# Symbol Error Rate Analysis in Cooperative Transmission: AF Relaying Scenarios and Optimal Power Allocations

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***Abstract*—In this paper, we present relay power optimization in terms of Sum Relay Power (SRP) constraint in order to minimize the probability of symbol error and improve the network reliability. Then, the optimum number of relays taking into account the introduced constraint has been derived. Avoiding one channel impact on another, the orthogonal fading channel is assumed. First, the parallel relays strategy is considered where information is sensed by relays independently in communicating with source and resending it to destination using Amplify and Forward (AF) strategy. Next, we consider the case where the information is being sent through whole relays sequentially in one branch to the destination. Finally, we extend the SRP constraint to the general case, where we have multi-branches including several relays for each one. In conclusion, it can be derived from simulations that fewer number of relays is much more reliable than relatively more number of them in terms of low SRP constraint and vice versa. Furthermore, increasing power in relatively few number of relays only improves the network reliability insignificantly than employing more number of relays which causes sharp decrease in probability of symbol error.**

***Index Terms*—relay, fading channel, Symbol error rate, SNR, cooperative network.**

## I. Introduction

Cooperative Diversity or User Cooperation can be classified as Multi-User MIMO technique which aims to maximize the network capacity by decoding and combining the received signal from relays in addition to direct signal from source. In the prevalent method, destination receives the signal directly from source in a single-hop system and considers the relays signals as additional noise. However in cooperative transmission scheme, information detection has been implemented using the combination of all received signals in order to maximize signal to noise ratio (SNR). One can enhance diversity gain in the cost of frequency spectrum or allocating higher amount of power at source. In this paper, we assumed that there exists a limited amount of frequency spectrum and source power, So these factors are unchangeable.

Cooperative communication has been studied in [1] where one spatial diversity method has been considered. This system exploits users cooperation in multi-user network to robust users from signal attenuation and declines the probability of error considerably by transmitting the message through several relays, considering independent channels for each one. The use of space diversity among relays cooperative communication has been studied in [2], where Amplify and Forward(AF), Selection Relaying(SR), and Decode and Forward(DF) strategy for cooperative relays has been considered to decrease fading impact significantly. In [3], the Symbol Error Rate (SER) with AF relaying strategy has been formulated using the Probability Density Function (PDF) of the summation of the SNR's from whole relaying pathes. [4] addresses the minimum power allocation strategy taking into account the limited SER through AF relaying. A full diversity space time code has been used to enhance bandwidth efficiency in Cooperative Networks, see[5]. Synchronization issue between source and destination, and calculating lower and upper bounds on the outage capacity of wireless relaying system taking into account some practical limitation like synchronised duplexing in relays has been studied in [6].

Optimal power allocation from transmitter to relays aiming to achieve the highest SNR in the aspect of signal processing under the constraint of a limited number of relays in the Gaussian channel has been studied in [7]. [8] considers cooperative network among source and some relay nodes to send message reliably to the destination given a total SNR in destination. Using the network's residual energy after network's life time expiration and sensor's initial energies effect on total network's lifetime has been studied in [9]. A closed form formula for Symbol Error Probability (SEP) for Cooperative Diversity links using the P.D.F. of SNR at destination by maximum ratio combining (MRC) detection method is derived in [10]. One new strategy based on AF relaying strategy named Laneman's AAF which allows correlation between the last and the next transmitting message in order to achieve higher rates has been proposed in [11].

Comparison between two kind of clustering protocols, named LEACH and LEACH-C, has been made in [12] to maximize network lifetime. The optimum solution in maximizing the short-term throughput and maximizing the information transmitted to the destination for the nodes equipped with rechargeable batteries has been investigated in [13]. Optimizing power allocation in cooperative network using AF relaying scheme in order to make the network reliable by meeting symbol error rate requirement has been studied in [14], and maximizing wireless network lifetime taking into account the total SER requirement has been considered in [15].

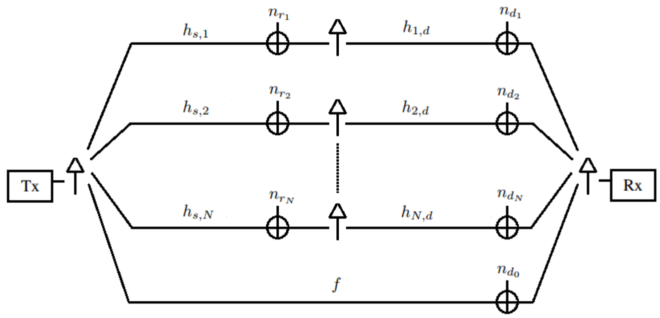



Fig. 1: Cooperative transmission with multi-branch two-hop relaying scheme.

In this paper, we attempt to optimize power allocation at relays in order to minimize the probability of error in three cooperation scenario, taking into account the limited SRP, which can be interpreted as limited amount of energy at a given time interval. Then we will find the optimum number of relays taking into account the same constraint to achieve the same goal in terms of different given SRP constraint. It is assumed that all relay channels are orthogonal rayleigh fading in all discussed scenarios.

This paper is organized as follows: Section II explains the system model and the mathematical equations which are followed up in them. Section III details the optimization problem and the proposed solutions. Section IV makes survey on the simulation and important results. Finally, section V summarizes the conclusions.

## II. System Model

In this paper, we introduce our system based on cooperative diversity where $N$ relays, $\{r_1, r_2, ..., r_N\}$, by use of AF-relaying strategy cooperate in transmitting data from the source, $\mathcal{S}$, to the destination, $\mathcal{D}$. It is assumed that each node has only one antenna. In the rest of paper we consider three cooperating scanrios, depicted in figures 1-3, as

- multi-branch two-hop relay network,
- single-branch multi-relay network,
- multi-branch multi-relay network.

We analytically derive the optimum number of relays and optimal power allocation subject to sum-power constraint at the relays to provide the most reliable cooperating network.

### *A. Multi-Branch Two-Hop Relay Cooperative Diversity*

In this model, we assume in addition to the direct link from $\mathcal{S}$ to $\mathcal{D}$, there are $N$ orthogonal cooperating path through $N$ AF relays. Therefore the destination receives $N+1$ version of the transmitted signal. In other words, this system could be modeled as a virtual MIMO system, see Fig. 1.

- The received signal at $\mathcal{D}$ and relays are formulated as
$$y_{r_i} = h_{s,i}x + n_{r_i} \text{ for } i = 1, ..., N \tag{1}$$
where $x$ is the transmitted signal from $\mathcal{S}$ and $y_{r_i}$ is the received signal at $i^{th}$ relay subject to $\mathbb{E}(x^2) = p_s$. Moreover, $h_{s,i}$ and $n_{s_i}$ are the fading coefficient from $\mathcal{S}$ to $i^{th}$ relay and Additive White Gaussian Noise(AWGN), respectively. Here, $\mathbb{E}(n_{r_i}^2) = N_0$ for $i = 1, ..., N$.
- Relays use AF strategy for transmission such that
$$x_{r_i} = A_i y_{r_i}, \tag{2}$$
where $x_{r_i}$ is the transmitted signal from $i^{th}$ relay and $y_{r_i}$ is the received signal at the relay. $A_i$ is the amplifying factor to satisfy the power constraint at the $i^{th}$ relay.
- At destination, we have
$$\begin{aligned} y_{d_0} &= fx + n_{d_0} \\ y_{d_i} &= h_{i,d}x_{r_i} + n_{d_i} \quad \text{for} \;\; i = 1, ..., N \end{aligned} \tag{3}$$
where $y_{d_0}$ and $y_{d_i}$ are the received signal at ,$\mathcal{D}$ from $\mathcal{S}$ and from $i^{th}$ relay, respectively. $f$ and $h_{i,d}$ are the fading coefficient of the direct link from $\mathcal{S}$ to $\mathcal{D}$ and the link from $i^{th}$ relay to $\mathcal{D}$, respectively. Furthermore, $n_{d_0}$ and $n_{d_i}$ are the AWGN at $\mathcal{D}$ associated to the direct link and the $i^{th}$ relay respectively.

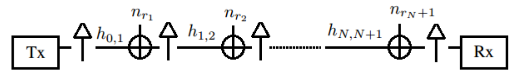



Fig. 2: Cooperative transmission with single-branch two-hop relaying scheme.

### *B. Single-Branch Multi-Relay Cooperative Diversity*

In this case, we assume that the information passes serilay through $N$ relay nodes to reach $\mathcal{D}$ ad demonstrated in Fig. 2.

- The received signal at each relay is
$$y_{r_{i+1}} = h_{i,i+1}x_{r_i} + n_{r_{i+1}} \quad \text{for} \;\; i = 0, ..., N, \tag{4}$$
where, $h_{i,i+1}$ indicates the channel coefficient between the two consecutive relays.
- Relays by use of AF strategy transmit the signal similar to equation (2).

### *C. Multi-branch Multi-Relay Cooperative Diversity*

In this model, we consider a general case in which several branches and several relays in each branch exist. The general case depicted in Fig 3. Similar to the previous scenarios, one can formulate the signals. This cooperative structure, combines three systems; a SIMO system between the source node and the relays, a SISO system between two sequential relays in each branch, and MISO system between relays and the destination node.

In all the three mentioned scenarios, we assume that the channels are Rayleigh fading and relay channels are orthogonal. Thus, the destination uses MRC method to recover the transmitted message. To this goal, we have [10]
$$\gamma_{tot} = \sum_{i=1}^{M} \gamma_i, \tag{5}$$
where $\gamma_i$ is the SNR of the received signal at $\mathcal{D}$ from the $i^{th}$ channel.

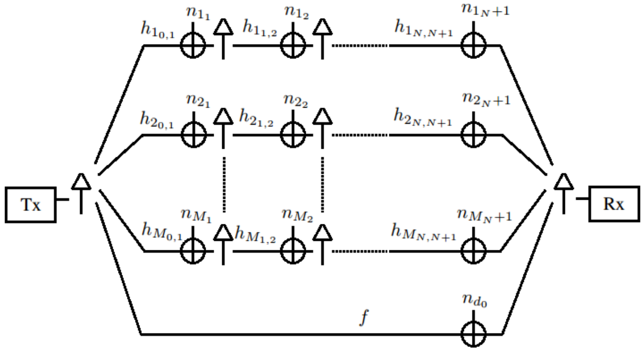



Fig. 3: Cooperative network with multi-branch multi-relays system

## III. Optimal Power Allocation

In this section, for each cooperatind scenarios, we derive optimal power allocation for each relay and optimum number of active relays to minimize the SER subject to the sum-power constraint at the relays.

### A. Multi-Branch Two-Hop Relay Cooperative Diversity

The average SER in multi-branch network is formulated as [15]

$$P_e(N) = \frac{C(N,k)}{\gamma_{sd}} \prod_{i=1}^{N} \left(\frac{1}{\gamma_{si}} + \frac{1}{\gamma_{id}}\right), \tag{6}$$

where $\gamma_{sd} = \bar{f}^2 p_s/N_0$, $\gamma_{si} = \bar{h}^2_{s,i} p_s/N_0$, and $\gamma_{id} = \bar{h}^2_{i,d} p_i/N_0$ denote source to destination, source to relay, and relay to destination's signal to noise ratio, respectively. Knowing that $p_s$ is the transmission power and $N_0$ is the noise power, $\bar{f}^2 = \frac{1}{d^{\alpha}_{sd}}$, $\bar{h}^2_{s,i} = \frac{1}{d^{\alpha}_{si}}$, $\bar{h}^2_{i,d} = \frac{1}{d^{\alpha}_{id}}$ indicates Rayleigh fading variance which are inversely depended on the distance between two nodes and $\alpha$ is fading factor. In (6), For M-PSK modulation $C(N,k)$ is given by

$$C(N,k) = \frac{\prod_{i=1}^{N+1} [\frac{2i-1}{2(M+1)!}]}{k^{M+1}}, \tag{7}$$

where $k$ is a constant value as

$$k = 2sin^2(\pi/M). \tag{8}$$

Without loss of generality, we assume $N_0 = 1$ and 4-PSK modulation, so $k = 1$. Now, rewriting (6), we have

$$SER = \frac{C(N,k)}{p_s \bar{f}^2} \prod_{i=1}^{N} \left(\frac{1}{p_s \bar{h}^2_{s,i}} + \frac{1}{p_i \bar{h}^2_{i,d}}\right), \tag{9}$$

which shows the outstanding concept that more number of relays will result in more reliable network under the condition of allocating enough power for each relay. In (9), $p_s$ is the transmission power at the source and $p_i$ is the transmission power at $i^{th}$ relay to the destination. We aim to minimize SER subject to total energy consumption of the active relays. Hence, our optimization problem is presented as

$$\begin{aligned} &\min_{p_1,..,p_N} \quad SER \\ &\sum_{i=1}^{N} p_i \le p_{sum} \\ &p_i \ge 0, \quad \text{for} \quad i = 1, ..., N \end{aligned} \tag{10}$$

From (9) it can be argued that SER is a convex function of $p_i$, while the sum power constraint is a linear function. Therefore, the optimization problem (10) is a convex one and it has a unique minimum. Therefore, to solve the optimization problem (10), we use Lagrangian method to find the optimum relay power vector, which minimize SER . The lagrangian function is written as

$$\begin{aligned} Ł(p_1, ..., p_N) = &\frac{C(N,k)}{p_s \bar{f}^2} \prod_{i=1}^{N} \left(\frac{1}{p_s \bar{h}^2_{s,i}} + \frac{1}{p_i \bar{h}^2_{i,d}}\right) - \\ &\lambda\left(\sum_{i=1}^{N} p_i - p_{sum}\right) - \sum_{i=1}^{N} \vartheta_i p_i. \end{aligned} \tag{11}$$

Following the Karush-Kuhn-Tucker (KKT) procedure, we obtain the conditions as follows

$$\begin{aligned} &\lambda \ge 0, \vartheta_i \ge 0 \\ &\lambda\left(\sum_{i=1}^{N} p_i - p_{sum}\right) = 0, \vartheta_i p_i = 0. \end{aligned} \tag{12}$$

By derivative of Ł with respect to $i^{th}$ relay power, we obtain

$$\begin{aligned} \frac{\partial Ł(p_1, ..., p_N)}{\partial p_i} = &- \frac{C(N,k)}{p_s p_l^2 \bar{f}^2 \bar{h}^2_{l,d}} \prod_{i=1, i \ne l}^{N} \left(\frac{1}{p_s \bar{h}^2_{s,i}} + \frac{1}{p_i \bar{h}^2_{i,d}}\right) \\ &- \lambda - \vartheta_l = 0. \end{aligned} \tag{13}$$

Now, the optimal relays power is written as

$$p_i = \sqrt{-\frac{C(N,k)}{(\lambda + \vartheta_l) p_s \bar{f}^2 \bar{h}^2_{l,d}} \prod_{i=1, i \ne l}^{N} \left(\frac{1}{p_s \bar{h}s, i^2} + \frac{1}{p_i \bar{h}^2_{i,d}}\right)}. \tag{14}$$

From (9) and (12) it can be observed that considering $p_i = 0$ for one or some of $i = 1, ..., N$ leads SER to infinity which contradicts the optimization objective i.e. minimizing SER. As a result, $\vartheta_i = 0$ for all $i = 1, ..., N$. Moreover, from (10) and (12), it can be argued that the SRP constraint would be satisfied with equality. Assuming that this constraint is satisfied with inequality, we can add some more power to one or some of $p_i$'s in order to reach to the equality point and achieve less SER. So, we can consider that optimization problem (10) always satisfies the first constraint with equality.

Consequently, trying to solve optimization problem (10), we would have a nonlinear system with $N+1$ equations and $N+1$

unknowns as follows

$$
\begin{aligned}
&p_i = \sqrt{-\frac{C(N,k)}{\lambda p_s \bar{f}^2 \bar{h}_{s,l}^2} \prod_{i=1, i\neq l}^{N} (\frac{1}{p_s \bar{h}_{s,i}^2} + \frac{1}{p_i \bar{h}_{i,d}^2})} \\
&\sum_{i=1}^{N} p_i = p_{sum}.
\end{aligned} \tag{15}
$$

*B. Single-Branch Multi-Relay Cooperative Diversity*

Here, just as before, the goal is to minimize symbol error rate taking into account the SRP constraint. In this case, average SER has been given as [15]

$$P_e(N) = C(N,k) \sum_{i=0}^{N} \frac{1}{\gamma_{i,i+1}}. \tag{16}$$

Here, Source is considered as $0^{th}$ relay and $\gamma_{i,i+1} = p_t \bar{h}_{i,i+1}^2 / N_0$ where, as quoted before, $\bar{h}_{i,i+1} = 1/d_{i,i+1}^{\alpha}$. Since we have only one branch with sequentially $N$ relays from the source to the destination, $C(N,k)$ would be changed to $C(1,k)$. As a result, SER is rewritten as

$$SER = C(1,k) \sum_{i=0}^{N} \frac{1}{p_i \bar{h}_{i,i+1}^2}, \tag{17}$$

where $p_0$ is the source power and $p_i$ is the $i^{th}$ relay power. Thus, the average SER is written as

$$
\begin{aligned}
&\min_{p_1,..,p_N} \quad SER \\
&\sum_{i=1}^{N} p_i \leq p_{sum} \\
&p_i \geq 0, \quad \text{for} \quad i = 1, ...N
\end{aligned} \tag{18}
$$

To solve optimization problem (18), just as the section before, it can be argued that the optimization problem is a convex one. It enables us to use lagrangian method to find the optimum relay power vector which minimize SER under SRP constraint. Hence, lagrangian function is written as

$$
\begin{aligned}
Ł(p_0, ..., p_N) = &C(1,k) \sum_{i=0}^{N} \frac{1}{p_i \bar{h}_{i,i+1}^2} - \lambda(\sum_{i=1}^{N} p_i - p_{sum}) \\
&- \sum_{i=1}^{N} \vartheta_i p_i.
\end{aligned} \tag{19}
$$

Now, we can write KKT condition for the lagrangian function (19) as

$$
\begin{aligned}
&\lambda \geq 0, \vartheta_i \geq 0 \\
&\lambda(\sum_{i=1}^{N} p_i - p_{sum}) = 0, \vartheta_i p_i = 0.
\end{aligned} \tag{20}
$$

Derivative of Ł with respect to $i^{th}$ relay power, we have

$$\frac{\partial Ł(p_1, ..., p_N)}{\partial p_i} = -C(1,k) \frac{1}{p_l^2 \bar{h}_{l,l+1}^2} \quad -\lambda - \vartheta_l = 0. \tag{21}$$

Therefire, the optimum relay power obtained as

$$p_i = \sqrt{-C(1,k) \frac{1}{(\lambda + \vartheta_l) \bar{h}_{l,l+1}^2}}. \tag{22}$$

From (17) and (20), it can be observed that considering $p_i = 0$ for one or some of $i = 1, ..., N$ leads SER to infinity which contradicts the optimization objective i.e. minimizing SER. As a result, $\vartheta_i = 0$ for all $i = 1, ..., N$. Moreover, from (18), it can be argued that the sum relay power constraint would be satisfied with equality. Assuming that this constraint is satisfied with inequality, we can add some more power to one or some of $p_i$'s in order to reach to the equality point and achieve less SER. So, we can consider that optimization problem (18) always satisfies the first constraint with equality. Consequently, trying to solve the optimization problem (18), we would have a nonlinear system with $N+1$ equations and $N+1$ unknowns as follows

$$
\begin{aligned}
&p_i = \sqrt{-C(1,k) \frac{1}{\lambda \bar{h}_{l,l+1}^2}} \quad \text{for} \quad i = 1, ..., N \\
&\sum_{i=1}^{N} p_i = p_{sum}.
\end{aligned} \tag{23}
$$

*C. Multi-branch Multi-Relay Cooperative Diversity*

For this general scheme, the average SER can be formulated as [15]

$$P_e(M) = \frac{C(M,k)}{\gamma_{sd}} \prod_{j=1}^{M} \sum_{i=0}^{N} (\frac{1}{\gamma_{j_{i-1,i}}} + \frac{1}{\gamma_{j_{i,i+1}}})), \tag{24}$$

where $\gamma_{j_{i-1,i}}$ is the average SNR at $i^{th}$ relay at $j^{th}$ branch. Therefore, the average SER at the can be written as

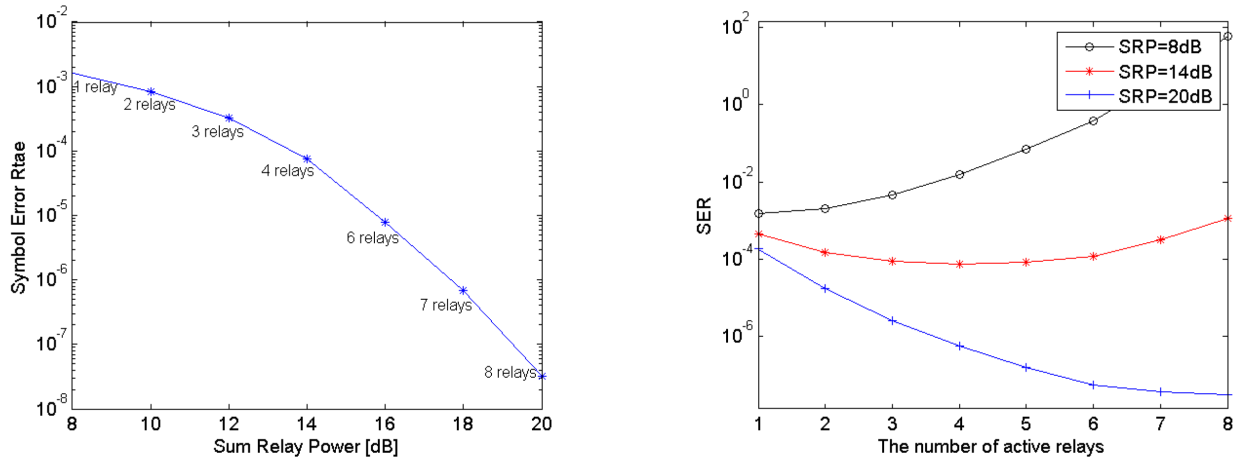
$$SER = \frac{C(M,k)}{p_s \bar{f}^2} \prod_{j=1}^{M} \sum_{i=0}^{N} (\frac{1}{p_s \bar{h}_{j_{i-1,i}}^2} + \frac{1}{p_{j_i} \bar{h}_{j_{i,i+1}}^2}). \tag{25}$$

Like before, we aim to minimize the SER taking into account the SRP at whole active relays does not exceed a specific value. So, the optimization problem is written as

$$
\begin{aligned}
&\min_{p_{0_1},..,p_{M_N}} \quad SER \\
&\sum_{j=1}^{M} \sum_{i=0}^{N} p_{j_i} \leq p_{sum} \\
&p_{j_i} \geq 0, \quad \text{for} \quad j = 1, ..., M \; \& \; i = 1, ..., N
\end{aligned} \tag{26}
$$

Since the optimization problem is convex, we can write the lagrangian equation as

$$
\begin{aligned}
Ł(p_{0_1}, ..., p_{M_N}) = &\frac{C(M,k)}{p_s \bar{f}^2} \prod_{j=1}^{M} \sum_{i=0}^{N} (\frac{1}{p_s \bar{h}_{j_{i-1,i}}^2} + \frac{1}{p_{j_i} \bar{h}_{j_{i,i+1}}^2}) - \\
&\lambda(\sum_{j=1}^{M} \sum_{i=1}^{N} p_{j_i} - p_{sum}) - \sum_{j=1}^{M} \sum_{i=1}^{N} \vartheta_{j_i} p_{j_i}.
\end{aligned} \tag{27}
$$




(a) (b)

Fig. 4: Multi-branch two-hop relay system (a) Optimum number of active relay's with respect to SRP where $p_s = 20$ [dB] (b) Minimum value of SER with respect to the number of active relays for three value of SRP=$8, 14, 20$ [dB] where $p_s = 20$ [dB]

As two cases before, KKT condition can be acquired as

$$\begin{aligned} &\lambda \geq 0, \vartheta_{j_i} \geq 0 \\ &\lambda(\sum_{j=1}^{M}\sum_{i=1}^{N} p_{j_i} - p_{sum}) = 0, \vartheta_{j_i} p_{j_i} = 0. \end{aligned} \tag{28}$$

Equation (27) is differentiated with respect to each relay power as

$$\frac{\partial Ł(p_{1_2}, ..., p_{M_N})}{\partial p_{l_q}} = -\frac{C(M,k)}{p_s p_{l,q}^2 \bar{f}^2 \bar{h}_{l,q}^2} \prod_{j=1, j\neq l}^{M} \sum_{i=1, i\neq q}^{N} (\frac{1}{p_s \bar{h}_{j_{i-1,i}}^2} + \frac{1}{p_{j_i} \bar{h}_{j_{i,i+1}}^2}) - \lambda - \vartheta_{j_i} = 0. \tag{29}$$

Repeating the same procedure as before, it can be easily concluded that $\vartheta_{j_i} = 0$ for $j = 1, ..., M$ and $i = 1, ..., N$. Furthermore, sum relay power constraint would be satisfied with equality. Therefore, we would have $MN + 1$ equations and $MN + 1$ unknowns as follows

$$p_{l,q} = \sqrt{-\frac{C(M,k)}{\lambda p_s p_{l_q}^2 \bar{f}^2} \prod_{j=1, j\neq l}^{M} \sum_{i=1, i\neq q}^{N} (\frac{1}{p_s \bar{h}_{j_{i-1,i}}^2} + \frac{1}{P_{j_i} \bar{h}_{j_{i-1,i}}^2})}$$
$$\sum_{j=1}^{M}\sum_{i=1}^{N} p_{j_i} = p_{sum}. \tag{30}$$

## IV. Numerical Discussions

The numerical result for multi-branch two-hop relaying network has been shown in Fig .4. Inherently, the high SRP let us activate larger number of relays to employ. As it can be seen with clarity, it is optimized to exploit only one relay for SRP less than 8 [dB], see Fig. 4.a. As the SRP rises to 10 [dB] the number of optimized active relays turns up to be two. This trend continues to SRP=20 [dB] where 8 is the optimized number of relays with SER=$10^{-7.5}$. Although cooperative diversity decreases SER in cooperative network, omitting the relays whose channel fading variance is high would be vital. It is due to the fact that these kind of relays increase SER and pull down the network reliability, see Fig. 4.b. In addition, it should be noted even if one spends the high amount of SRP=20 [dB] in one relay, it declines SER even less than 10 [dB] in comparison with using the low amount of SRP=8 [dB]. However applying the more number of relays e.g 8 relays would decline SER to the lowest point of $10^{-7.5}$. Finally, it can be seen that the optimum number of relays to be employed is 1,4, and 8 for SRP=8,14, and 20[dB], respectively.

## V. Conclusion

To sum up, there is a direct relation between sum relay power and the number of optimum relays in cooperative diversity networks. Using a few number of relays will not provide a reliable wireless network even if high hum relay power is available. However, distributing sum relay power to larger number of relays for high sum relay power declines SER drastically and make reliable system.

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