Double Opportunistic Transmit Cooperative Relaying System with GSC in Rayleigh Fading Channels

Nam-Soo Kim[1] · Ye Hoon Lee[2]

Abstract

In a conventional opportunistic transmit (COT) cooperative relaying system, only the relays that receive signal-to-noise ratio (SNR) from the source and that exceed the threshold transmit to the destination. The COT system, however, only considers the SNR of the source-relay (S-R) path regardless that the SNR of the relay-destination (R-D) path is the opportunistic transmission condition. For that reason, it is not guaranteed that all the transmitted signals from relays exceed the threshold at the destination. Therefore we propose a double opportunistic transmit (DOT) cooperative relaying system - when both of the received SNR from a source and from a destination exceed the threshold, the relay transmits to the destination. It is shown that the proposed DOT system reduces power consumption by 6.9, 20.9, 32.4, and 41.4 % for K=3, 5, 7, and 9, respectively under the given condition of P_{out}=$1\times10^{-3}$and $\bar{\gamma}_{SR}/\Gamma_{SR}$=30 dB, compared to the COT system. We noticed that the performance of the DOT system is superior to that of the COT system for the identical number of active transmit relays under the same condition of the normalized average SNR of $\bar{\gamma}_{RD}/\Gamma_{RD}$.

Key words : Cooperative Diversity, Opportunistic Transmission, GSC, Rayleigh Fading, DOT.

Ⅰ. Introduction

Ad-hoc networks have focused on key technology for next generation wireless systems. However, the power consumption of wireless ad-hoc networks is critical to maintain network lifetime and communication reliability [1]. Recently, cooperative diversity has been applied to wireless ad-hoc networks to reduce power consumption and improve system performance by mitigating the fading effects of wireless channels [2～5].

Most cooperative diversity systems adapt opportunistic transmission with decode-and-forward (DF) relays [6, 7]. In this conventional opportunistic transmit (COT) relaying system, when the received signal-to-noise ratio (SNR) exceeds the threshold, the relay transmits. The COT system, however, only considers the SNR of the source-relay (S-R) path regardless of the SNR of the relay-destination (R-D) path.

For that reason, it cannot be guaranteed that all the transmitted signals from the opportunistic relays will satisfy the target threshold of a destination.

Moreover, the number of diversity branches (i.e., rake receiver fingers) of a receiver at a destination is usually limited. The excess number of transmit relays compared to the number of rake receiver fingers causes undue power consumption and interferes with other systems. On the other hand, fewer transmit relays cause performance degradation.

To improve system performance in fading channels, generalized selection combining (GSC) was introduced [8～10]. GSC adaptively combines L_c strong signals among L signals. If we apply GSC to the COT, the strong L_c signals received from relays are selected up to the limited number of branches and combines, which has better performance than maximal ratio combining (MRC) with arbitrary selection among L signals. However GSC requires additional power consumption to order the received signals.

In this paper, we propose a double opportunistic transmit (DOT) relaying system that considers both SNRs from S-R and R-D paths. By monitoring the received SNRs from a source and from a destination, the DOT system has the following functions by adjusting the threshold at a relay: (a) it controls the average number of transmit relays and (b) it sorts the strong signals received at the relays. With the GSC occurring at a destination in the DOT system, an equivalent performance can be achieved without additional power consumption at the destination by transferring the ordering function to the opportunistic relays.

This paper is organized as follows. Section Ⅱ provides the model of the proposed DOT relay system and

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describes the transmit protocol. The outage probability and the average number of transmit relays for the DOT system with GSC is derived in Section Ⅲ. Section Ⅳ considers some numerical examples and reviews the results. Finally, Section Ⅴ summarizes the results of this paper.

Ⅱ. COT System Model and Transmit Protocol

We begin our discussion by reviewing the system model and transmission protocol of the COT system.

2-1 COT System Model

In the general COT system, the relay that receives SNR that exceeds the predetermined threshold transmits to the destination. When amplify-and-forward (AF) or decode-and-forward (DF) relays with low SNR transmit to a destination, errors increase at that destination.

Fig. 1 shows the model of the COT relay system in which S, R, and D denote source, relay, and destination, respectively. R_k (k =1, 2, 3, ···, K) denotes the k^{th} relay. The solid lines show the source transmit step, and the dashed lines denote the relay transmit step.

We assume a DF relay. The multipath channels are assumed to be independent identically distributed (i.i.d) Rayleigh fading channels. Each signal received from R_k is independently faded and combined at D for the diversity gain [11].

2-2 COT Transmit Protocol

The COT transmit protocol has the following three steps:

a) Source transmit step: The source transmits the information to the relays. Each relay compares the received SNR to the source-relay threshold (Γ_{SR}).
b) Relay transmit step: When the received SNR exceeds Γ_{SR}, then the relays transmit.
c) Diversity combining step: The multipath signals are received at D and are diversity combined.

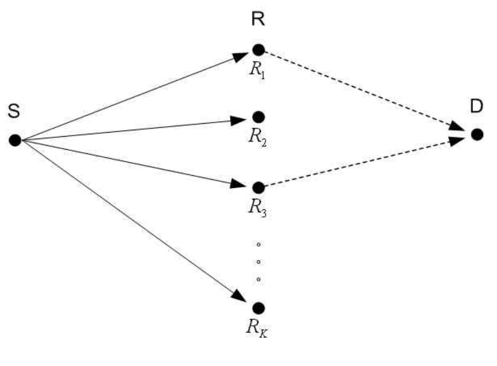

Fig. 1. COT system model.

Ⅲ. Proposed DOT System Model and Transmit Protocol

3-1 Proposed DOT System Model

The proposed system model is identical to that of the COT system in Fig. 1, S, R_k(k=1, 2, 3,···, k), and D. The COT system, described in the preceding section, only considers the SNR received from S as the opportunistic transmit condition. This means the transmit condition at R_k is dependent on the source-relay (S-R_k) path, but is independent of the relay-destination (R_k-D) path.

In this paper, we propose the DOT system, which has two opportunistic transmit conditions-both the SNR of the S-R_k path and the SNR of the R_k-D path exceed the threshold. When the channel is reciprocal, the channel characteristics of the R_k-D path and the D-R_k paths are identical. Also, the received SNR (γ_{R_kD}) from R_k at D and the SNR (γ_{DR_k}) received from D at R_k are equal.

3-2 DOT Transmit Protocol

The transmit protocol of the proposed DOT system consists of the following four steps (see Fig. 2):

a) Source transmit step: The source transmits the information to the relays. Each relay compares the SNR received to the source-relay threshold (Γ_{SR}).
b) Destination transmit step: The destination transmits a pilot tone to the relays. Each relay compares the SNR received to the relay-destination threshold (Γ_{RD}).
c) Relay transmit step: When both received SNRs exceed their respective thresholds, then the relays transmit.
d) Diversity combining step: The multipath signals are received and combined at D.

Note that the destination transmit step in (b), which is not shown in the COT relay system, is newly inserted to include the D-R path condition whether the relay transmits at a specific time. In this step, the ordering function is done at R because the L_c relays which satisfy the condition of $\gamma_{R_kD} > \Gamma_{RD}$ are selected among L relays.

3-3 GSC Combining

MRC diversity is superior to the other special diversity techniques. However, the required hardware is complex. When the SNR is low, the MRC is very sensitive to channel estimation errors. While the hardware complexity of SC is low, the performance of SC is inferior to

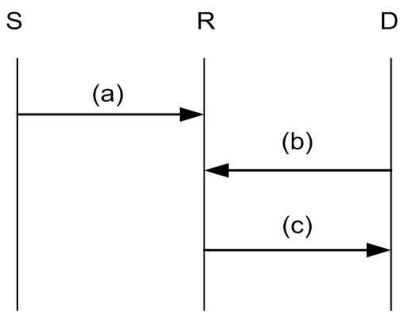

Fig. 2. Transmit protocol of the DOT system.

MRC. Recently GSC has been proposed to avoid the two extremes, and select the strong resolvable paths from all received paths [12].

There are two steps in GSC to combine the received signals. First in the ordering step, the GSC receiver orders the received signals before combining. Second in the combining step, the receiver combines strong L_c paths from $L(L \geq L_c)$ paths. Usually, the ordering step is performed at the GSC receiver: however, it requires time and additional power consumption [12]. On the other hand, in our proposed DOT system, this ordering step is performed at R_k rather than at the receiver. In the relay transmit step of the DOT transmit protocol, R_k examines whether the received SNR exceeds the predetermined threshold. During this opportunistic transmit condition check, the ordering function is done automatically. When L_c relays transmit among L relays, the strong L_c paths are sorted at R. As we assumed in section 3-2, where the channel is reciprocal, the SNR received from the R-D and D-R paths is identical. Therefore, the ordering result at R is the same as at D. Consequently, only the combining function is enough for GSC diversity for D.

The received signal y_{AB} between a transmit node A and a receiver node B can be written as

$$y_{AB} = h_{AB} x + n_B, \tag{1}$$

where h_{AB} is the channel amplitude gain between the transmit node A and the receiver node B. We assume this channel gain is Rayleigh distributed and the channel is reciprocal; h_{AB} equals h_{BA}. n_B is zero mean additive white Gaussian noise (AWGN) with variance N at node B.

In this paper, we assume the noise power of each node is equal to N and x is the information with transmit power P_S. Therefore, the received SNR γ_{AB} at node B is given by

$$\gamma_{AB} = |h_{AB}|^2 \frac{P_S}{N}. \tag{2}$$

The outage probability P_{out} is defined as received SNR being less than the threshold, and can be written as

$$P_{out} = \Pr(\gamma < \Gamma), \tag{3}$$

where γ and Γ denote the received SNR and the threshold, respectively.

Ⅳ. Outage Probability

4-1 Outage Probability

In Fig. 2, the end-to-end outage probability can be written by the conditional probability as

$$P_{out} = \sum_{i=0}^{K} \Pr\left(\gamma_c < \Gamma_{RD} \middle| |C| = i\right) \Pr(|C| = i) \tag{4}$$

where γ_c and Γ_{RD} denotes the combined SNR at the destination and the threshold of the R-D path, respectively. K represents the number of relay nodes in the system. C is the active relay set, defined by

$$C = \{\gamma_{Sk} > \Gamma_{SD}, \text{ and } \gamma_{kD} > \Gamma_{RD}, k = 1, 2, \ldots, K\}, \tag{5}$$

where γ_{Sk} and γ_{kD} denote the received SNR at $R_k(k$=1, 2, 3,⋯, $K)$ of the S-R_k path and that of the R_k-D path, respectively. If the channel is reciprocal, γ_{kD} equals γ_{kD}. Γ_{SR} and Γ_{RD} are the thresholds of the S-R path and that of the R-D path, respectively. $|C|$ represents the size of the active relay set. $\Pr(|C| = i)$ is defined as the probability of i relays being transmitted among K relays and can be written as

$$\Pr(|C| = i) = \binom{K}{i} \left[\Pr\left(\gamma_{iD} > \Gamma_{RD}, \gamma_{Si} > \Gamma_{SR}\right)\right]^i \times \left[1 - \Pr\left(\gamma_{iD} > \Gamma_{RD}, \gamma_{Si} > \Gamma_{SR}\right)\right]^{K-i}. \tag{6}$$

If we assume an i.i.d Rayleigh fading channel and DF relaying, then this probability can be rewritten as

$$\begin{aligned} \Pr\left(\gamma_{iD} > \Gamma_{RD}, \gamma_{Si} > \Gamma_{SR}\right) &= \Pr\left(\gamma_{Si} > \Gamma_{SR}\right) \Pr\left(\gamma_{iD} > \Gamma_{RD}\right) \\ &= \exp\left[-\left(\frac{\Gamma_{SR}}{\bar{\gamma}_{Si}} + \frac{\Gamma_{RD}}{\bar{\gamma}_{iD}}\right)\right]. \end{aligned} \tag{7}$$

Notice that the COT relay system only considers the first term $\mathbf{Pr}(\gamma_{Si} > \Gamma_{SR})$ in (7) [10]. This means that when the received SNR from the S-R_k path is greater than the threshold, the relay transmits. However, even though the SNR received at R_k from the S-R_k path exceeds the threshold, it is not guaranteed that the SNR received at a destination will exceed the threshold.

To guarantee SNR at a relay and at the destination, we include the second term $\mathbf{Pr}(\gamma_{iD} > \Gamma_{RD})$ in (7). If we assume the channel is reciprocal, γ_{iD} is greater than Γ_{RD} and it can be interpreted that γ_{Di} is greater than the threshold Γ_{RD}. This denotes the sorting function, which is the selection of the strong SNR above the threshold at a destination and which is transferred to each relay. If we apply GSC at the destination, the sorted strong signals (i.e., number of *i* relays among *K* relays) arrive at the destination. Therefore, the conditional probability in (4) can be written as

$$\Pr\left(\gamma_c < \Gamma_{RD} \| C| = i\right) = \binom{K}{i}\{1-\exp\left(-\gamma_T/\overline{\gamma}_{iD}\right)\times \sum_{l=0}^{i-1}\frac{\left(\gamma_T/\overline{\gamma}_{iD}\right)^l}{l!} + \sum_{l=1}^{K-i}(-1)^{i+l-1}\binom{K-i}{l}\left(\frac{i}{l}\right)^{i-1}\times \left[\frac{1-e^{-(1+l/i)(\gamma_T/\overline{\gamma}_{iD})}}{1+l/i} - \sum_{m=0}^{i-2}\left(-\frac{l}{i}\right)^m\left(1-e^{-\gamma_T/\overline{\gamma}_{iD}}\sum_{k=0}^{m}\frac{(\overline{\gamma}_T/\overline{\gamma}_{iD})^k}{k!}\right)\right]\}. \quad (8)$$

4-2 Average Number of Transmit Relays

The average number of transmit relays that satisfy the transmit condition-the received SNR (γ_{si} and γ_{iD}) of a relay is greater than the respective threshold (i.e., Γ_{SR} and Γ_{RD})-can be written as [13],

$$\begin{aligned} M_{DOT} &= \sum_{i=0}^{K} i\binom{K}{i}\left[\Pr\left(\gamma_{iD} > \Gamma_{RD},\ \gamma_{Si} > \Gamma_{SR}\right)\right]^i \times \left[1-\Pr\left(\gamma_{iD} > \Gamma_{RD},\ \gamma_{Si} > \Gamma_{SR}\right)\right]^{K-i} \\ &= \sum_{i=0}^{K} i\binom{K}{i}\left[\exp\left\{-\left(\frac{\Gamma_{SR}}{\overline{\gamma}_{Si}}+\frac{\Gamma_{RD}}{\overline{\gamma}_{iD}}\right)\right\}\right]^i\left[1-\exp\left\{-\left(\frac{\Gamma_{SR}}{\overline{\gamma}_{Si}}+\frac{\Gamma_{RD}}{\overline{\gamma}_{iD}}\right)\right\}\right]^{K-i} \\ &= K\exp\left\{-\left(\frac{\Gamma_{SR}}{\overline{\gamma}_{Si}}+\frac{\Gamma_{RD}}{\overline{\gamma}_{iD}}\right)\right\}. \end{aligned} \quad (9)$$

The average number of transmit relays depends on both thresholds, Γ_{SR} and Γ_{RD}. From (9), we can obtain the threshold Γ_{RD}, as follows:

$$\Gamma_{RD} = -\overline{\gamma}_{iD}\left[\frac{\Gamma_{SR}}{\overline{\gamma}_{Si}} + \ln\left(\frac{M}{K}\right)\right]. \quad (10)$$

By adjusting the threshold, we can control the number of the transmit relays. In the case of the diversity branches being fixed at a destination (i.e., a Rake receiver with fixed fingers), the transmit relays can be controlled by the thresholds. The excess or fewer numbers of transmit relays can be adjusted by controlling the threshold. Consequently, the power consumption from the excess relays and the performance degradation resulting from fewer relays can be avoided.

In order to evaluate the proposed relay system, we compare the DOT system with GSC and the COT system with MRC. The average number of transmit relays in the COT system can be obtained easily from (5) and (9) as a special case of

$$C_{COT} = \{\gamma_{Sk} > \Gamma_{SD},\ k = 1,\ 2, ..., K\}. \quad (11)$$

Then the average number of transmit relays is given by

$$M_{COT} = K\exp\left(-\frac{\Gamma_{SR}}{\overline{\gamma}_{Si}}\right). \quad (12)$$

The average number of transmit relays depends on the single threshold Γ_{SR}.

Ⅴ. Numerical Examples

For numerical analysis, we assume the transmit power of a node is identical, and the average SNR received at each relay is the same (i.e., $\overline{\gamma}_{Si} = \overline{\gamma}_{SR}$, $\overline{\gamma}_{iD} = \overline{\gamma}_{RD}$). The wireless channel is assumed to be reciprocal (i.e., $\overline{\gamma}_{RD} = \overline{\gamma}_{DR}$).

Fig. 3 shows the outage probability of the proposed DOT relay system versus $\overline{\gamma}_{RD}/\Gamma_{RD}$ for different *K* with $\overline{\gamma}_{SR}/\Gamma_{SR}$=30 dB in Rayleigh fading. For $\overline{\gamma}_{SR}/\Gamma_{SR}$=30 dB, the outage probability at a relay is small, so we would like to focus on the effect of $\overline{\gamma}_{RD}/\Gamma_{RD}$ on the outage probability at the destination (end-to-end outage probability). At a given outage of 1×10^{-3}, the normalized average SNR $\overline{\gamma}_{RD}/\Gamma_{RD}$ is 10.1, 5.4, 3.3, and 2.1 dB for *K*=3, 5, 7, and 9, respectively. This shows that the normalized average SNR decreases as the number of relays increases. The number of transmit relays increases with the total number of relays in the system (see Fig. 4).

In Fig. 4, the average number of transmit relays is shown for different *K* with $\overline{\gamma}_{SR}/\Gamma_{SR}$=30 dB. Note that the average number of transmit relays in the COT system is constant, irrespective of $\overline{\gamma}_{RD}/\Gamma_{RD}$. However, the average number of transmit relays in the DOT system increases

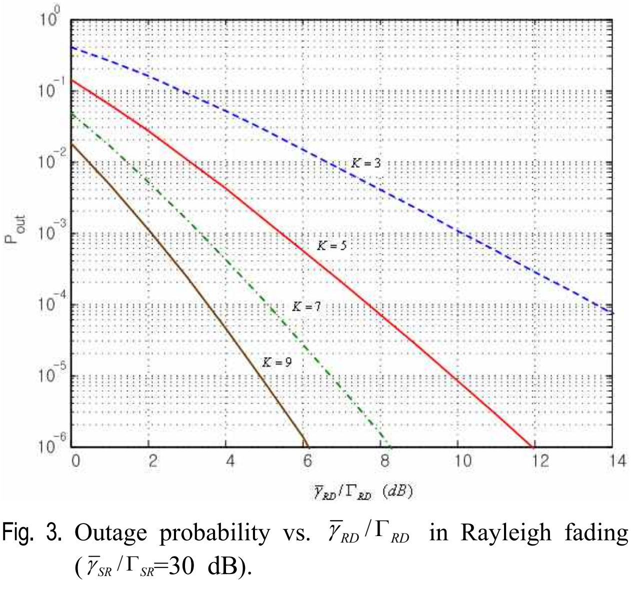

Fig. 3. Outage probability vs. $\overline{\gamma}_{RD}/\Gamma_{RD}$ in Rayleigh fading ($\overline{\gamma}_{SR}/\Gamma_{SR}$=30 dB).

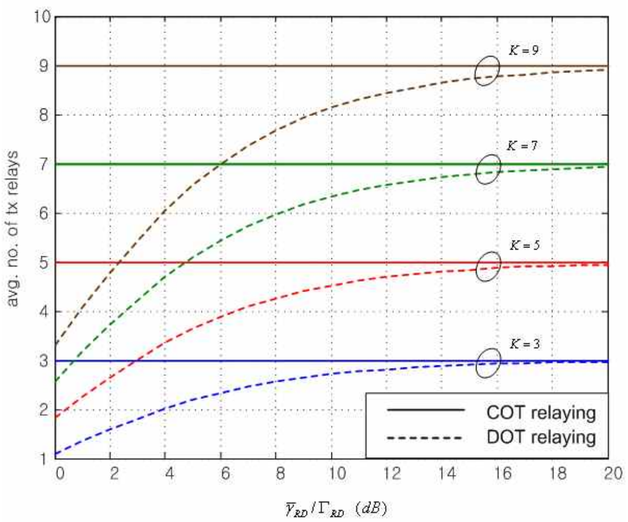

Fig. 4. Average number of transmit relays for different K ($\bar{\gamma}_{SR}/\Gamma_{SR}$=30 dB).

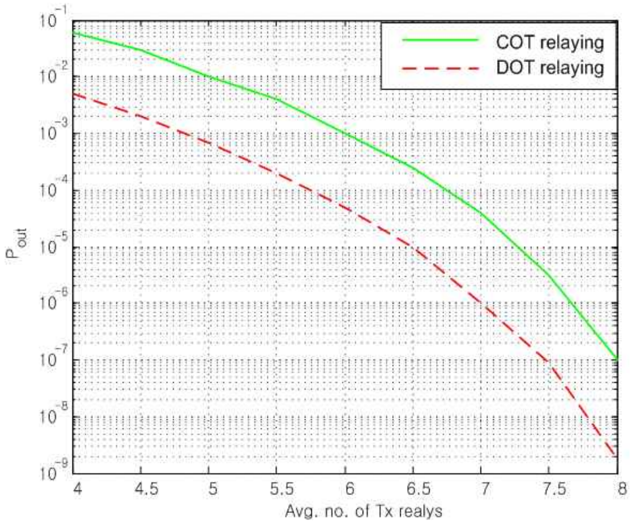

Fig. 5. Outage probability vs. average number of relays (K=9).

with $\bar{\gamma}_{RD}/\Gamma_{RD}$. Therefore, the average number of transmit relays in the DOT system can be controlled by $\bar{\gamma}_{RD}/\Gamma_{RD}$. The average number of transmit relays to meet the outage probability of 1×10^{-3} is 2.72, 3.74, 4.4, and 4.85 for K=3, 5, 7, and 9, respectively. This implies that the number of active relays is reduced to 9.2, 25.1, 37.1, and 46.1 % compared to that of the COT system for K=3, 5, 7, and 9, respectively. Consequently, the proposed DOT relay system can be reduced to 6.9, 20.9, 32.4, and 41.4 % power consumption compared to the power consumption of the COT relay system for K=3, 5, 7, and 9, respectively.

The performance comparisons between the DOT and COT systems are shown in Fig. 5 for K=9. In this figure, the average number of active relays in the DOT system is calculated using (9). On the other hand, the average number of active relays in the COT system is calculated using (12). The outage probability of both systems is obtained from (4). In the DOT system, $\bar{\gamma}_{SR}$ and Γ_{SR} are fixed at 30 dB and 1, respectively. In the COT system, $\bar{\gamma}_{SR}$ is fixed at 30 dB and Γ_{SR} changes according to the average number of active relays (notice that the average number of active relays is a function of $\bar{\gamma}_{SR}/\Gamma_{SR}$ and $\bar{\gamma}_{RD}/\Gamma_{RD}$ in the DOT system and is a function of $\bar{\gamma}_{SR}/\Gamma_{SR}$ in the COT system).

The performance of the DOT system is superior to that of the COT system for the identical number of active transmit relays under the same condition of $\bar{\gamma}_{RD}/\Gamma_{RD}$ in Fig. 5. Regardless of the normalized SNR $\bar{\gamma}_{RD}/\Gamma_{RD}$ of the R-D path, the COT system controls the number of transmit relays by the threshold Γ_{SR}. On the other hand, the DOT system relay must satisfy the two conditions, $\gamma_{Sk}>\Gamma_{SD}$ and $\gamma_{kD}>\Gamma_{RD}$, for transmission in (5). By adding the condition of $\gamma_{kD}>\Gamma_{RD}$, the ordering function that selects the strong L_c path among L path is transferred to each relay.

Ⅵ. Conclusions

Recently, opportunistic transmission has been shown to be an effective way to mitigate fading in wireless channels, save power and improve the performance of ad-hoc or sensor networks. The conventional opportunistic transmit system, however, does not consider the SNR received from the R-D path as a transmit condition. For that reason, it is not guaranteed that all received SNRs exceed the threshold at D. Therefore, we propose the DOT system that considers the SNR received from both the S-R and R-D paths.

The performance of the proposed DOT system is analytically derived and compared to that of the COT system. In the DOT relay system, the average number of transmit relays can be controlled by adjusting the threshold in (9). The proposed DOT system reduces power consumption by 6.9, 20.9, 32.4, and 41.4 % for K=3, 5, 7, and 9, respectively under the given conditions of $P_{out}=1\times10^{-3}$ and $\bar{\gamma}_{SR}/\Gamma_{SR}$=30 dB, compared to the COT system.

Power optimization by controlling the threshold in the DOT system can be a future research topic.

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