

Superposition Coding Relaying with Only Destination-to-Relay Channel State Feedback under Long Term Power Constraint

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Abstract—Superposition coding relaying (SC-relaying) has the merit of high throughput. At the same time, the investigation of diversity-multiplexing tradeoff (DMT) is also particularly useful for the design and analysis of cooperative relaying strategy. In this work, we consider a two-level rate SC-relaying strategy with only destination-to-relay channel state feedback (DR-CSF) under a long term power constraint. For the SC-relaying strategy with DR-CSF, the allocation rules of relay power SNR exponent are obtained firstly. With the power exponent allocation rules, the DMT of additional signal is investigated as well as its optimizing close-form solution.

Keywords—wireless cooperative relaying, superposition coding, diversity-and-multiplexing tradeoff

I. INTRODUCTION

Cooperative relaying has been shown to be a practical technique to enhance the performance of wireless networks [1]-[4]. Recently, with the increasing demand in wireless communications, the research on cooperative relaying is attracting a great deal of attention.

Varieties of cooperative schemes have been proposed with different design issues and channel information assumption. Among these schemes, two of the most famous ones are amplify-and-forward (AF) and decode-and-forward (DF) [1]. For most pioneer AF schemes, every relay cooperates and each relay uses maximal transmit power. This is an analog method that results in noise amplification. For most DF schemes, whether a relay decodes only depends on the quality of the channel between the relay and the transmitters, and the relay does not send any information to the destination if the relay can not decode the source information correctly. As a result, this method does not makes full use of all the resources available in system, and hence causes some loss in performance. Based on these cooperative strategies, a variety of cooperative coding strategies have also been widely researched. Among these coding cooperative relaying, the superposition coding strategy which was firstly presented in [5] and was further studied in [6]-[10] has been shown an effective method to not only increase the throughput (transmitting rate), but also eliminate both noise amplification and information loss at the relay.

Currently, there exist varieties of literatures focused on the superposition coding relaying (SC-relaying) [6]-[10]. However, most of the literatures are specially focused on the throughput with less consideration on the diversity-

multiplexing-tradeoff (DMT) [2][11]. In practice, the DMT plays an absolutely necessary role on the design and optimization of cooperative relaying. The objective of this work is the power allocation rules and DMT investigation on two-level rate SC-relaying strategy with only destination-to-relay channel state feedback (DR-CSF) under a long term power constraint.

II. SYSTEM MODEL

Figure 1 shows a two-level rate (R_0 , R_1) SC-relaying model with only DR-CSF under a long term power constraint. In this model, a quasi-static Rayleigh channel modeling is considered [7]. The wireless channel fading coefficient h_0 , h_1 and h_2 are independent and identically distributed (i.i.d) complex Gaussian Random variables with zero mean and unit variance.

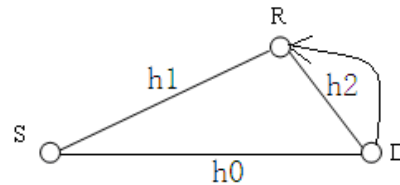


Figure 1 The SC-relaying system model with DR-CSF

In essence, SC-relaying strategy belongs to the class of Decode-and-Forward (DF) strategy [7]. In learning phase, by using 2-level rate superposition coding the source encodes basic message m_0 to sequence S_0 and additional message m_1 to sequence S_1 with rate R_0 and R_1 respectively. Therefore the signal transmitted by the source is $S=S_0+S_1$ in learning phase. In relaying phase the relay retransmits the signal received correctly and the destination listens to the relay. The superposition of information enables both the relay and the destination to decode the information successively at two different rates R_0 and R_1 [7].

In this SC-relaying cooperation scheme, because only the relay knows partially the relay-destination channel state through using the DR-CSF, the source dimension and source power SNR exponent allocations are impossible, i.e., at the source the basic signal and the additional signal are always transmitted with the constant power exponent $p_1=p$ and $q_1=1$. And in this SC-relaying system, the dimension fraction β is also a constant. But at the relay, the power exponents of both the basic signal and the additional signal are adaptable, which are denoted as p_k and q_k respectively. The DR-CSF, at the destination, is constructed based on the correct decoding of the basic signal. Thus we have [7][11]

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$$I(h_0, h_2, r_0) = \begin{cases} 1 & \text{if } \beta \log \left(1 + \frac{|h_0|^2 \text{SNR}^p}{1 + |h_0|^2 \text{SNR}} \right) + (1 - \beta) \log \left(1 + \frac{|h_2|^2 \text{SNR}^{p_k}}{1 + |h_2|^2 \text{SNR}^{q_k}} \right) < r_0 \log \text{SNR} \\ \min_{k \in (1, \dots, K)} & \text{if } \beta \log \left(1 + \frac{|h_0|^2 \text{SNR}^p}{1 + |h_0|^2 \text{SNR}} \right) + (1 - \beta) \log \left(1 + \frac{|h_2|^2 \text{SNR}^{p_k}}{1 + |h_2|^2 \text{SNR}^{q_k}} \right) \geq r_0 \log \text{SNR} \end{cases} \quad (1)$$

Where K is the resolution of feedback link, γ_0 is the multiplexing gain of basic signal. Let $p_1 < p_2 < \dots < p_K$, and $q_1 < q_2 < \dots < q_K$. Equa. (1) denotes that from a finite set $k \in (1, K)$ the destination select the minimum k so that the destination can decode basic signal S_0 reliably when the power exponent pair (p_k, q_k) is allocated at the relay. If the link is still in outage for signal S_0 with rate R_0 when the maximal available power exponent pair (p_k, q_k) is allocated, the feedback index $I(h_0, h_2, \gamma_0) = 1$ is allocated. When the relay receives the DR-CSF, the relay can adapt the power exponents of basic signal and additional signal. At the relay, a long term adaptable power constraint is adapted, which is given by [11]

$$\lim_{L \rightarrow \infty} \frac{1}{L} \sum_{l=1}^L (P_{I(h_0, h_2)} + Q_{I(h_0, h_2)}) \leq \text{SNR} \quad (2)$$

Where P_l and Q_l are the relay power allocated for signal S_0 and S_1 at the relay. Due to a long term power constraint applied, the relay power SNR exponent allocation of basic signal satisfies the following expression under the CFS $I(h_0, h_2, \gamma_0) = k$ sent back to relay from destination [11].

$$P_{I(h_0, h_2)} = \frac{\text{SNR}}{P_{\text{out}}(I(h_0, h_2, r_0) = k)} = \text{SNR}^{p_k} \quad (3)$$

$$D_k = \begin{cases} p + 1 + D_{k-1} - \frac{r_0}{1 - \beta} - \frac{r_1}{1 - \beta} & \text{if } \frac{1}{2} \leq \beta < 1 - \frac{r_1}{1 + D_{k-1} - r_0 / (1 - \beta)} \\ p - 1 - \frac{r_0}{\beta} + \frac{1}{\beta} (1 - r_1) + \left(\frac{1}{\beta} - 1 \right) D_{k-1} & \text{if } \beta \geq \max \left(\frac{1}{2}, 1 - \frac{r_1}{1 + D_{k-1} - r_0 / (1 - \beta)} \right) \end{cases} \quad (6) \quad \square$$

Obviously, in (5) the DMT characteristic of additional signal S_1 is determined by not only β but also γ_0 . Our intention is to find the optimizing close-form explicitly solution of the outage exponent. However, from (5) we find that it is difficult to find a close-form solution of the optimizing outage exponent over the channel uses fraction β because β is the function of D_k and D_k is variable with different k . Thus we can only find the approximate close-form solution taking $K \rightarrow \infty$, which indeed means the relay knows both h_0 and h_2 perfectly. At the same time, for simplicity we assume $p_1 = p = 1$. Thus the asymptotic close solution is given by Theorem 2, and the proof is presented in Appendix B.

III. DMT PERFORMANCE ANALYSIS

When DMT is investigated, we have

$$R_i \doteq r_i \log \text{SNR}, P_{\text{out}}(r_i \log \text{SNR}) \doteq \text{SNR}^{-D(r_i)} \quad [2].$$

Where r_i denotes the multiplexing gain, $D(\gamma_i)$ denote the diversity gain, $i \in (0, 1)$, and P_{out} denotes the outage probability. For simplicity, we only consider the DMT characteristic of additional signal as well as its close-form optimizing expression over the channel uses fraction β . The power exponent allocation rules and the optimizing outage exponent of the additional signal are given by the theorem 1. The proof is proposed in appendix A

Theorem 1: For the two-level rate SC-relaying cooperation strategy with the DR-CSF, the power exponents constraints at the relay terminal are given by

$$p_k = 1 + D_{k-1}, \quad q_k = 1 + D_{k-1} - r_0 / (1 - \beta) \quad (4)$$

And with the power exponents, the optimizing outage exponent of additional signal S_1 with rate R_1 is

$$D_o^{\text{DRF-K}}(r) = \sup_{\beta \in [\max(0.5, r_1), 1]} \min((2 - 2r_1 / \beta), D_k) \quad (5)$$

In (4) and (5)

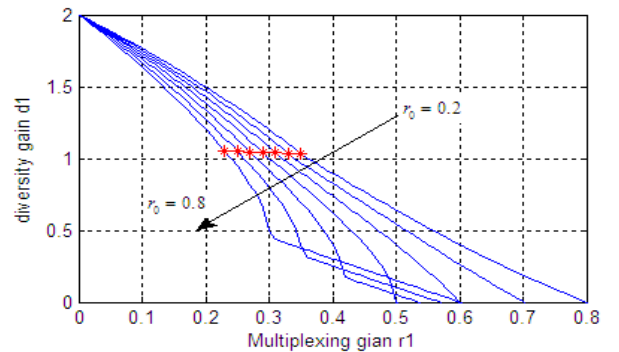


Figure 2. The asymptotical optimizing outage exponent of the SC-relaying with DR-CSF

Theorem 2: For the two-level rate SC-relaying strategy with only DR-CSF based on the correct decoding of basic

signal S_0 at the destination, when we consider the asymptotical case $K \rightarrow \infty$, a tight constraint $r_1 + r_0 \leq 1$ is required generally. The asymptotic slope solution of the optimizing outage exponent of additional signal S_1 with rate R_1 is obtained by

$$\lim_{K \rightarrow \infty} D_O^{DRF-K}(r_1) = \begin{cases} 2 - \frac{4r_1}{2 - r_1 - r_0} & \text{if } r_1 < \frac{2 - r_0}{5} \\ 2 - \frac{16r_1}{(3 + 3r_1 - r_0) + \sqrt{(3 + 3r_1 - r_0)^2 - 32r_1}} & \text{otherwise} \end{cases} \quad (7)$$

Figure 2 shows the asymptotical optimizing DMT of the additional signal with different basic signal multiplexing gain $\gamma_0 = 0.2, 0.3 \dots$ and 0.8 . The asterisk denotes the value $\gamma_1 = (2 - \gamma_0)/5$ for different γ_0 . It is clear that the optimizing DMT decreases with the increase of γ_0 . It also shows when $\gamma_0 \leq 0.5$, the tight asymptotical constraint $r_1 + r_0 \leq 1$ is satisfied perfectly. However, when $\gamma_0 \geq 0.5$ the constraint can be slacked. With this figure, the maximal scope of r_1 is $0.5 \sim 0.6$ when $\gamma_0 > 0.5$.

IV. CONCLUSION

In this work, we have considered a two-level rare SC-relaying strategy with only the DR-CSF under a long power constraint. The research method employed in this work can be used to other SC-relaying strategy. For example, we can investigate the basic signal DMT of the scheme proposed in this paper. And the DR-CSF can also be constructed based on the correct decoding of the additional signal at the destination. Obviously, the DMTs of the basic signal and the additional signal are different when the scheme employed is different. For the same scheme, we can obtain the same power allocation rules.

Appendix A: The proof of Theorem 1

For this scheme, due to the existence of the simultaneous DR-CSF $I(h_0, h_2, \gamma_0)$, the outage event only happens when $I(h_0, h_2, \gamma_0) = K$. In this case, the maximal available power SNR exponent p_K and q_K are allocated to the basic signal S_0 and the additional signal S_1 respectively at the relay. With this CSF $I(h_0, h_2, \gamma_0) = K$, the outage probability of the additional information S_1 is given by

$$P_{out}(r_1 \log SNR) = P_r(Q_1) + P_r(Q_2) + P_r(Q_3)$$

Where Q_1 denotes the event that both the relay and the destination fail to decode S_1 . Thus we have [11]

$$P_r(r_1 \log SNR, Q_1) =$$

$$P_r(\beta \log(1 + |h_0|^2 SNR) < r_1 \log SNR,$$

$$\beta \log(1 + |h_1|^2 SNR) < r_1 \log SNR) = SNR^{-D_1}$$

This leads to $D_1 = 2(1 - r_1 / \beta)$

And Q_2 denotes both the basic signal and the additional signal can be decoded reliably at the relay. The outage probability is

$$P_r(r_1 \log SNR, Q_2) =$$

$$P_r(I = K, (\beta \log(1 + \frac{|h_1|^2 SNR^p}{1 + |h_1|^2 SNR}) \geq r_0 \log SNR, \beta \log(1 + |h_1|^2 SNR^p) \geq r_1), \quad (8)$$

$$\beta \log(1 + |h_0|^2 SNR) + (1 - \beta) \log(1 + |h_2|^2 SNR^{q_K}) < r_1 \log SNR$$

$$= P_r(I = K, \beta(1 - a_0)^{+1} + (1 - \beta)(q_K - a_2)^{+1} < r_1) = SNR^{-D_{2,K}}$$

In our scheme, we only given dimension fraction β and $p_1 = p, q_1 = 1$. However in above equation (8), the solution $D_{2,K}$ is the function of power SNR exponent q_K . So we must first get the derivations of q_K and p_K . For $I(h_0, h_2, \gamma_0) = 1$, it is given that $p_1 = p, q_1 = 1$, i.e., $P_1 = SNR^{-p}, Q_1 = SNR^{-1}$. Thus based on the definition of CSF index in (1), when the DR-CSF $I(h_0, h_2, \gamma_0) = 2$, we have

$$P(I = 2) = P_r\left(\beta \log\left(1 + \frac{|h_0|^2 SNR^p}{1 + |h_0|^2 SNR}\right) + (1 - \beta) \log\left(1 + \frac{|h_2|^2 SNR^{p_2}}{1 + |h_2|^2 SNR^{q_2}}\right) \geq r_0 \log SNR, \right. \\ \left. \beta \log\left(1 + \frac{|h_0|^2 SNR^p}{1 + |h_0|^2 SNR}\right) + (1 - \beta) \log\left(1 + \frac{|h_2|^2 SNR^{p_2}}{1 + |h_2|^2 SNR^{q_2}}\right) < r_0 \log SNR\right) = SNR^{-D_{2,1}}$$

With $p_1 = p$, leading to

$$D_{2,1} = \begin{cases} 2p - r_0 / (1 - \beta) & 0.5 \leq \beta < 1 - r_0 / p \\ (p - r_0) / \beta & \beta \geq \max(0.5, 1 - r_0 / p) \end{cases}$$

Thus, according to (3) when $I(h_0, h_2, \gamma_0) = 2$, the power for basic signal S_0 is given by $P_2 = SNR^{-(1 + D_{2,1})}$, and the power SNR exponent is $p_2 = 1 + D_{2,1}$. For the power exponent q_2 of additional signal, it satisfies

$$\beta \log\left(1 + \frac{|h_0|^2 SNR^p}{1 + |h_0|^2 SNR}\right) + (1 - \beta) \log\left(1 + \frac{|h_2|^2 SNR^{p_2}}{1 + |h_2|^2 SNR^{q_2}}\right) \geq r_0 \log SNR$$

$$\beta(p - a_0 - (1 - a_0)^+) + (1 - \beta)(p_2 - a_2 - (q_2 - a_2)^+) \geq r_0$$

Thus

$$q_2 \leq p_2 - r_0 / (1 - \beta) = 1 + D_{2,1} - r_0 / (1 - \beta)$$

In order to enhance the reliability of additional signal S_1 , in above equation we take the maximum of q_2 . Continuing this recursive processing, we have the constraint relationship of power SNR exponent at the relay

$$p_k = 1 + D_{2,k-1}, \quad q_k = 1 + D_{2,k-1} - r_0 / (1 - \beta) \quad (9)$$

Thus, the outage exponent in (8)

$$D_{2,K} = \begin{cases} p + 1 + D_{2,k-1} - \frac{r_0}{1 - \beta} - \frac{r_1}{1 - \beta} & \text{if } \frac{1}{2} < \beta < 1 - \frac{r_1}{1 + D_{2,k-1} - r_0 / (1 - \beta)} \\ p - 1 - D_{2,k-1} + \frac{r_0}{1 - \beta} + \frac{1 + D_{2,k-1} - \frac{r_0}{1 - \beta} - r_1}{\beta} & \text{if } \beta \geq \max\left(\frac{1}{2}, 1 - \frac{r_1}{1 + D_{2,k-1} - r_0 / (1 - \beta)}\right) \end{cases} \quad (10)$$

And Q_3 denote only basic signal can be decoded reliably at the relay, thus

$$P_r(r_1 \log SNR, Q_3) =$$

$$P_r(I = K, \beta \log\left(1 + \frac{|h_1|^2 SNR^p}{1 + |h_1|^2 SNR}\right) \geq r_0 \log SNR, \beta \log(1 + |h_1|^2 SNR) < r_1 \log SNR,$$

$$\beta \log(1 + |h_1|^2 SNR) + (1 - \beta) \log(1 + |h_2|^2 SNR^{q_K}) < r_1 \log SNR) = SNR^{-D_{3,K}}$$

$$D_{3,K} = \begin{cases} 2 + D_{2,k-1} - \frac{r_0}{1 - \beta} - \frac{r_1}{1 - \beta} + 1 + \frac{r_1}{\beta} \\ -D_{2,k-1} + \frac{r_0}{1 - \beta} + \frac{1 + D_{2,k-1} - \frac{r_0}{1 - \beta} - r_1}{\beta} + 1 + \frac{r_1}{\beta} \end{cases}$$

Noticing that $D_{2,K} < D_{3,K}$, we take the slowest decayed term, thus we only take into account $D_{2,K}$. And $D_K = D_{2,K}$, shown in (10).

Appendix B: The proof of Theorem 2

Let $K \rightarrow \infty$ and $p_1 = p = 1$, we have $D_\infty = \lim_{K \rightarrow \infty} D_K$. The optimizing outage exponent of additional signal S_1 with rate R_1 shown in (5) can be wrote as

$$D_o^{DRF-K}(r_1) = \sup_{\beta \in [\max(0.5, r_1), 1)} \min((2 - 2r_1/\beta), D_\infty)$$

From D_K shown in (5) and (6), we find that the considering sequence D_K is increasing. Thus for any given r_1, r_0 and β , $1 - r_1/(1 + D_{K-1} - r_0/(1 - \beta))$ is a increasing function of D_{K-1} . Refer to (6), we consider the asymptotic close solution with two different case.

Case 1: Firstly, consider the case of $\beta > 1 - r_1/(1 + D_\infty - r_0/(1 - \beta))$. Because this is the increasing function of variable D_K , it is achieved that $\beta > 1 - r_1/(1 + D_{K-1} - r_0/(1 - \beta))$. Then, we have the following recursive expression of D_K with the convention $(1/\beta - 1)D_0 = r_0/\beta$.

$$D_1 = (1 - r_1)/\beta$$

$$\vdots$$

$$D_K = \left(p - 1 - \frac{r_0}{\beta} + \frac{1}{\beta}(1 - r_1) \right) \left(1 + \dots + \left(\frac{1 - \beta}{\beta} \right)^{K-2} \right) + \left(\frac{1}{\beta} - 1 \right)^{K-1} D_1$$

In (5), $\beta > 0.5$ and (6) required, the close expression of D_K

$$D_K = \left(p - 1 - \frac{r_0}{\beta} + \frac{1}{\beta}(1 - r_1) \right) \frac{1 - ((1 - \beta)/\beta)^{K-1}}{1 - ((1 - \beta)/\beta)} + \left(\frac{1}{\beta} - 1 \right)^{K-1} D_1$$

Thus $\lim_{K \rightarrow \infty} D_K = \beta(p - 1) + \frac{1 - r_1 - r_0}{2\beta - 1}$. To satisfy

$$\beta > 1 - \frac{r_1}{1 + D_{K-1} - r_0/(1 - \beta)}, \text{ we must have}$$

$$\beta > \frac{2 - r_1 - r_0}{2} \quad (11)$$

Considering the constraint $\beta \geq \max(0.5, r_1)$ and combining (11), we have $r_1 > (2 - r_0)/3$ and $r_1 + r_0 \leq 1$. That is to say, in this two-level rate SC-relaying scheme the constraint $r_1 + r_0 \leq 1$ is required generally when the asymptotical case is considered. So $(2 - r_1 - r_0)/2 > 0.5$ is always held when $r_1 + r_0 \leq 1, \forall r_1, r_0 \in (0, 1)$.

We next compute

$$D_{case1} = \sup_{\beta \in [\max(r_1, \frac{2 - r_1 - r_0}{2}), 1)} \min \left(2 \left(1 - \frac{r_1}{\beta} \right), \frac{1 - r_1 - r_0}{2\beta - 1} \right)$$

When $r_1 < \frac{2 - r_0}{5}, \forall \beta \in \left[\frac{2 - r_1 - r_0}{2}, 1 - r_0 \right)$, having

$2 - 2\frac{r_1}{\beta} > \frac{1 - r_1 - r_0}{2\beta - 1}$. Thus the optimizing maximal outage exponent is obtained by taking the minimum $\beta = (2 - r_1 - r_0)/2$. Leading to

$$D_{case1} = \frac{1 - r_1 - r_0}{2\beta - 1} = \frac{1 - r_1 - r_0}{2 - r_1 - r_0 - 1} = 1 \quad \forall r_1 < \frac{2 - r_0}{5}$$

For $r_1 \geq (2 - r_0)/5$ the maximum is always the intersection of the two component functions that lies inside $\left[\max \left(\frac{2 - r_1 - r_0}{2}, r_1 \right), 1 - r_0 \right)$. Let

$$2 - \frac{2r_1}{\beta} = \frac{1 - r_1 - r_0}{2\beta - 1}, \text{ to solve the equation, having}$$

$$\beta^* = \frac{(3 + 3r_1 - r_0) + \sqrt{(3 + 3r_1 - r_0)^2 - 32r_1}}{8}$$

And

$$D_{case1} = 2 - \frac{16r_1}{(3 + 3r_1 - r_0) + \sqrt{(3 + 3r_1 - r_0)^2 - 32r_1}}$$

Thus

$$D_{case1} = \sup_{\beta \in \left[\max \left(r_1, \frac{2 - r_1 - r_0}{2} \right), 1 - r_0 \right)} \min \left(2 \left(1 - \frac{r_1}{\beta} \right), \frac{1 - r_1 - r_0}{2\beta - 1} \right)$$

$$= \begin{cases} 1 & \text{if } r_1 < \frac{2 - r_0}{5} \\ 2 - \frac{16r_1}{(3 + 3r_1 - r_0) + \sqrt{(3 + 3r_1 - r_0)^2 - 32r_1}} & \text{if } r_1 \geq \frac{2 - r_0}{5} \end{cases}$$

Case II. Considering

$$\beta < 1 - \frac{r_1}{1 + D_\infty - r_0/(1 - \beta)} \Leftrightarrow \beta \leq \frac{2 - r_1 - r_0}{2},$$

which only happens when $r_1 < \frac{2 - r_0}{3}$. So with a fixed

r_0 and $r_1 + r_0 \leq 1$ there exists an integer $\bar{k} \in [0, \infty)$. So that

$$1 - \frac{r_1}{1 + D_{\bar{k}} - r_0/(1 - \beta)} > \beta \geq 1 - \frac{r_1}{1 + D_{\bar{k}-1} - r_0/(1 - \beta)}$$

According to the construction of D_k , we have $D_{\bar{k}+1} = 2 + D_{\bar{k}} - \frac{r_0}{1 - \beta} - \frac{r_1}{1 - \beta}$. Thus leads to

$$D_{\bar{k}+1} = D_{\bar{k}} + l \left(2 - \frac{r_0}{1 - \beta} - \frac{r_1}{1 - \beta} \right).$$

Since $\beta < \frac{2 - r_1 - r_0}{2}$, we have $2 - \frac{r_1 + r_0}{1 - \beta} > 0$.

Thus $D_\infty = \lim_{l \rightarrow \infty} D_{\bar{k}+1} = \infty$. So

$$D_{case2} = \sup_{\beta \in \left[\max\left(\frac{1}{2}, r_1\right), \frac{2-r_1-r_0}{2} \right)} \min \left(2 \left(1 - \frac{r_1}{\beta} \right), D_{\infty} \right)$$

$$= \sup \left(2 \left(1 - \frac{r_1}{\beta} \right) \right) = 2 - \frac{4r_1}{2 - r_1 - r_0}$$

With D_{case1} and D_{case2} , the result can be obtained.

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