Information Alignment for Mitigating Jamming in Wireless Relay Networks

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Abstract - We propose *information alignment* that enables the destination to mitigate jamming in wireless multi-source relay networks. A central idea is to make the message packets from the sources and those from the relay aligned in the same direction such that they can be canceled each other and only the forwarded decoding error caused by jamming remains at the destination. This enables the destination to determine the forwarded decoding error and to remove it from the received packet to restore the true codeword. We show that the proposed scheme can achieve the performance close to what can be achieved by the genie relay that completely knows the message packets and therefore always forwards the correct information.

I. Introduction

Wireless medium is inherently susceptible to radio jamming due to the shared nature of the wireless medium. Although jamming is a major problem in military networks, it may also occur in commercial and industrial networks. With the fast growing number of mobile devices that operate in the unlicensed Industrial, Scientific, and Medical (ISM) band, even a low energy transmission per device can cause similar denial-of-service [1].

Many anti-jamming techniques have been proposed, spanning many layers in the network stack [2], [3]. The standard physical layer defense against jamming involves various forms of spread spectrum techniques [5], such as frequency hopping and code spreading, combined with error correction. Other measures include antennas with steerable or adaptive nulls and multiple-element antenna arrays [4], [6], [7], [8]. At the link layer, channel hopping utilizes a number of orthogonal radio channels and channel switching is controlled at the software-level [9], [10], [11], [12].

However, the mitigation of jamming has not received much attention in the context of wireless relay networks, where the relay assists communication between source and destination. In this paper, we consider a wireless multiple access relay network in which the relay encodes (combines) the message packets that are received from multiple sources and forwards the coded packet, hereafter referred to as *codeword*, to the destination. In this process, the received packets are interfered by the signals from other sources, such as baby monitors and cordless phones[1], such that the coded packet contains a significant number of errors. If the message recovery is attempted using the erroneous codeword, the original message cannot be recovered.

In this paper, we propose *information alignment* to mitigate jamming at the relay. A central idea is to make the message packets from the sources and those from the relay aligned in the same direction such that they can be canceled each other and only the forwarded decoding error caused by jamming remains at the destination. This enables the destination to determine the forwarded decoding error and to *remove* it from the received packet to restore the true codeword. The destination may then recover the message based on the restored codeword. The idea of information alignment is illustrated in Fig. 1.

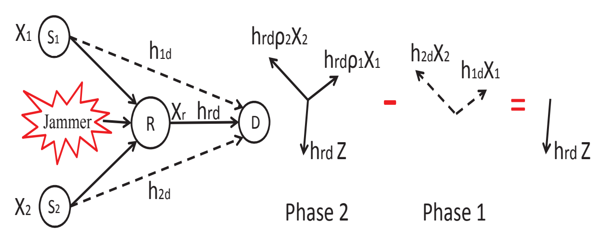

Fig. 1. Information alignment in two sources, one relay, and one destination network. In phase 1 each source sends its packet X_i, $i = 1, 2$, to the relay and destination. In phase 2 the relay encodes the received packets $\hat{X}_1$ and $\hat{X}_2$ and forwards the encoded packet $X_r = \rho_1 \hat{X}_1 + \rho_2 \hat{X}_2 = \rho_1 X_1 + \rho_2 X_2 + Z$ to the destination, where $Z = \rho_1(\hat{X}_1 - X_1) + \rho_2(\hat{X}_2 - X_2)$ is the weighted sum of decoding errors caused by jamming. The encoding coefficients ρ_1 and ρ_2 are chosen such that the packet received from source i, $g_i X_i$, is aligned with that from the relay, $h_{rd}\rho_i X_i$, at the destination. The destination subtracts the received signal in phase 1 from that in phase 2 such that only the forwarded decoding error Z remains. Then, the destination detects Z and cancels it from X_r to restore the true coded packet $\rho_1 X_1 + \rho_2 X_2$.

II. Related Work

The concept of *interference alignment* was originally developed for wireless interference channels [16], [17]. In [16], the authors demonstrated that each user is able to access one half of the available spectrum regardless of the number of

[1]Recent studies from Ofcom [13], Jupiter Research [14], and Cisco [15] report that such interferers are responsible for more than half of the problems reported in customer networks.

interferers by pre-processing signals at the transmitters in a manner that aligns interference at the receivers. This discovery of everyone gets half of the pie has spurred considerable interest in the wireless communication community. Authors in [18] combined interference alignment with interference cancelation, termed IAC, and showed that the combination increases the throughput in scenarios where neither alignment nor cancelation helps alone. Authors in [19] studied the application of IAC in more general, multi-hop wireless networks and demonstrated that it is NP-hard to determine the optimal IAC scheme. Authors in [20] applied interference alignment techniques to the problem of network coding across different unicast sessions over directed acyclic graphs. They discussed the condition for feasibility of alignment and their relation to network structure.

Our work was inspired by the IAC scheme. However, our work aims at mitigating the jamming originated from unknown sources which make it impossible or hard to align them. To the best of our knowledge, this paper is the first to align the desired signals, rather than the interfering (jamming) signals, and to mitigate the forwarded error caused by the interfering signals in wireless relay networks. Unlike previous interference alignment schemes, the proposed approach does not require pre-processing the signals at the source nodes (senders) nor the receiver collaboration. Correspondingly, no collaboration is required among senders or receivers in the proposed approach.

III. System Model

Consider the K-source, single-relay, single-destination network, where each source wishes to send its message reliably to the destination D. In phase 1 each source broadcasts its message packet to the relay and destination. We assume that each message packet is of rate R bits per second per Hertz (b/s/Hz) and length L, and is independently chosen from the associated Gaussian random codebook. The signal received by the relay and destination can, respectively, be written as

$$Y_{kr} = h_{kr}X_k + J_k + N_{kr} \quad (1)$$

$$Y_{kd} = h_{kd}X_k + N_{kd} \quad (2)$$

for $k = 1, \cdots, K$, where X_k is the message packet of the kth source. We assume that X_k is complex Gaussian distributed with mean zero and variance $E[|X_k|^2]/L = P$ for all k; h_{kr} and h_{kd} are the complex Gaussian channel gain between the kth source and the relay and that between the kth source and the destination, respectively, with $E[|h_{kr}|^2] = d_{kr}^{-m}$ and $E[|h_{kd}|^2] = d_{kd}^{-m}$ where d_{kr} and d_{kd} are the distance between the kth source and relay and that between the kth source and dth destination, respectively; m is the path loss exponent; J_k is the jamming signal on the kth message; and N_{kr} and N_{kd} are the additive white Gaussian noise with mean zero and variance σ_n^2. We assume J_k is Gaussian distributed with mean zero and variance σ_j^2. A slow, flat, block Rayleigh fading environment is assumed, where the channel gain remains static for one codeword period and changes independently in different periods. We assume that $d_{kd} > d_{kr}$ such that the received signal at the destination is weaker than that at the relay.

We permit the relay to use superposition coding [?] to retransmit the decoded words. The relay transmits a codeword:

$$X_r = \sum_{k=1}^{K} \rho_k \hat{X}_k \quad (3)$$

where $\hat{X}_k$ denotes the estimate of X_k based on Y_{kr} at the relay and $\{\rho_k\}$ are encoding coefficients. All operations in (3) are over the complex field. We assume that $|\rho_k|^2 = 1/K$ such that $E[|X_r|^2]/L = P$. The coded packet can be expressed as

$$X_r = \sum_{k=1}^{K} \rho_k X_k + Z \quad (4)$$

where

$$Z = \sum_{k=1}^{K} \rho_k (\hat{X}_k - X_k) \quad (5)$$

is the weighted sum of decoding errors at the relay. That is, the forwarded packet is composed of the true coded packet plus a weighted sum of decoding errors at the relay, where the additions and multiplications are over the complex field.

In phase 2 the relay sends the coded packet X_r and the destination receives

$$\begin{aligned} Y_{rd} &= h_{rd}X_r + N_{rd}, \\ &= h_{rd}\left(\sum_{k=1}^{K} \rho_k X_k + Z\right) + N_{rd} \end{aligned} \quad (6)$$

where h_{rd} denotes the channel gain between the relay and the destination, and N_{rd} is the additive white Gaussian noise with mean zero and variance σ_n^2.

IV. Proposed Mitigation Approach

In this section we describe the proposed approach for detecting the forwarded error Z, subtracting it from the received signal Y_{rd} to restore the true codeword, and recovering the message from the restored packet. A central idea is to exploit the overheard signals $\{Y_{kd}\}$ that provide (noisy) information about the original messages $\{X_k\}$ and to remove them from what is received from the relay to detect Z. Once the forwarded decoding error Z is known, it can be removed from the forward packet and thus the jamming effect can be removed.

A. Information Alignment

Our approach to remove the combined decoding error Z from the received signal Y_{rd} in (6) builds on the idea of *information alignment*. The information component X_k in the received packet Y_{kd} in phase 1 and that in Y_{kr} in phase 2 can be aligned in the same direction at the destination if

$$\alpha_k h_{kd} = h_{rd}\rho_k, \ k = 1, \cdots, K \quad (7)$$

where α_k is a constant. This can be done by choosing α_k as $\rho_k h_{rd}/h_{kd}$.

B. Information Cancelation

The information alignment allows the destination to remove the information component $h_{rd}\sum_{k=1}^{K}\rho_k X_k$ in the received packet Y_{rd} by subtracting $\sum_{k=1}^{K}\alpha_k Y_{kd}$ from Y_{rd}:

$$\begin{aligned} Y_Z &= Y_{rd} - \sum_{k=1}^{K}\alpha_k Y_{kd} \\ &= h_{rd}Z + N_{rd} - \sum_{k=1}^{K}\alpha_k N_{kd} \end{aligned} \tag{8}$$

Then, the forwarded decoding error Z may be detected from Y_Z if the rate of Z is less than the mutual information between Z and Y_Z.

C. Decoding of Message

Once the combined decoding error is estimated, the estimate $\hat{Z}$ may be subtracted from Y_{rd} to get a "recycled" signal

$$\tilde{Y}_{rd} = h_{rd}\left(\sum_{k=1}^{K}\rho_k X_k + Z - \hat{Z}\right) + N_{rd} \tag{9}$$

If $\hat{Z} = Z$, the received signal is fully recycled and the message can be recovered based on $\{Y_{kd}\}$ and $\tilde{Y}_{rd}$. However, if Z cannot be determined, i.e. $\hat{Z} = ?$, then the message X_k can be recovered based on Y_{kd} only. The additional information provided by $\tilde{Y}_{rd}$ when $\hat{Z} = Z$ can lower the outage probability.

V. Numerical Results and Discussion

In this section we present the outage probability of the proposed scheme for the case of $d_{sd} = 1, d_{sr} = 0.5, d_{rd} = 0.5$ and $m = 4$, and compare with other relaying schemes: selective relay, decode-and-forward, and genie relay. The selective relay adapts the relaying format according to the channel gain between source and relay. The relay forwards the codeword X_r when $\hat{X}_k = X_k$ for all $k \in \{1, \cdots, K\}$, i.e. $Z = 0$. If at least one of K source-relay links fall below a certain threshold such that $\hat{X}_k \neq X_k$ for some $k \in \{1, \cdots, K\}$, i.e. $Z \neq 0$, then the relay does not forward X_r. The destination decodes X_k based on $\{Y_{kd}\}$ and Y_{rd} when $Z = 0$ and, otherwise, decodes based on Y_{kd} only. The decode-and-forward relay forwards X_r no matter what Z is and the decoder uses X_r in recovering the message. If X_r contains any error, $Z \neq 0$, then the decoder output will be erroneous. The genie relay knows $\{X_k\}$ perfectly and therefore the sum of decoding error Z in (5) is always equal to 0.

Fig. 2 shows the end-to-end outage probability versus the received SNR between source and destination. At high SNR the proposed scheme performs the same as the genie relay. This is because the destination may reliably decode the source codewords $\{X_k\}$ and thus can remove the forwarded error by the relay. We also can see that the proposed scheme can provide a significant SNR gain of over the selective relaying or decode-and-forward schemes that do not cancel the forwarded decoding error.

Fig. 3 shows the end-to-end outage probability versus the rate R. We can see that the proposed scheme performs close

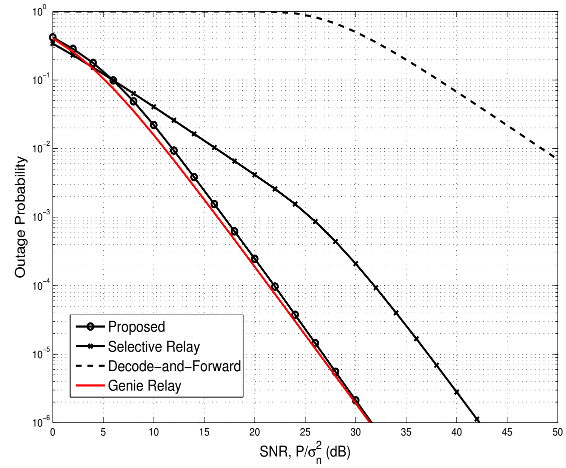

Fig. 2. Outage probability versus transmit SNR, P/σ_n^2; $p = 1$, $K = 4$, $R = 0.5$, σ_j^2/σ_n^2=40dB, $d_{kr1} = 0.2$, $d_{kr2} = 0.5$, $d_{rd} = 0.8$, $d_{kd} = 1$.

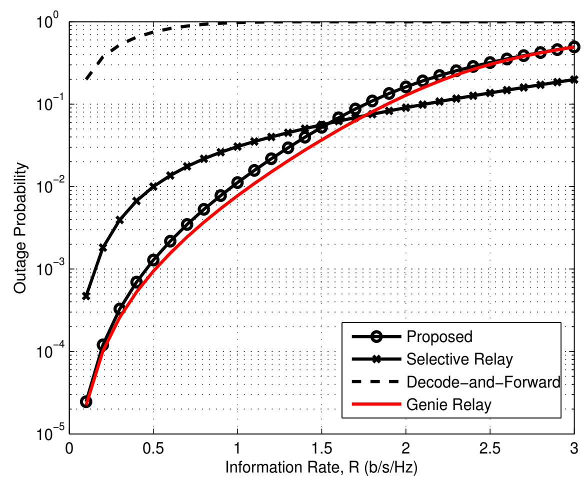

Fig. 3. Outage probability versus information transmission rate, R; $K = 2$, σ_j^2/σ_n^2=30dB, P/σ_n^2=15dB, $p = 1$, $d_{kr1} = 0.2$, $d_{kr2} = 0.5$, $d_{rd} = 0.8$, $d_{kd} = 1$.

to the genie relay for all rate R. However, if the rate is above a certain threshold where the probability of decoding error at the relay is very high, the selective relay performs even better than the genie relay. This is due to the loss of effective rate by transmitting the codeword which does not help reducing the error rate when the information rate is high enough. This suggests an adaptive relaying scheme that adapts between the proposed scheme and selective relaying scheme depending on the rate or the outage rate between source and relay. This adaptive relaying scheme has the potential to achieve the lower envelope of two outage probabilities.

Fig. 4 shows the end-to-end outage probability versus the distance between relay and destination d_{rd} when the distance between the kth source and relay d_{kr} is set to $d_{kd} - d_{rd}$.

We can see that the outage probability for the proposed scheme increases with increasing distance between relay and destination. This is due to the effect of increased channel propagation loss between relay and destination that makes the detection of Z less reliable. However, the outage probability is fairly robust to the relay location.

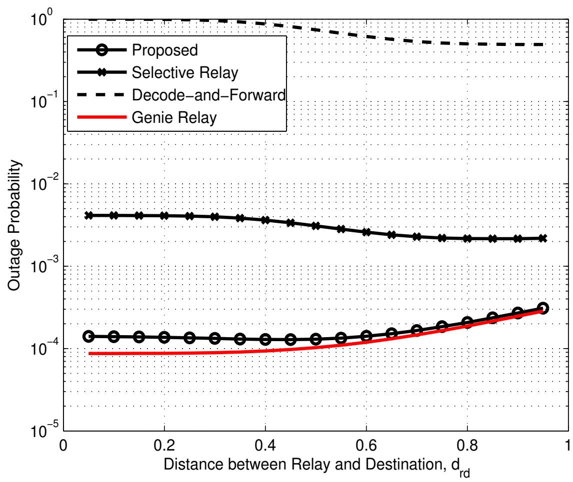

Fig. 4. Outage probability versus distance between relay and destination, d_{rd}; $K = 4$, $R = 0.5$, P/σ_n^2=20dB, σ_j^2/σ_n^2=30dB, $d_{kd} = 1$, $d_{kr1} = d_{kd} - d_{rd}$, $d_{kr2} = 0.5$.

VI. Conclusion

We proposed *information alignment* that makes the message packet from the source and that from the relay aligned in the same direction at the destination such that they can be canceled each other and only the decoding error caused by jamming remains at the destination. This enables the destination to determine the forwarded error and to *remove* it from the jammed packet to recover the true message packet. We showed that the proposed scheme can perform close to what genie-aided relaying scheme can provide where the genie relay perfectly knows the original message hence always forwards the true packet.

Acknowledgement

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