The performance efficiency of the system has been presented using average bit error rate (ABER) as a performance criteria. In the second part, a power allocation algorithm has been derived and employed in a multi-hop cooperative relay network having 4-nodes, with amplify and forward (AF) protocol as its relaying technique. The efficiency of the power allocation algorithm (OPA) has been further investigated with respect to relay location in a network. Simulation results validate the performance efficiency of OPA in different transmission scenarios.**

***Keyword*— Power Allocation, Cooperative Relay Network, Multi-hop Transmission, Relaying Technique, Multiple Input Multiple Output and Diversity Combining.**

I. INTRODUCTION

For the past few years there has been a substantial increase in wireless communication services and applications. This advancement has brought us to the critical issue of efficiently utilizing the network resources. Communication through cooperating relay nodes is one such technology that uses the network resources dynamically rather than the traditional fixed access approach. These cooperating relays share their network resources to enhance the network productivity by providing distributed transmission [1]. This new wireless network seems quite promising, as it incorporates extra capabilities to a traditional WSN and at the same time increases spectrum efficiency in a significant way [2]. In a nutshell, a cooperative relay network (CRN) can provide its end users with high bandwidth efficiency, extended service coverage and ubiquitous connectivity.

In this technique spatial diversity gain is achieved by sharing the antenna resource of cooperating relay nodes to form a virtual MIMO system, as proposed in [3][4]. The source node and the involved relay nodes simultaneously transmit data over independent fading paths. At the receiver node these multiple streams of same correlated data is used to achieve a spatial diversity gain. The gain achieved due to diversity offers advantages like reduction in both error rate and the required transmission power. The relaying protocols being run on the nodes can be categorized into different types [5]. Among these types, amplify and forward (AF) protocol is a widely adopted one. This protocol simply amplifies the received signal and then forwards it to the next node without any complex processing, making it an efficient and less complex technique [6]. So, the system analysis has been carried out using AF relaying protocol.

In order to practically integrate this promising technique in the future wireless networks there are few issues, which need to be addressed. Among them transmission power management is a crucial one. Although extensive research has been carried out for relay networks but very few are focusing the issue of power efficiency. Optimal power allocation (OPA), is one of the techniques that allocates the transmission power optimally between the source and the involved relay nodes. Therefore, a substantial amount of node power is saved while maintaining the link quality [7]. The power allocation of a two-hop AF cooperation network was examined in [8] and [9] for Rayleigh fading, but they only considered a single relay network. In [10], the power allocation has been discussed for a multi-node network but decode-and-forward (DF) relaying protocol has been employed over Rician fading channel.

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Moreover in [11] [12] and [13], OPA has been derived for AF dual-hop network with arbitrary number of relays over Rayleigh fading. In [14], an OPA technique has been proposed for a multi-hop cooperative relay network but the network scenarios based on the location of relay in the network have been discussed very briefly.

The remainder of this paper is organized as follows. Section II, presents the network model and parameters. In Sections III, the mathematical expressions of the received signals have been derived for different phases of transmission. ABER has been taken as criteria to show the performance efficiency of power allocation algorithm. In Sections IV, the expressions for the required transmission power of the source and the relay nodes have been derived for the corresponding 4-node network configuration. The performance efficiency gained by employing the proposed technique is presented in form of performance curves, in Section V. Section VI, concludes the paper.

II. Multi-Hop Cooperative Network

A. Network Model

For this scenario the network model is shown below in Fig 1. This network has four communication nodes; a source node *S*, two relay nodes namely *R1* and *R2* and lastly a destination node *D*. The channel gains for the source to destination, source to relay1, relay1 to relay2 and relay2 to destination are represented by terms G_{SD}, G_{SR1}, G_{R1R2} and G_{R2D} respectively. The network model is designed based on few assumptions. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and variance σ^2. Every communicating node in the network will obey rules of half duplex transmission that means it will either transmit or listen at any given instant. The multiple signals received by the receiver node will be combined using Maximal Ratio Combining (MRC) technique. Finally, the power constraints are applied for the whole communication link instead of intermediate hops and AF protocol has been employed as a relaying strategy.

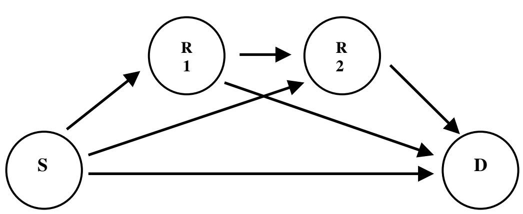

Figure 1. Cooperative Relay Network (2-Relays)

In the first phase the source node *S* broadcasts the data *X* with its transmission power P_S to both relays and destination node, as shown in the next figure. The channel gains for the source-relay1 and from source- relay2 links are G_{SR1} and G_{SR2} respectively. The AWGN present at the relay 1 and relay 2 nodes will be n_{SR1} and n_{SR2} respectively. The equation of received signals in the phase-I at the relay 1 and relay 2 will be expressed as Y_{R1} and Y'_{R2} respectively

$$Y_{R1}[n] = \sqrt{P_S}\; G_{SR1}.X[n] + n_{SR1}[n] \quad (1)$$

$$Y'_{R2}[n] = \sqrt{P_S}\; G_{SR2}.X[n] + n_{SR2}[n] \quad (2)$$

After Phase-II, the relay2 node has received two signals Y'_{R2} and Y_{R2}, first one was in phase-I (broadcasting) and the second one was forwarded by relay1 with its amplification factor β_{R1} in phase-II. G_{R1R2} is the channel gain for relay1-relay2 link and n_{R1R2} is the noise at the relay node2 in phase-II. But since the link between source-relay2 is weak as compared to the link between relay1 and relay2 so the node relay2 discards the signal Y'_{R2} and the received signal Y_{R2} is defined as:

$$Y_{R2}[n] = \beta_{R1}.Y_{R1}[n].\,G_{R1R2} + n_{R1R2}[n] \quad (3)$$

Relay gains β_{R1} and β_{R2} are used to properly fine-tune the powers at the corresponding relays to reduce variations in the source-relay and relay–destination links. The relaying node's amplifier can provide a maximum gain defined by the following expressions:

$$\beta_{R1} = \sqrt{\frac{P_{R1}}{P_S|G_{SR1}|^2 + N_0}} \quad (4)$$

$$\beta_{R2} = \sqrt{\frac{P_{R2}}{P_{R1}|G_{R1R2}|^2 + N_0}} \quad (5)$$

Since, amplify-and-forward protocol may induce some noise amplification but the MRC detector employed is quite competitive therefore with the help of its weights it can compensate effect of induced noise [15]. The output of the MRC detector at the destination node will be:

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \alpha_1(\beta_{R2}.Y_{R2}[n].G_{R2D} + n_{R2D}[n]) \quad (6)$$

Substituting equation (3) into (6):

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \alpha_1(\beta_{R2}.(\beta_{R1}.Y_{R1}[n].G_{R1R2} + n_{R1R2}[n]).G_{R2D} + n_{R2D}[n]) \quad (7)$$

Substituting equation (1) into (7):

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \alpha_1(\beta_{R2}.(\beta_{R1}.(\sqrt{P_S}\;G_{SR1}.X[n] + n_{SR1}[n]).G_{R1R2} + n_{R1R2}[n]).G_{R2D} + n_{R2D}[n]) \quad (8)$$

In the above equation (6-8), α_0 and α_1 are the weights of the maximal-ratio-combiner. These combining weights compensate for the effects of likely incorrect decisions and are therefore chosen accordingly. Here α_1, is the weight of the signals which is being forwarded by the relays placed in a linear topology.

$$\alpha_0 = \frac{\sqrt{P_S}\,G_{SD}^{*}}{N_0}$$

$$\alpha_1 = \frac{\sqrt{P_S}\,.\,\beta_{R1}.\,\beta_{R2}\,.\,G_{SR1}^{*}\,.\,G_{R1R2}^{*}\,.\,G_{R2D}^{*}}{N_0}$$

III. Optimal Power Allocation

Now, the probability of bit error for the 4-node configuration will be calculated using Moment Generating Function (MGF) approach. With the help of moment generating function approach the error probability for the QPSK modulation scheme will be expressed as an exponential function of γ, defined below.

$$P_e = \frac{1}{\pi}\int_0^{\left(\frac{N-1}{N}\right)\pi} \prod_{n=0}^{1} N_{\gamma_n}\left(\frac{g_{QPSK}}{sin^2\theta}\right) d\theta \tag{9}$$

$$N_{\gamma_n} = \int_0^{\infty} P_{\gamma_n}(\gamma) e^{s\gamma} d\gamma \tag{10}$$

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{g_{QPSK}}{sin^2\theta}\gamma_n\right)^{-1} \tag{11}$$

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{\gamma_n}{sin^2\theta}\right)^{-1} \tag{12}$$

Since ($\gamma_n >> 1$) equation (12) becomes:

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

$$P_e = \frac{3}{8}(\gamma_0.\gamma_1)^{-1} \tag{13}$$

$$P_e = \frac{3{N_0}^2}{8}\left[\frac{1}{P_S.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{SR1}} + \frac{1}{P_S.P_1.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R1R2}} + \frac{1}{P_S.P_2.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R2D}}\right] \tag{14}$$

As the outage probability has been formulated for this 4-node configuration, now this system will be expressed as a constrained optimization problem with transmission power as a constraint entity.

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

$$\text{Subject to}\quad P_S + \sum_1^N P_R \leq P_T$$

Now as we have established the constrained optimization problem, a closed form expression of this optimization problem will be found using Lagrange Method. The Lagrange cost function of this problem is defined as:

$$\mathrm{J} = P_e + \lambda\,(P_S + \sum_1^2 P_R - P_T) \tag{15}$$

$$\mathrm{J} = \frac{3{N_0}^2}{8}\left(\frac{1}{{P_S}^2\,\sigma^2{}_{SD}\;\sigma^2{}_{SR1}} + \frac{1}{P_S P_1\,\sigma^2{}_{SD}\;\sigma^2{}_{R1R2}} + \frac{1}{P_S P_2\,\sigma^2{}_{SD}\;\sigma^2{}_{R2D}}\right) + \lambda(P_S + P_1 + P_2 - P_T) \tag{16}$$

Now taking the partial derivatives of the Lagrange cost function J (P, λ), with respect to P_s, P_1, P_2 and λ. Afterwards these derivatives will be equated to zero, like defined below

$$\frac{\partial \mathrm{J}}{\partial P_S} = \frac{3N_0^2}{8}\left[\frac{-2P_S.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{SR1}}{({P_S}^2.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{SR1})^2} - \frac{P_1.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R1R2}}{(P_S.P_1.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R1R2})^2} - \frac{P_2.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R2D}}{(P_S.P_2.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R2D})^2}\right] + \lambda = 0 \tag{17}$$

$$\frac{\partial \mathrm{J}}{\partial P_1} = \frac{3N_0^2}{8}\left[\frac{-P_S.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R1R2}}{(P_S.P_1\,.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R1R2})^2}\right] + \lambda = 0 \tag{18}$$

$$\frac{\partial \mathrm{J}}{\partial P_2} = \frac{3N_0^2}{8}\left[\frac{-P_S.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R2D}}{(P_S.P_2\,.\,\sigma^2{}_{SD}\,.\,\sigma^2{}_{R2D})^2}\right] + \lambda = 0 \tag{19}$$

$$\frac{\partial \mathrm{J}}{\partial \lambda} = P_S + P_1 + P_2 - P_T = 0 \tag{20}$$

After some algebraic manipulations the above equations are used to solve the value of source node power P_S, relay1 node power P_1 and relays2 node power P_2.

$$P_S = \begin{cases} \dfrac{A - 4B + \sqrt{A^2 + 8AB}}{4(A - B)} P_T \\ \dfrac{2}{3} P_T \end{cases}$$

$$P_1 = \frac{\sigma_{2D}}{\sigma_{2D} + \sigma_{R1R2}}(P_T - P_S)$$

$$P_2 = P_T - P_1 - P_S$$

Where, in the above equation A=$(\sigma_{R2D} + \sigma_{R1R2})^2.\,\sigma^2{}_{R1R2}.\,\sigma^2{}_{SR1}$ and B= $\sigma^2{}_{R2D}.\,\sigma^3{}_{R1R2}$

IV. Simulation Results

Fig. 2, compares the performance of OPA with that of EPA in terms of ABER for a cooperative network having 2 relays. The results show that OPA outperforms EPA when employed to a cooperative relay network having similar configuration. The performance gap remains same for the increasing values of SNR. It was also an observation that the performance of a system employing EPA can be increased only if the relays were placed symmetrically but OPA performs better for both symmetric and asymmetric configurations.

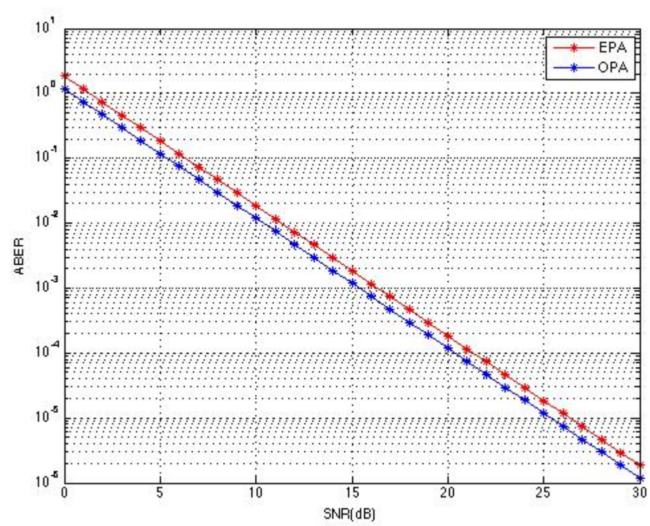

Figure 2. Equal power allocation and Optimal power allocation

Fig. 3, compares the performance of case 1: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) with case 2: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) in terms of ABER for a cooperative network having 2 relays. Here, channel link quality is denoted by "10" if the two communicating nodes are closer to each other while if the two nodes are far from each other channel link quality is "1". For this network simulation, case 2:($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) shows the best performance because in this case relays2 is closer to destination node and source node is closer to relay1 node. Case 1: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) shows slightly worse performance because only relay2 node is closer to the destination node.

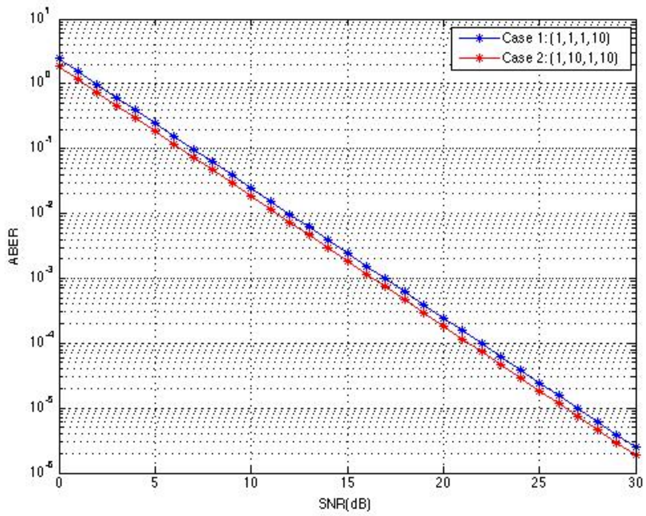

Figure 3. Cooperative Transmission Scenarios (Case1 & Case2)

Fig. 4, compares the performance of case 3: ($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 1$) with case 4: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 10$; $\sigma^2{}_{R2D} = 10$) in terms of ABER for a cooperative network having 2 relays.

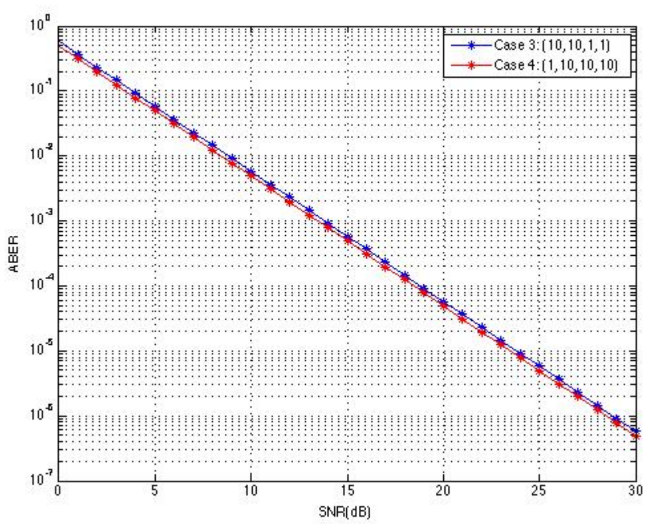

Figure 4. Cooperative Transmission Scenarios (Case3 & Case4)

For this network simulation, case 4:($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 10$; $\sigma^2{}_{R2D} = 10$) shows the best performance because in this case the channel link quality for every transmisson hop is strong. Case 3: ($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 1$) shows slightly worse performance because only relay1 node is closer to source node.

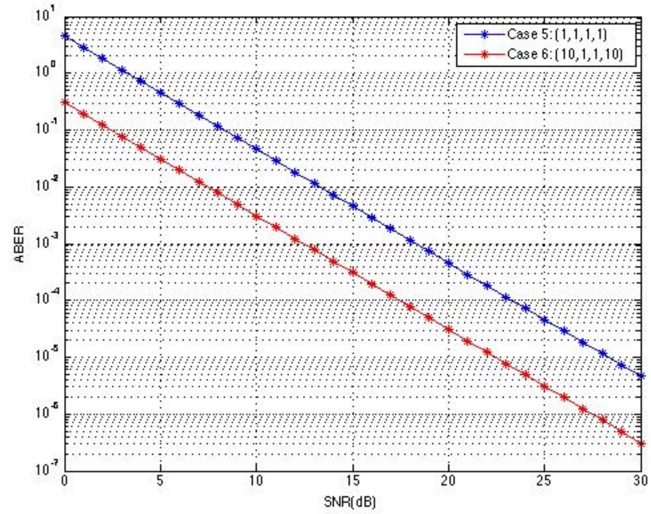

Figure 5. Cooperative Transmission Scenarios (Case5 & Case6)

Fig. 5, compares the performance of case 5: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 1$) with case 6: ($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) in terms of ABER for a cooperative network having 2 relays. Out of all simulations, case 5: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 1$) is the worst one as every tranmsission link is weak . On the contrary, Case 6: ($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) is the best possible scenario because not only relay2 node is closer to destination node but also the direct link between source and destination is also strong.

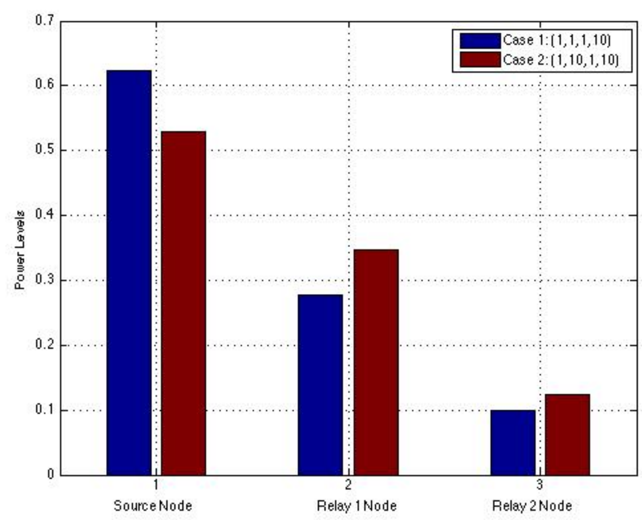

Figure 6. Allocated Power Levels (Case1 & Case2)

Fig. 6, compares the transmission power values for case 1: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) represented by blue bar and case 2: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) represented by red bar.

For case 1: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 1$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 10$) the only strong link is between relay2 and destination node. So it is visible from the above graph that the value of transmission power (0.0986) allocated to relay2 node is the lowest when compare to the power values of source node (0.6236) and relay1 node (0.2778). For case 2: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 10$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 10$) the power allocation algorithm assigns a transmission power of (0.529) to the source node, a power of (0.348) to the relay1 node and a tranmission power of (0.123) to the relay2 node, satisfying the total power constraint of “1”, as defined in the derived mathematical expressions.

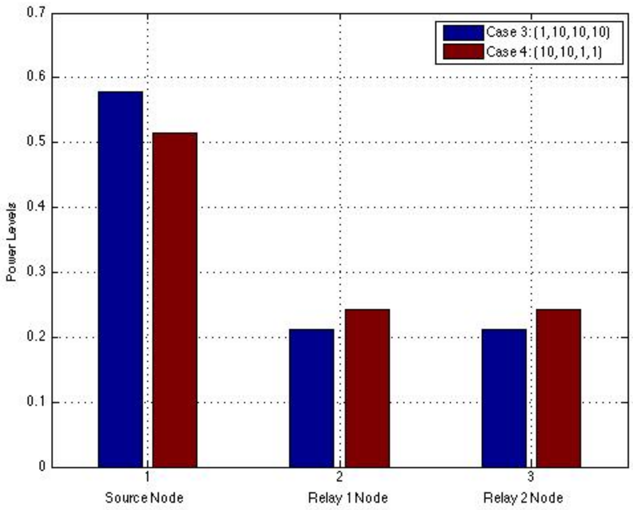

Figure 7. Allocated Power Levels (Case3 & Case4)

Fig. 7, compares the transmission power values for case 3: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 10$; $\sigma^2_{R1R2} = 10$; $\sigma^2_{R2D} = 10$) represented by blue bar and case 4: ($\sigma^2_{SD} = 10$; $\sigma^2_{SR1} = 10$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 1$) represented by red bar. For case 3: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 10$; $\sigma^2_{R1R2} = 10$; $\sigma^2_{R2D} = 10$) the channel link quality for every transmisson hop between the source and destination is strong so the value of tranmission power allocated to the the relay1 and relay2 node will be equal (0.2113) and source node will be allocated the maximum value of (0.5774). For case 4: ($\sigma^2_{SD} = 10$; $\sigma^2_{SR1} = 10$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 1$) the power allocation algorithm assigns a transmission power of (0.5144) to the source node, a power of (0.2428) to the relay1 node and a tranmission power of (0.2428) to the relay2 node, satisfying the total power constraint of “1”.

Fig. 8, compares the transmission power values for case 5: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 1$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 1$) represented by blue bar and case 6: ($\sigma^2_{SD} = 10$; $\sigma^2_{SR1} = 1$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 10$) represented by red bar. For case 5: ($\sigma^2_{SD} = 1$; $\sigma^2_{SR1} = 1$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 1$) the channel link quality for every transmisson hop between the source and destination is weak so the value of tranmission power allocated to the the relay1 and relay2 node will be equal (0.2113) and source node will be allocated the maximum value of (0.5774). For case 6: ($\sigma^2_{SD} = 10$; $\sigma^2_{SR1} = 1$; $\sigma^2_{R1R2} = 1$; $\sigma^2_{R2D} = 10$) the power allocation algorithm assigns a transmission power of (0.6236) to the source node, a power of (0.2778) to the relay1 node and a tranmission power of (0.0986) to the relay2 node, satisfying the total power constraint of “1”.

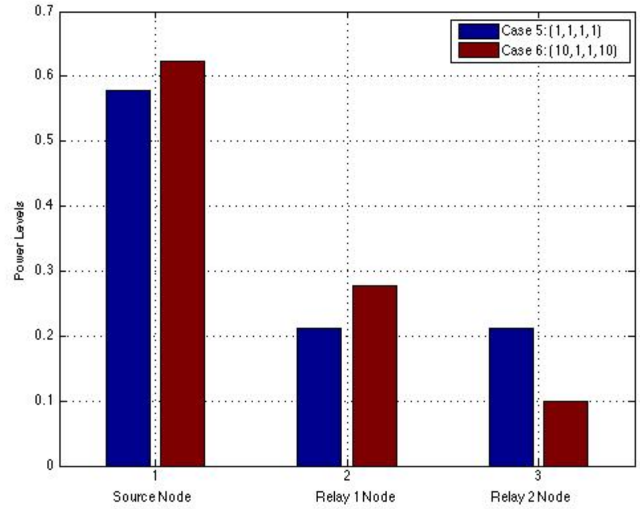

Figure 8. Allocated Power Levels (Case5 & Case6)

V. Conclusion

In this paper, we investigated the effect of optimal power allocation and the effect of relay location for a transmission using cooperative relays. The results show that instead of using the traditional EPA if OPA is employed in a cooperative relay network then the system performance can be enhanced substantially. Moreover, OPA is vital for these infrastructure-less networks having un-balanced communication links. With help of the above results it has been found out that the communication links between the source node (S) and the first-relay (R_1) and the link between the last-relay (R_N) and the destination node (D) have the most significant effect on the system performance. Other communication links have slightly less effect on the system performance. Finally as a future direction, optimum relays should be determined first based on their location. Then these relays should be used for transmission, by doing so the system performance can be further enhanced.

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