# Optimal Relaying Strategy for UE Relays

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***Abstract*—In cooperative cellular wireless networks, a user equipment (UE) relay can be a good alternative to rendering an end user by forwarding the signal overheard from the source to the end user. However, due to its practical limitation, it has no cell-specific reference signal. Therefore, different from conventional fixed relay station, the channel state information (CSI) is not available to the UE relay. Since the UE relay cannot estimate relay-to-destination (R-D) channel capacity, there arises the possibility of an outage event in cooperating phase. In this paper, we introduce an outage based rate control under multiple relay networks in which there are one source, multiple UE relays and one end user. To achieve maximal overall transmission rate, resource allocation during the cooperating phase is done at the source in advance by considering both the expected transmission rate and the resulting outage probability. Especially we consider three cases of relaying strategies in such open-loop R-D links and observe that they complement each other depending on the R-D link geometry and channel conditions, leading to optimal relaying strategy for UE relays.**

***Index Terms*—UE relay, outage based rate control, open-loop transmission, optimal relaying strategy.**

## I. INTRODUCTION

End users which are far from the base station usually experience poor signal-to-noise ratio (SNR), so their links could be weak and unacceptable. To overcome this issue, relays, either fixed or mobile, emerge as the most promising communications technology to increase the cell coverage and the transmission rate recently. One distinct feature of fixed versus mobile relays is whether it has cell-specific reference signal or not, that is used for the channel measurement. In this paper, we are interested in UE relay case which has not a cell-specific reference signal, so that the relay-to-destination (R-D) link transmission should be operated in open-loop mode. Except such a weakness, UE relay is cheap and has the potential to improve transmission rate, and hence UE relay can be a good alternative for next generation cellular systems.

Fig. 1 illustrates the characteristics of such UE relay and how to operate in cooperative cellular wireless networks. As seen in the figure, UE relay cannot create a new cell because of no cell-specific reference signal [1], [2].

Prior works on fixed relay communications, they usually assumed that the channel state information (CSI) is available at the transmitter [3]. Then, all transmissions can be scheduled with an exact rate control, in which case the transmitter does not have to consider an outage event. However, since the UE relaying is operated in open-loop mode as explained above, we may consider a proactive scheduling at the source to pre-allocate the resource (time/frequency slots) for the UE relay, taking into account the possible outage event over open-loop R-D link. To realize our proposed scheme, we assume that average channel statistics of R-D link (i.e., average SNR) are available at the source.

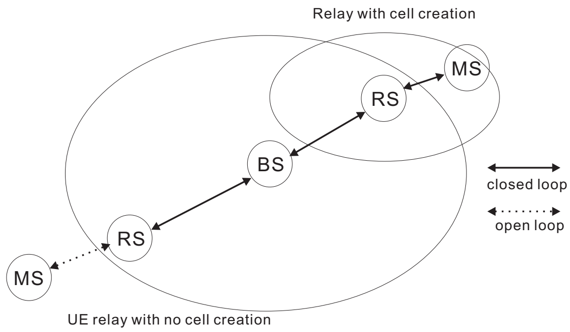


Fig. 1. The characteristics of UE relay

In case an outage event occurs over open-loop R-D link, retransmission for error recovery is requested to the UE relay. With incremental redundancy combining using two or more different data streams, only partial data that is not decoded in cooperating phase is needed for successful decoding at the destination. Hence, the overall rate control in proactive manner is performed in conjunction with hybrid ARQ to minimize the rate loss due to the outage event.

For illustration, we assume one source (BS), one end user (MS) and two UE relays (RSs). Under the multiple UE relay networks, we consider three different relaying strategies, such as best relay selection, relay cooperation and ordering. Firstly, best relay selection strategy is that a single relay with highest rate is selected to forward the signal overheard from the source. Secondly, two relays cooperate to forward the received signal using orthogonal space-time coding in relay cooperation strategy. Lastly, relays are placed in order for multi-hop transmission in relay ordering strategy. We compare them and observe that they complement each other according to different relay placements and channel conditions [4], leading to optimal relaying strategy for UE relays.

The rest of the paper is organized as follows. In Section II, we introduce the multiple UE relay network model along with relevant assumptions and some notations which are used throughout this paper. Section III describes three relaying strategies under such network model and make their analyses. Simulation results are presented in Section IV and concluding remarks are given in Section V.

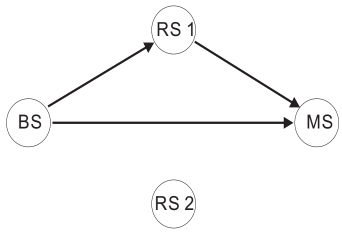


Fig. 2. Best relay selection.

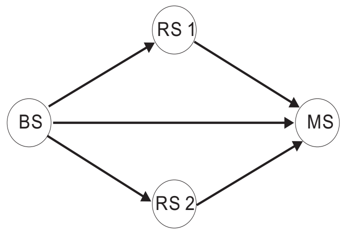


Fig. 3. Relay cooperation.

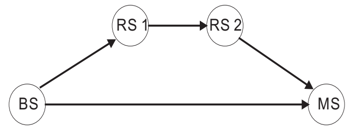


Fig. 4. Relay ordering.

## II. SYSTEM MODEL

We consider a cooperative cellular wireless network model with single BS, two RSs and single MS, as shown in Figs. 2-4. Each node is equipped with single antenna and employs half-duplex communication mode. We assume that source-to-relay (S-R) and source-to-destination (S-D) link channel gains are perfectly known to the transmitter. However, R-D link instantaneous channel gain is not available due to the UE relay limitation. Here, quasi-static fading channel is assumed where all channel gains remain constant until MS receives a block of whole data.

The maximum node error-free rate $R_{ij}$ (bits/symbol) with normalized bandwidth is given by

$$R_{ij} = \log_2(1 + \gamma_{ij}) \tag{1}$$

where $\gamma_{ij}$ is the instantaneous link SNR defined as $\gamma_{ij} = \rho_{ij}|h_{ij}|^2$ for the average link SNR $\rho_{ij}$ and the complex normalized Gaussian channel coefficient $h_{ij}$. Here, subscript $ij$ indicates $i$-to-$j$ link, for example $h_{sd}$ denotes the channel gain of S-D link.

A whole transmission is divided into two steps which are broadcasting phase and cooperating phase. In broadcasting phase, BS broadcasts the signal to RSs and MS. Then, RSs forward the received signal to MS in cooperating phase. In case of an outage event MS requests retransmission, in the form of incremental relaying, namely hybrid ARQ.

## III. OPTIMAL RELAYING STRATEGY

We now turn our attention to the outage based rate control where two RSs coexist between BS and MS. We discuss three different relaying strategies to forward the signal overheard in between BS and MS and how we can formulate each strategy. As the primary focus of our analysis is on R-D link transmission in open-loop mode, we concentrate on downlink transmission for which BS performs resource scheduling over open-loop R-D links in proactive manner.

### *A. Best relay selection*

In open-loop R-D link operation, the best relay selection strategy is to maximize the expected transmission rate via a chosen relay subject to the outage probabilities in the cooperating phases when hybrid ARQ is employed for error recovery. In this case, one of two RSs is chosen to forward the received signal, and the other RS keeps quiet during the whole transmission. Fig. 2 shows an overall transmission. In broadcasting phase, the source (BS) broadcasts the signal to the UE relays (RS $i$, $i = 1, 2$) and destination (MS), and the data rates over S-R and S-D links are formulated as

$$R_{sr} = \log_2(1 + \gamma_{sr}), \quad R_{sd} = \log_2(1 + \gamma_{sd}). \tag{2}$$

Next, the chosen RS forwards the received signal to MS over open-loop R-D link. Let define $T_2$ as the variable second hop time compared to $T_1 = 1$ as the normalized first hop time, then the outage probability of R-D link in the second hop can be evaluated as

$$\begin{aligned} R_{rd} &= \log_2(1 + \rho_{rd}|h_{rd}|^2) \\ P_{out}^{rd} &= \Pr\left[R_{rd} < \frac{R_{sr} - R_{sd}}{T_2}\right] \\ &= \Pr\left[|h_{rd}|^2 < \frac{2^{(R_{sr}-R_{sd})/T_2} - 1}{\rho_{rd}}\right] \\ &= \int_0^{\frac{2^{(R_{sr}-R_{sd})/T_2 - 1}}{\rho_{rd}}} e^{-x}\,dx \\ &= 1 - \exp\left[-\left(2^{(R_{sr}-R_{sd})/T_2} - 1\right)/\rho_{rd}\right] \end{aligned} \tag{3}$$

where $\rho_{rd}$ denotes the selected R-D link average SNR. Here we have assumed that MS can receive the data with rate $R_{sd}$ in the first hop, and the incremental redundancy $(R_{sr} - R_{sd})$ is required to decode a whole block of data.

Since retransmission may be requested from MS when an outage event occurs over R-D link, we also need to design the outage based rate control in conjunction with hybrid ARQ (H-ARQ). Previously we have assumed that the channel gain would not change during a whole transmission, and we can derive the outage probability by adopting $T_3$ as retransmission time in the third hop as

$$\begin{aligned} P_{out}^{H-ARQ} &= \Pr\left[R_{rd} < \frac{R_{sr} - R_{sd}}{T_2 + T_3} \,\middle|\, R_{rd} < \frac{R_{sr} - R_{sd}}{T_2}\right] \\ &= \frac{1}{P_{out}^{rd}} \Pr\left[|h_{rd}|^2 < \frac{2^{(R_{sr}-R_{sd})/(T_2+T_3)} - 1}{\rho_{rd}}\right] \\ &= \frac{1}{P_{out}^{rd}}\left[1 - \exp\left(-\frac{2^{(R_{sr}-R_{sd})/(T_2+T_3)} - 1}{\rho_{rd}}\right)\right]. \end{aligned} \tag{4}$$

Note that the outage probability of H-ARQ procedure is defined by the conditional probability because H-ARQ is contingent upon the outage occurring in the second hop.

Now, using the above results, the expected transmission rate of best relay selection strategy $R_{best}$ can be evaluated as

$$R_{best} = \frac{R_{sr}}{1+T_2}\left(1 - P_{out}^{rd}\right) + \frac{R_{sr}}{1+T_2+T_3}\, P_{out}^{rd} \times \left(1 - P_{out}^{H-ARQ}\right). \quad (5)$$

The best relay is then pre-selected to maximize the above transmission rate. Also, forwarding and retransmission hop times $T_2$ and $T_3$ can be optimized in (5). It is to be noted that as the transmission time gets longer, the outage probability becomes lower, or vice versa. Therefore, the transmission times $T_2$ and $T_3$ should be carefully optimized to balance the outage probability and the transmission time [5].

The best relay selection is the simplest relaying strategy than the others that we discuss below. Since only the selected R-D link channel gain appears random to the transmitter, the procedure for finding optimal transmission times is rather simple, which allows for the proactive scheduling at BS.

### B. Relay cooperation

The two RSs cooperate to forward the received signal to MS, using ideal orthogonal space-time transmission approach. Fig. 3 describes the structure of transmission. To satisfy the total power constraint, we define $\beta$ as a power division factor between the two relays. Since both relays need to be ready for forwarding the signal before the cooperating phase, $R_{sr}$ should be set by the minimum S-R link SNR as

$$R_{sr} = \log_2\left[1 + \min(\gamma_{s,r1}, \gamma_{s,r2})\right]. \quad (6)$$

In cooperating phase, the achievable rate of open-loop R-D link through relay cooperation is defined as

$$R_{rd} = \log_2\left[1 + (1-\beta)\rho_{r1,d}|h_{r1,d}|^2 + \beta\rho_{r2,d}|h_{r2,d}|^2\right]. \quad (7)$$

Then, the outage probability with relay cooperation can be formulated as

$$\begin{aligned}
P_{out}^{rd} &= \Pr\Big[(1-\beta)\rho_{r1,d}|h_{r1,d}|^2 + \beta\rho_{r2,d}|h_{r2,d}|^2 \\
&\qquad < 2^{(R_{sr}-R_{sd})/T_2} - 1\Big] \\
&= \int_0^{2^{(R_{sr}-R_{sd})/T_2}-1} \int_0^{2^{(R_{sr}-R_{sd})/T_2}-1-y} \\
&\qquad \frac{1}{(1-\beta)\rho_{r1,d}}\, e^{-\frac{x}{(1-\beta)\rho_{r1,d}}}\, \frac{1}{\beta\rho_{r2,d}}\, e^{-\frac{y}{\beta\rho_{r2,d}}}\, dx\, dy \\
&= 1 - \exp\left[-\frac{2^{(R_{sr}-R_{sd})/T_2}-1}{\beta\rho_{r2,d}}\right] \\
&\quad - \frac{(1-\beta)\gamma_{r1,d}}{\beta\gamma_{r2,d}-(1-\beta)\gamma_{r1,d}} \exp\left[-\frac{2^{(R_{sr}-R_{sd})/T_2}-1}{(1-\beta)\rho_{r1,d}}\right] \\
&\quad \times \exp\left[\frac{\beta\rho_{r2,d}-(1-\beta)\rho_{r1,d}}{\beta(1-\beta)\rho_{r1,d}\rho_{r2,d}}\left(2^{(R_{sr}-R_{sd})/T_2}-1\right)\right].
\end{aligned} \quad (8)$$

Similarly as in the previous case, the outage probability for hybrid ARQ in the third hop can be derived as

$$P_{out}^{H-ARQ} = \frac{1}{P_{out}^{rd}} \times P_{out}^{rd}\Big|_{T_2 \to (T_2+T_3)}. \quad (9)$$

Also, the expected transmission rate of relay cooperation strategy $R_{coop}$ can be evaluated in (5) upon substitution of $P_{out}^{rd}$ and $P_{out}^{H-ARQ}$ above. At the same time, the transmission times $T_2$ and $T_3$, and the power division factor $\beta$ are jointly optimized in (5). In relay cooperation strategy, since the two relays cooperate to forward the received signal, higher diversity gain is expected. However, it incurs the rate loss as relays are waiting until all relays receive the signal [6], especially when there exist asymmetric S-R links.

### C. Relay ordering

With this cooperative strategy, the signal is sent through multi-hop transmission as shown in Fig. 4. In broadcasting phase, BS broadcasts the signal to RSs and MS, and the relay with higher S-R link SNR is chosen as RS1. The data rate in broadcasting phase is determined such that RS1 can decode the received data fully as $R_{s,r1} = \log_2(1+\gamma_{s,r1})$. After decoding, RS1 forwards the received signal to RS2 whose S-R link SNR is relatively lower. Since RS1-to-RS2 link transmission is also operated in open-loop mode, the corresponding outage probability is evaluated as

$$\begin{aligned}
P_{out}^{r1,r2} &= \Pr\left[R_{r1,r2} < (R_{s,r1} - R_{s,r2})/T_2\right] \\
&= \Pr\left[\log_2\left(1 + \rho_{r1,r2}|h_{r1,r2}|^2\right) < (R_{s,r1} - R_{s,r2})/T_2\right] \\
&= \Pr\left[|h_{r1,r2}|^2 < \frac{2^{(R_{s,r1}-R_{s,r2})/T_2} - 1}{\rho_{r1,r2}}\right] \\
&= 1 - \exp\left[-\left(2^{(R_{s,r1}-R_{s,r2})/T_2} - 1\right)/\rho_{r1,r2}\right].
\end{aligned} \quad (10)$$

Note that RS2 has received the data with rate $R_{s,r2}$ in the first hop, and the incremental redundancy $(R_{s,r1} - R_{s,r2})$ needs to be sent in the second hop.

Once RS2 has decoded the full data in the second hop, then forwards it to MS. Since MS has received the data from BS and RS1 in the first and second hop, respectively, the incremental redundancy $(R_{sr1} - R_{sr2} - R_{sd})$ is required for full decoding at MS. Therefore, the outage probability with relay ordering can be evaluated as

$$\begin{aligned}
a &= \frac{2^{(R_{s,r1}-R_{sd})/T_2} - 1}{\rho_{r1,d}} \\
b(x) &= \frac{2^{(R_{s,r1}-R_{sd})/T_3}(1+\rho_{r1,d}x)^{T_3/T_2} - 1}{\rho_{r2,d}} \\
P_{out}^{rd} &= \Pr\left[R_{r1,d}T_2 + R_{r2,d}T_3 < R_{s,r1} - R_{sd}\right] \\
&= \Pr\Big[T_2\log_2\left(1+\rho_{r1,d}|h_{r1,d}|^2\right) \\
&\qquad + T_3\log_2\left(1+\rho_{r2,d}|h_{r2,d}|^2\right) < R_{s,r1} - R_{sd}\Big] \\
&= \int_0^a \int_0^{b(x)} e^{-x} e^{-y}\, dy\, dx \\
&= 1 - e^{-a} - \int_0^a e^{-x-b(x)}\, dx
\end{aligned} \quad (11)$$

Similarly, the outage probability for hybrid ARQ in the fourth hop is given as

$$P_{out}^{H-ARQ} = \frac{1}{P_{out}^{rd}} \times P_{out}^{rd}\Big|_{T_3 \to (T_3+T_4)}. \quad (12)$$

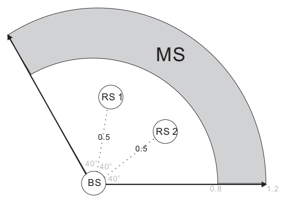


Fig. 5. Random RS placement: Two RSs are randomly located in the shaded area.

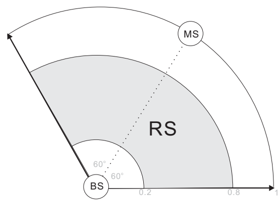


Fig. 6. Random MS placement: MS is randomly located in the shaded area

Using the results in (10) - (12), the expected transmission rate for relay ordering strategy $R_{ord}$ can be evaluated as

$$R_{ord} = \frac{R_{s,r1}}{1+T_2+T_3}\left(1-P_{out}^{r1,r2}\right)\left(1-P_{out}^{rd}\right) + \frac{R_{s,r1}}{1+T_2+T_3+T_4}\left(1-P_{out}^{r1,r2}\right)P_{out}^{rd} \times \left(1-P_{out}^{H-ARQ}\right). \quad (13)$$

Here, the transmission times $T_2$, $T_3$ and $T_4$ can be jointly optimized by maximizing the overall transmission rate in (13). Note that the error recovery of RS1-to-RS2 link was not reflected in (13) for tractable analysis, but the analysis can be made in the same way as for the open-loop R-D link, though complicated. This implies that we still have room to reduce the outage probability. Also, we notice that this strategy is useful especially in case that one relay is closer to BS and the other is nearer to MS, so that it is easy to realize multi-hop transmission. But, to evaluate the expected transmission rate, the random variables which are R1-R2, R1-D and R2-D link channel gains should be considered. Therefore, this strategy involves the most complex optimization problem in determining the transmission times.

### D. Summary

Before BS transmits the signal, an optimal relaying strategy and associated resource parameters (transmission times and power division factor) are determined in proactive manner to maximize the expected overall transmission rate between BS and MS. In other words, the source schedules not only the relaying strategy but also the resource (time/frequency slots) jointly. As we are mainly concerned with the time-division multiplexing (TDM) based cooperative networks, it is a crucial issue to allocate a proper time slot for each hop. Further, using some useful codes (e.g., universal code [7]), the receiver is allowed to gain information for full decoding through the accumulation of incremental redundancy within its link capacity. Therefore, hybrid ARQ with incremental redundancy relaying can be realized by using those codes.

## IV. Results

To gain insights into the effect of R-D link geometry and channel conditions on the achievable rate, we consider two cooperative cellular wireless network models as exemplified in Figs. 5 and 6. In the network models, the path loss coefficient is assumed to be three, the average link SNR of $i$-to-$j$ node is given by $\rho_{ij} = 1/(\sigma^2 d_{ij}^3)$ for the noise variance $\sigma^2$ and distance of $i$-to-$j$ node $d_{ij}$.

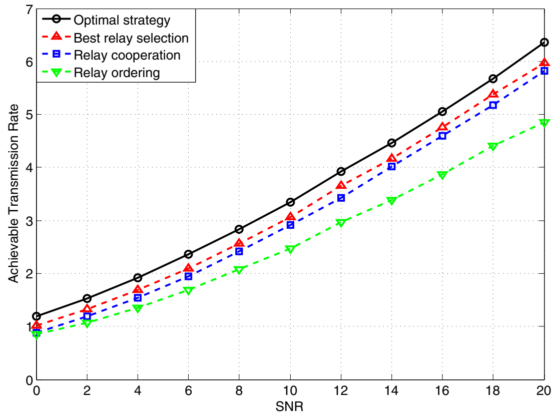


Fig. 7. The achievable transmission rate for random RS placement.

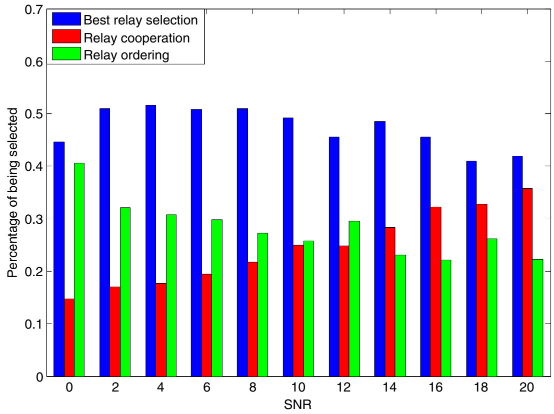


Fig. 8. Relative frequency of relaying strategies for random RS placement.

First, RSs are randomly located in the shaded area and MS is fixed in the middle of unit-length arc, as shown in Fig. 5. Thus, the path loss of each link randomly varies depending on RSs location. The achievable rate and relative frequency of relaying strategies for the above exemplary random RS placement are shown in Figs. 7 and 8, respectively. The achievable rates of three relaying strategies, and the optimal one as well are shown in Fig. 7. Here, the optimal relaying strategy is defined as the best one at each realization of a set of instantaneous channel gains in simulation. X-axis denotes the nominal SNR given by $1/\sigma^2$. We see that the optimal relaying strategy yields a noticeable performance for better transmission rate. Bar graphs in Fig. 8 illustrate the relative frequency that each relaying strategy is selected. In this simulation, best relay selection strategy is the most frequently chosen because it is not much affected by RSs location.

Next, when RSs are placed in symmetric locations and MS is randomly located in the shaded area as shown in Fig. 6, the similar performance behaviors are observed in Figs. 9 and 10, which show the achievable transmission rate and relative frequency of each relaying strategy being selected,

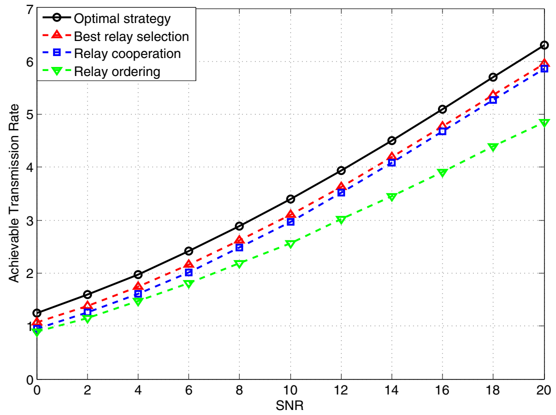


Fig. 9. The achievable transmission rate for random MS placement.

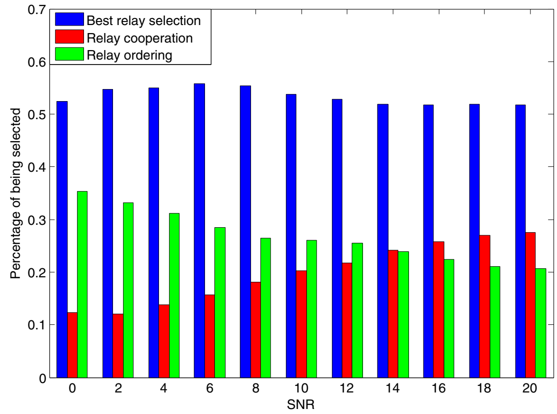


Fig. 10. Relative frequency of relaying strategies for random MS placement.

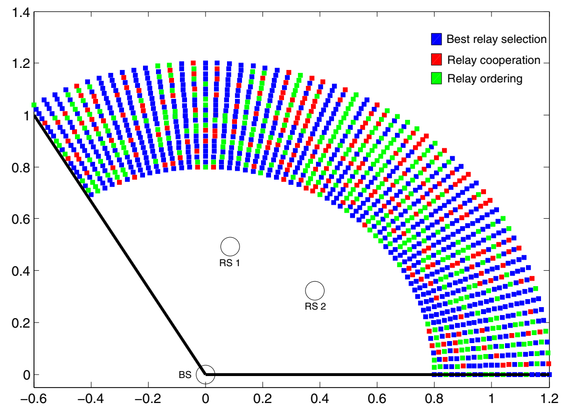


Fig. 11. The geometrical MS distribution associated with optimal relaying strategy when RSs are placed in the symmetric locations.

respectively. Here, we notice that best relay selection strategy is more likely to be chosen as the best one when compared to that under the previous random RS placement in Fig. 5. Besides Fig. 11 demonstrates the geometrical distribution that a relaying strategy is selected as the best one according to MS location. As anticipated, it is less likely to choose best relay selection strategy as the best one when MS is located around the middle of the arc, since the opposite corners exhibit the asymmetric R-D link capacity that results in enhanced diversity gain with best relay selection strategy.

In both exemplary RS placements, as the nominal SNR is higher, the relative frequency of relay cooperation strategy being selected is increased. To the contrary, relay ordering strategy is selected less frequently as the SNR becomes higher. But, we may see different performance behaviors depending on the specific network models along with R-D link geometry and channel conditions.

## V. Conclusion

We have considered a cooperative cellular wireless network with multiple UE relays in between BS and MS. We have investigated three possible relaying strategies and formulated the procedure on how to choose one of them optimally. Best relay selection is the simplest and most frequently selected strategy. Relay cooperation provides higher diversity gain for open-loop R-D link, but causes some rate loss between BS and RSs. Relay ordering is suitable for multi-hop transmission. To find an optimal relaying strategy according to R-D link geometry and channel conditions, we have compared them in terms of the achievable rate and the relative frequency of being selected under different locations of RSs and MS. Since open-loop R-D link transmission involves an outage event, we have discussed the expected transmission rate and its optimization problem to perform the proactive scheduling at the source. Further extension of our proposed framework to the case of multiple MSs will be an interesting topic for future work.

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