# Area Spectral Efficiency of Cooperative Network With Opportunistic Relaying


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***Abstract*—In this paper, we investigate the area spectral efficiency (ASE) in a three-node cooperative network with opportunistic relaying. On one hand, in conventional cellular network, ASE is defined to be the average data rate per unit bandwidth per unit area supported by a base station. On the other hand, in cooperative network, since there is no such a central base station, we redefine ASE to be the average data rate per unit bandwidth within a particular area, in which simultaneous transmissions are not allowed. In addition, to maximize the instantaneous capacity between the source and the destination, we apply a transmission mode selection criterion to determine whether the direct transmission or the multi-hop relay transmission is utilized. We derive the mathematical expression of ASE with the consideration of the relay node location and the impact of path-loss and fading effects. We show through selected numerical examples the effect of relay node position on the performance metric of ASE.**



***Index Terms*—cooperative network, area spectral efficiency, opportunistic relay.**


## I. Introduction

Relay-assisted multi-hop communication is one of the most attractive approaches to improve the capacity and reliability of a wireless network by deploying relay stations (RSs) between the source and destination to help their communications. For instance, in the network-level design for large scale coverage, infrastructure RSs are deployed between base station (BS) and mobile stations (MSs) to provide a cost effective approach to increase the capacity and improve the coverage of cellular wireless systems for high data rate services [1]- [4]. Another example is the wireless media system (WMS), which is a new wireless network architecture using infrastructure relays to provide cell-edge or shadowed area coverage [2]. However, in the small scale coverage scenario, deploying an infrastructure RS may not be feasible. Therefore, the roles of source, destination and relay are all taken by mobile stations. Under this circumstance, cooperative communication is an alternative way to offer the benefit of relaying. With the increasing interests in wireless communications, research in cooperative communication is attracting more and more attention.

Typically, two types of relaying protocols are most utilized [5], [6]. Non-regenerative RSs amplify-and-forward (AF) the received signals, while regenerative RSs decode-and-forward (DF) received signals to the destination. In general, RSs are usually assumed to operate in half-duplex mode where the relay transmissions are carried out in two steps [7]: source to relay and then relay to destination. Both steps require appropriate time/spectral resource allocation, which leads to a certain penalty to the overall link spectral efficiency. A cross layer methodology for calculating network throughput and area-averaged spectral efficiency (AASE) was presented in [8], whose results showed that the additional time and/or frequency resources required by relaying may result in poorer system throughput and AASE.

Another challenge for cooperative relay network is the relay selection criterion where several schemes have been proposed in literature. The *Best Relay Selection* selects the relay whose path has the maximum SNR [9]- [12]. The *Nearest Neighbor Selection* selects the relay that is the nearest to the source node [13], [14]. The *Best Worse Channel Selection* focuses on dual-hop protocols where each relay has two channels: the channel from source to relay and the channel from relay to destination. The relay is selected in a "*Max-Min*" fashion [14], [15]. The *Best Harmonic Mean Selection* chooses the relay with the largest harmonic mean of the two channels' magnitudes [15], [16]. Moreover, many cross-layer relay selections are proposed based on these schemes. A load-based relay selection algorithm was proposed in [17] to adjust the transmission mode (direct or relay transmission mode) in order to make the long-term average data rate of relay and direct links equal. A location-based relay selection scheme was proposed in [18] that maximizes the Medium Access Control (MAC) layer throughput by jointly optimizing relay selection and relay transmit power.

In this paper, we investigate the ASE in a three-node cooperative network with opportunistic relaying. First, we provide a transmission mode selection criterion based on the *Best Worse Channel Selection* to determine whether direct transmission or relay transmission should be used. We then obtain the instantaneous ASE of this three-node network through statistical analysis with the consideration of these two transmission mode. Finally, the optimal location of the relay node is given with respect to the performance metric of ASE.

The remainder of this paper is organized as follows. Section II presents the system model. Based on the model, mathematical analysis of ASE is given in Section III. Numerical examples are presented in Section IV with related discussion.

## II. System and Channel Models

### A. System Model

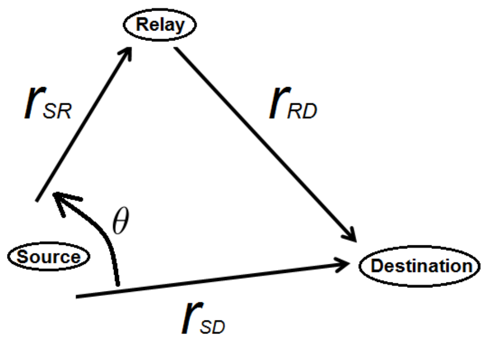


Fig. 1. Network Architecture.

As shown in Fig. 1, we consider a cooperative network that consists of three nodes: the source, the destination and the relay. The source node can communicate with the destination node via the direct link, whose distance is $r_{SD}$, or with the help of the relay node. The distances from source to relay and relay to destination are denoted by $r_{SR}$ and $r_{RD}$, respectively. We assume that the relay transmissions are half-duplex, that is, a relay node cannot transmit and receive in the same time slot. In addition, the relay node employs the *decode-and-forward* (DF) scheme. In the first time slot, we assume the relay can always successfully receive and decode the transmission from the source. Then in the following time slot, relay re-encodes the received signal and forwards it to the destination. All the transmissions from the source and relay are assumed to take place in a time division multiplex approach with *fixed time allocation* scheme, where the durations of the time slots are equal.

We consider the effect of deterministic path loss and multipath fading in the following analysis. With the simplified path-loss model, the received signal power can be expressed as [19]:

$$P_{\text{Rx}} = P_{\text{Tx}}/PL(r), \tag{1}$$

where $PL(r)$ is the path loss and can be modeled as:

$$PL(r) = kr^a, \tag{2}$$

where $k$ is a constant parameter and $a$ is the path loss exponential, ranging from 2 to 6.

We assume that the transmission also experiences slow Rayleigh fading. The PDF of received signal power at distance $r$ over Rayleigh fading channel is given by:

$$f_{\text{P}}(p|r) = \frac{1}{\bar{p}(r)} e^{-\frac{p}{\bar{p}(r)}}, \tag{3}$$

where $\bar{p}(r)$ is the average received signal power at distance $r$ decided by path loss. For the sake of simplicity, we ignore the effect of shadowing in the analysis.

We also assume that accurate estimation of the received signal to noise ratio (SNR) can be obtained and sent back to the source and relay via an error-free feedback path. The time delay in this feedback path is negligible. Thus, the source and relay can adapt their transmission rates to the actual channel state.

## III. ASE Analysis

In this section, we derive the analytical expression of ASE in a three-node cooperative network. In conventional cellular network, ASE is defined to be the average data rate per unit bandwidth per unit area supported by a base station [20]. In cooperative network, since there is no such a central base station, we redefine ASE to be the average data rate per unit bandwidth, denoted by $\overline{C}$, within a particular area that blocks other simultaneous transmission, denoted by $A_{\text{block}}$, i.e.:

$$\text{ASE} = \frac{\overline{C}}{A_{\text{block}}}. \tag{4}$$

Since the source node can communicate with the destination node via direct link or relay link, to maximize the average network capacity, we provide a selection criterion to choose the transmission mode with larger instantaneous capacity.

In particular, the instantaneous capacity of direct transmission mode is given by:

$$C_d = \log_2(1 + \gamma_{SD}), \tag{5}$$

where $\gamma_{SD}$ is the received SNR at the destination, whose PDF is given by:

$$f_{\gamma_{SD}}(\gamma) = \frac{1}{\bar{\gamma}_{SD}} e^{-\gamma/\bar{\gamma}_{SD}} = \lambda_{SD} e^{-\lambda_{SD}\gamma}, \tag{6}$$

where $\bar{\gamma}_{SD} = \frac{1}{\lambda_{SD}}$ is the average received SNR at the destination node from the source node. According to (1) and (2), the average received SNR can be written as:

$$\bar{\gamma}_{SD} = \frac{P_{\text{Tx}}}{k \cdot r_{SD}^a}. \tag{7}$$

To block the simultaneous transmission in the area, we utilize the *RTS/CTS* scheme in 802.11 protocol [21]. In direct transmission mode, the source node first sends a RTS frame to the destination node. The destination node returns a CTS frame with transmission power $P_{\text{CTS}}$ to the source node, meanwhile, all the terminals that receive the CTS frame cannot transmit over the same channel. Thus, the blocked area $A_{\text{block}}$ refers to the area that the CTS frame covers and determined by $P_{\text{CTS}}$. In order to accommodate more simultaneous transmission in a particular region, the destination node should limit the transmission power $P_{\text{CTS}}$ to minimize the blocked area. Apparently, the minimum blocked area is determined by the distance between the source node and destination/relay node. Thus, in direct transmission mode, the blocked area for the source node is $A_{\text{block}}^{SD} = \pi r_{SD}^2$.

In relay transmission mode, the data to a destination node needs to be transmitted over the same bandwidth in two time slots. Therefore, the achieved data rate to the final destination with relay transmission is half of the minimum of the capacities of source to relay and relay to destination links. Accordingly, the instantaneous capacity of relay transmission mode is given by:

$$C_r = \frac{1}{2}\min\{\log_2(1+\gamma_{SR}), \log_2(1+\gamma_{RD})\}, \tag{8}$$

where $\gamma_{SR}$ and $\gamma_{RD}$ are the received SNRs at the relay node and destination node respectively, whose PDFs are given by:

$$f_{\gamma_{SR}}(\gamma) = \frac{1}{\bar{\gamma}_{SR}}e^{-\gamma/\bar{\gamma}_{SR}} = \lambda_{SR}e^{-\lambda_{SR}\gamma}, \tag{9}$$

$$f_{\gamma_{RD}}(\gamma) = \frac{1}{\bar{\gamma}_{RD}}e^{-\gamma/\bar{\gamma}_{RD}} = \lambda_{RD}e^{-\lambda_{RD}\gamma}, \tag{10}$$

where $\bar{\gamma}_{SR}$ and $\bar{\gamma}_{RD}$ are the average received SNRs at the relay and destination, given by:

$$\bar{\gamma}_{SR} = \frac{P_{\text{Tx}}}{k \cdot r_{SR}^a}, \tag{11}$$

$$\bar{\gamma}_{RD} = \frac{P_{\text{Tx}}}{k \cdot r_{RD}^a}. \tag{12}$$

As previously defined, the blocked area for the relay node is $A_{\text{block}}^{SR} = \pi r_{SR}^2$, and that for the destination node is $A_{\text{block}}^{RD} = \pi r_{RD}^2$. Note that the two transmission steps in relay transmission mode affect different areas.

### A. Transmission mode selection

In order to maximize the instantaneous capacity, we apply a capacity-based transmission mode selection criterion. When the capacity of the direct link is larger than that of the relaying link, we apply direct transmission, and vice versa. Therefore, the instantaneous capacity of this network is given by:

$$\begin{aligned} C_{\text{inst}} &= \max\{C_d, C_r\} \\ &= \frac{1}{2}\log_2\left\{\max\left\{X, Y^2\right\}\right\} = \frac{1}{2}\log_2 Z, \end{aligned} \tag{13}$$

where $Z = \max\left\{X, Y^2\right\}$, $X = \min\{(1+\gamma_{SR}), (1+\gamma_{RD})\}$ and $Y = 1+\gamma_{SD}$. The CDFs of $X$ and $Y$ are given by:

$$\begin{aligned} F_X(x) &= P\left\{\min\{(1+\gamma_{SR}), (1+\gamma_{RD})\} < x\right\} \\ &= 1 - e^{-(\lambda_{SR}+\lambda_{RD})\cdot(x-1)} \end{aligned} \tag{14}$$

$$F_Y(y) = F_{\gamma_{SD}}(y-1) = 1 - e^{-\lambda_{SD}\cdot(y-1)}. \tag{15}$$

The PDFs of $X$ and $Y$ are given by:

$$f_X(x) = (\lambda_{SR}+\lambda_{RD})e^{-(\lambda_{SR}+\lambda_{RD})\cdot(x-1)} \tag{16}$$

$$f_Y(y) = \lambda_{SD}e^{-\lambda_{SD}\cdot(y-1)}. \tag{17}$$

### B. Capacity of Direct Transmission Mode

If $X < Y^2$, we apply direct transmission. The CDF of $Z$ under the condition $X < Y^2$ is given by:

$$F_Z(\gamma|X<Y^2) = \frac{P\left\{X<\gamma, Y^2<\gamma, X<Y^2\right\}}{P\left\{X<Y^2\right\}} \tag{18}$$

where

$$\begin{aligned} &P\left\{X<\gamma, Y^2<\gamma, X<Y^2\right\} \\ =&\int_1^{\sqrt{\gamma}}\int_1^{y^2} f_{XY}(xy)\mathrm{d}x\mathrm{d}y \\ =&\int_1^{\sqrt{\gamma}}\lambda_{SD}e^{-\lambda_{SD}(y-1)}\mathrm{d}y - \lambda_{SD}\int_0^{\sqrt{\gamma}-1}e^{-(\lambda_{SR}+\lambda_{RD})(t^2+2t)-\lambda_{SD}t}\mathrm{d}t \\ =&F_Y(\sqrt{\gamma}) - \lambda_{SD}\mathfrak{R}(\sqrt{\gamma}-1;\alpha,\beta), \end{aligned}$$

where $\alpha = \lambda_{SR}+\lambda_{RD}$ and $\beta = 2\lambda_{SR}+2\lambda_{RD}+\lambda_{SD}$. According to [22, 2.33.1], we define:

$$\begin{aligned} \mathfrak{R}(x;\alpha,\beta) &\triangleq \int_0^x e^{-\alpha t^2-\beta t}\mathrm{d}t \\ &= \frac{1}{2}\sqrt{\frac{\pi}{\alpha}}e^{\frac{\beta^2}{4\alpha}}\left[\operatorname{erf}(\sqrt{\alpha}\cdot x+\frac{\beta}{2\sqrt{\alpha}}) - \operatorname{erf}(\frac{\beta}{2\sqrt{\alpha}})\right], \end{aligned}$$

where $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\mathrm{d}t$.

$P\{X<Y^2\}$ refers to the probability, $P_{\text{direct}}$, that the direct transmission is applied and is given by:

$$\begin{aligned} P_{\text{direct}} &= P\{X<Y^2\} \\ &= \int_1^{\infty}\int_1^{y^2} f_{XY}(x,y)\mathrm{d}x\mathrm{d}y \\ &= 1 - \int_1^{\infty}\lambda_{SD}e^{-\lambda_{SD}(y-1)-(\lambda_{SR}+\lambda_{RD})(y^2-1)}\mathrm{d}y \\ &= 1 - \lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta). \end{aligned} \tag{19}$$

Based on the above analysis, the CDF of $Z$ under the condition that $X<Y^2$ is given by:

$$\begin{aligned} F_Z(\gamma|X<Y^2) &= \frac{1-e^{-\lambda_{SD}(\sqrt{\gamma}-1)} - \lambda_{SD}\mathfrak{R}(\sqrt{\gamma}-1;\alpha,\beta)}{1-\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)} \\ &= \frac{F_Y(\sqrt{\gamma}) - \lambda_{SD}\mathfrak{R}(\sqrt{\gamma}-1;\alpha,\beta)}{1-\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}. \end{aligned} \tag{20}$$

Consequently, the PDF is given by:

$$\begin{aligned} f_Z(\gamma|X<Y^2) &= \frac{\mathrm{d}}{\mathrm{d}\gamma}F_Z(\gamma|X<Y^2) \\ &= \frac{f_Y(\sqrt{\gamma})\cdot F_X(\gamma)}{2\sqrt{\gamma}\cdot\{1-\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)\}}. \end{aligned} \tag{21}$$

The average capacity in direct transmission mode is given by:

$$\begin{aligned}\overline{C}_d &= \int_1^\infty \frac{1}{2}\log_2\gamma \cdot f_Z(\gamma|X<Y^2)\mathrm{d}\gamma \\ &= \int_1^\infty \frac{1}{2}\log_2\gamma \cdot \frac{f_Y(\sqrt{\gamma})\cdot F_X(\gamma)}{2\sqrt{\gamma}\cdot\{1-\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)\}}\mathrm{d}\gamma \\ &= \frac{1}{\ln 2}\cdot\frac{1}{1-\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}\Big\{e^{\lambda_{SD}}\,\mathrm{E}_1(\lambda_{SD}) \\ &\quad - \int_1^\infty \lambda_{SD}\ln(\gamma)e^{-(\lambda_{SR}+\lambda_{RD})(\gamma^2-1)-\lambda_{SD}(\gamma-1)}\mathrm{d}\gamma\Big\}.\end{aligned} \tag{22}$$

### C. Capacity of Relay Transmission Mode

If $X > Y^2$, we apply relay transmission. The CDF of $Z$ under the condition that $X > Y^2$ is given by:

$$\begin{aligned}&F_Z(\gamma|X>Y^2) \\ =& \frac{P\Big\{X<\gamma, Y^2<\gamma, X<Y^2\Big\}}{P\Big\{X>Y^2\Big\}},\end{aligned}$$

where

$$\begin{aligned}&P\Big\{X<\gamma, Y^2<\gamma, X>Y^2\Big\} \\ =& \int_1^{\sqrt{\gamma}}\int_{y^2}^{\gamma} f_{XY}(xy)\mathrm{d}x\mathrm{d}y \\ =& \int_1^{\sqrt{\gamma}}\Big\{e^{-(\lambda_{SR}+\lambda_{RD})(y^2-1)} \\ &\quad - e^{-(\lambda_{SR}+\lambda_{RD})(\gamma-1)}\Big\}\lambda_{SD}e^{-\lambda_{SD}(y-1)}\mathrm{d}y \\ =& \lambda_{SD}\mathfrak{R}(\sqrt{\gamma}-1;\alpha,\beta) - [1-F_X(\gamma)]\cdot F_Y(\sqrt{\gamma}).\end{aligned} \tag{23}$$

$P\{X > Y^2\}$ refers to the probability, $P_{\text{relay}}$, that the relay transmission is applied and is given by:

$$\begin{aligned}P_{\text{relay}} &= P\{X>Y^2\} \\ &= \int_1^\infty\int_{y^2}^\infty f_{XY}(x,y)\mathrm{d}x\mathrm{d}y \\ &= \int_1^\infty e^{-(\lambda_{SR}+\lambda_{RD})(y^2-1)}\cdot\lambda_{SD}e^{-\lambda_{SD}(y-1)}\mathrm{d}y \\ &= \lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta).\end{aligned} \tag{24}$$

Based on the above analysis, the CDF of $Z$ under the condition that $X > Y^2$ is given by:

$$\begin{aligned}&F_Z(\gamma|X>Y^2) \\ =& \frac{\lambda_{SD}\mathfrak{R}(\sqrt{\gamma}-1;\alpha,\beta) - [1-F_X(\gamma)]\cdot F_Y(\sqrt{\gamma})}{\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}.\end{aligned} \tag{25}$$

The PDF is then given by:

$$\begin{aligned}f_Z(\gamma|X>Y^2) &= \frac{\mathrm{d}}{\mathrm{d}\gamma}F_Z(\gamma|X>Y^2) \\ &= \frac{f_X(\gamma)\cdot F_Y(\sqrt{\gamma})}{\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}.\end{aligned} \tag{26}$$

The average capacity in relay transmission mode is given by:

$$\begin{aligned}\overline{C}_r &= \int_1^\infty \frac{1}{2}\log_2\gamma \cdot f_Z(\gamma|X>Y^2)\mathrm{d}\gamma \\ &= \int_1^\infty \frac{1}{2}\log_2\gamma \cdot \frac{f_X(\gamma)\cdot F_Y(\sqrt{\gamma})}{\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}\mathrm{d}\gamma \\ &= \frac{1}{\ln 2}\cdot\frac{1}{\lambda_{SD}\mathfrak{R}(\infty;\alpha,\beta)}\Big\{e^{\lambda_{SR}+\lambda_{RD}}\,\mathrm{E}_1(\lambda_{SR}+\lambda_{RD}) \\ &\quad - \int_1^\infty \lambda_{SD}\ln(\gamma)e^{-(\lambda_{SR}+\lambda_{RD})(\gamma-1)-\lambda_{SD}(\sqrt{\gamma}-1)}\mathrm{d}\gamma\Big\}.\end{aligned} \tag{27}$$

### D. Total ASE

With the definition of ASE as well as the equation (22) and (27), we can arrive at ASE of this three-node network, which is given by:

$$\text{ASE} = P_{\text{direct}}\cdot\frac{\overline{C}_d}{A_{\text{block}}^{SD}} + P_{\text{relay}}\cdot\frac{1}{2}\left(\frac{\frac{1}{2}\overline{C}_r}{A_{\text{block}}^{SR}} + \frac{\frac{1}{2}\overline{C}_r}{A_{\text{block}}^{RD}}\right) \tag{28}$$

where $P_{\text{direct}}$ and $P_{\text{relay}}$ are defined in (19) and (24).

## IV. Numerical Example

In this section, we show some numerical examples for the three-node cooperative network under study. The system parameters are listed in Table I.

TABLE I
SYSTEM PARAMETERS

| | |
|---|---|
| Transmission power $P_{\text{Tx}}$ | 19 dBm |
| $r_{SD}$ | 1000 m |
| Path-loss exponent $\alpha$ | 4 |
| Path-loss constant $k$ | 0.31 |
| Noise power $N$ | -100 dBm |

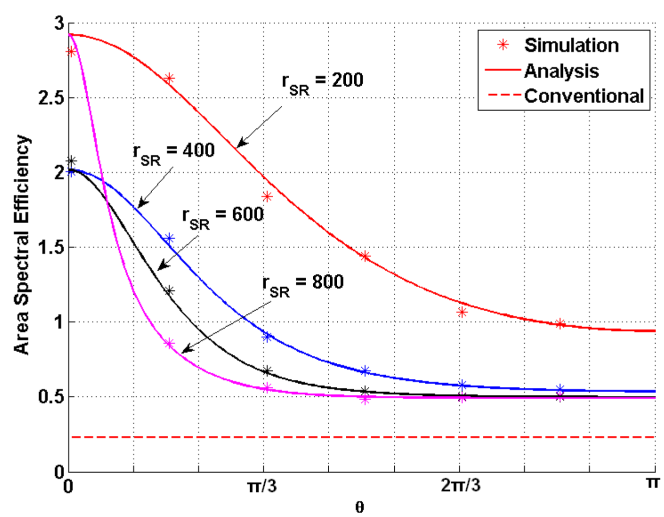


Fig. 2. The effect of the angle between source-destination and source-relay with different $r_{SR}$.

In Fig. 2, we plot ASE as a function of $\theta$, the angle between source-destination and source-relay. Meanwhile, we plot ASE of the conventional network, which is given by:

$$\mathrm{ASE}_{\mathrm{conv}} = \frac{C_{\mathrm{conv}}}{A_{\mathrm{block}}^{SD}}, \tag{29}$$

where $C_{\mathrm{conv}}$ is the average capacity for the conventional network, which is given by:

$$C_{\mathrm{conv}} = \int_0^{\infty} \log_2(1+\gamma) \cdot f_{\gamma_{SD}}(\gamma) \mathrm{d}\gamma. \tag{30}$$

The figure shows that ASE performance of the three-node cooperative network is always better than that of the conventional network. The reason is that: on one hand, since we apply a transmission selection criterion on the relay-assisted network, the relay transmissions always improve the total capacity of the network; on the other hand, both phrases of the relay transmission enjoy a smaller blocked area compared with the direct transmission. Furthermore, as $\theta$ increases from 0 to $\pi$, ASE of the three-node cooperative network decreases, especially for the case where the relay node is far from the source node. The peak of ASE appears at $\theta = 0$, which means the source, relay and destination nodes are all located on a straight line.

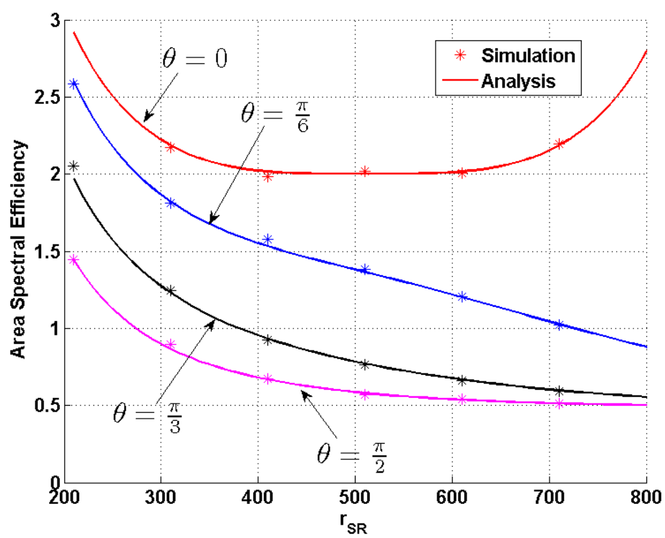


Fig. 3. The effect of distance between source and relay with different $\theta$.

In Fig. 3, we plot ASE as a function of $r_{SR}$, the distance between the source and the relay node. An interesting observation is that when $\theta = 0$, the curve appears to be symmetrical with the lowest point located at the midpoint of the line between the source and the destination. This implies that when $\theta = 0$, the best relay node location should be either close to the source node or to the destination node. This observation can also be justified from Fig. 2 where two curves in pair arrive at the same point when $\theta = 0$. However, if $\theta$ is larger than 0, ASE decreases as the distance between the source and the relay increases.

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