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Batu K. Chalise
Cleveland State University

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On the Performance of SR and FR Protocols for OSTBC based AF-MIMO Relay System with Channel and Noise Correlations

Batu K. Chalise, Senior Member, IEEE

Abstract—This paper proposes selection relaying (SR) protocol for a cooperative multiple-input multiple-output (MIMO) relay system that consists of a direct link between a source and a destination. The system has only receive-side channel state information (CSI), spatially correlated MIMO channels, and the receiver nodes observe spatially correlated noise. The transmit nodes employ orthogonal space-time block codes (OSTBC), whereas the receiver nodes employ optimum minimum mean-square-error (MMSE) detection. The SR protocol, which transmits via the relay only when the direct link between the source and destination is in outage, is compared with the fixed relaying (FR) protocol which always uses the relay. By deriving novel asymptotic expressions of the outage probabilities, it is analytically shown that both protocols provide the same diversity gain. However, the coding gain (CG) of the SR protocol can be much better than that of the FR protocol. In particular, when all MIMO links have the same effective rank, irrespective of its value, the SR protocol provides better CG than the FR scheme if the target information rate is greater than \( \ln(2) \) bits per channel use. Simulation results confirm that the SR scheme can significantly outperform FR method, which may justify the increased complexity due to one-bit feedback requirement in the SR protocol.

Index Terms—MIMO relay, channel state information, OSTBC, selection and fixed relaying, outage probability, MMSE receivers

I. INTRODUCTION

In recent years, cooperative communications with both single-antenna and multiple-input multiple-output (MIMO) relays have garnered significant interests [1]-[4]. Cooperative relays are also expected to be a part of heterogeneous networks in fifth generation communication systems [5]. By employing precoding and decoding techniques, cooperative systems with MIMO nodes provide both spatial multiplexing and diversity gains. However, precoding requires a transmitter to have channel state information (CSI) which is generally obtained via feedback from the receiver. In order to minimize the cost of CSI feedback and simplify the system design without compromising with the system diversity gain, the transmitter often employs orthogonal space-time block codes (OSTBC) [6]-[8]. Because of the optimal decoding at low complexity and the promising diversity gains, OSTBC based designs are also deployed in LTE systems, where full-rate OSTBCs, namely the Alamouti codes are employed in frequency domain for the transmitters with two and four antennas [9].

The OSTBC-based dual-hop non-coherent amplify-and-forward (AF) MIMO relay system is proposed in [10] and [11] for Rayleigh and Ricean fading channels, respectively. In both papers, source employs OSTBC encoding and the relay does not have receive-side CSI. On the other hand, performance analysis of the OSTBC-based dual-hop coherent AF AF relay system is proposed for Nakagami-\( m \) correlated channels in [12] and [13], where single-antenna and multi-antenna relay are considered, respectively. In [13], both source and relay nodes use OSTBC, whereas direct link between the source and destination is not considered in [10]-[13]. The closed-form expression of the exact outage probability and the corresponding asymptotic expression are derived in [14] for a coherent MIMO relay system that uses decode-and-forward relay protocol, OSTBCs at the source and relay nodes, and has the direct link. In [15], the performance of the OSTBC-based coherent AF MIMO relay network is analyzed, in which the relays estimate the source signal and forward it to the destination without decoding. This work is extended in [16] to MIMO channels with spatial correlation and the direct link with the keyhole effect. The works in [14]-[16] consider a fixed relaying (FR) scheme where the relay is always employed and the system follows a two-phase transmission, i.e., in the first phase the source transmits and in the second phase the relay transmits. Moreover, noise at both the relay and destination nodes are spatially uncorrelated.

In practice, spatial channel correlations and coupling among receiver antennas can make the received signal and noise to become correlated [17]-[18]. Many prior works have analyzed the effects of correlated noise (and colored interference) on the system design and performance for different applications. In [19], the authors determine the MIMO channel capacity in the presence of correlated noise, whereas in [20], coordinated beamforming technique is proposed for a broadcast channel with signal and noise correlation at the receiver, where correlation occurs in the presence of receiver mutual coupling. The optimum design of relay processing coefficients is proposed in [21] for an AF relay system where the noise among distributed single-antenna relays is assumed to be correlated, for example, due to common interference observed by the relays. In [22], the effects of spatial channel correlation, antenna coupling, superdirectivity and noise correlation are taken into account while designing the AF-MIMO relay for a system with multiple single-antenna sources and a multi-

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antenna destination. As in [10]-[16], both designs, [21] and [22], consider the FR protocol.

However, in the presence of the direct link between the source and destination, it is known from [23] that selection relaying (SR) for the AF relay system simplifies the joint design of the beamformers and performs better than the joint beamformer design based on FR protocol. In the SR approach, the AF relay is used only if the direct link fails to support the targeted information rate. Moreover, the source changes the modulation order in a way that the effective rate of information transmission via the relay remains same as that corresponding to the direct link. Motivated from [23], we propose SR protocol for an OSTBC-based cooperative coherent MIMO relay system that has a direct link, only receive-side CSI, and is subject to spatially correlated channels and noise. According to our best source of knowledge, neither such a system has been investigated nor the FR and SR protocols have been analytically compared in terms of diversity and coding gains (CG)\(^2\).

In this paper, we consider a cooperative MIMO relay system where the relay and destination nodes observe spatially correlated noise and the MIMO channels are subject to spatial correlation\(^3\). The source encodes its signal using OSTBC. The relay employs a general linear receiver such as the minimum mean-square error (MMSE) receiver to estimate the source signal and forwards the resulting signal to the destination after OSTBC encoding. The destination also uses MMSE receiver to estimate and decode the source signal, received via the source-destination (S-D) and the two hop source-relay-destination (S-R-D) links. The orthogonality property of OSTBC is exploited to obtain the symbol estimates, and the signal-to-noise ratios (SNRs) corresponding to the S-D and S-R-D links.

Using a single-bit feedback from the destination, the SR protocol employs MIMO relay only if the S-D link is in outage which is defined as an instant in which the supported information rate is below the rate targeted by the source. Since it is difficult to obtain sufficient insights from the exact outage probability expressions, novel asymptotic expressions are derived to obtain the coding and diversity gains of the SR and FR protocols. It is shown that the performance depends not only on the transmit and receive-side channel correlation matrices but also on the covariance matrices of noise at the receiver nodes. Although both protocols achieve the same diversity, the CG of the SR protocol can be much better than that of the FR protocol, especially for larger values of target information. In particular, when all MIMO links have the same effective rank\(^4\), irrespective of its exact value, the SR protocol provides better CG than the FR protocol for the target rates greater than \(\ln_2(3)\) bits per channel use (b.p.c.u). This performance improvement may justify the latter’s increased complexity due to one-bit feedback requirement.

The remainder of this paper is organized as follows. The system model and relaying protocols are described in Section II. The SNRs for the direct and dual-hop links are derived in Section III. In Section IV, performance analysis of the SR and FR protocols is presented along with the derivations for the diversity gains. The CGs of the two protocols are compared in Section V. Simulation results are presented in Section VI and conclusions are drawn in Section VII.

**Notations:** Upper (lower) bold face letters will be used for matrices (vectors); \((\cdot)^T, (\cdot)^H, E \{ \cdot \}, I_n\) and \(\text{diag}(\mathbf{x})\) denote the transpose, Hermitian transpose, mathematical expectation, \(n \times n\) identity matrix and the diagonal matrix formed from \(x\), respectively. \(\mathcal{R}(\cdot), \mathcal{I}(\cdot), \text{vec}(\mathbf{X}), \text{tr}(\cdot), C/R^{M \times M}, \otimes\), and \((\mathbf{X})_{k,\cdot}\) denote the real part, imaginary part, vectorized form of the matrix \(\mathbf{X}\), matrix trace operator, space of \(M \times M\) matrices with complex/real entries, the Kronecker product, and the \(k\)th row of the matrix \(\mathbf{X}\), respectively. The following relations for matrix operations are often used in this paper [24].

\[
\begin{align}
\text{Re}(\mathbf{AB}) &= [\text{Re}(\mathbf{A})][\text{Re}(\mathbf{B})]^T, \text{Im}(\mathbf{B})^T]_T \\
\text{Im}(\mathbf{AB}) &= [\text{Im}(\mathbf{A})][\text{Re}(\mathbf{B})]^T, \text{Im}(\mathbf{B})^T]_T \\
\text{tr}(\mathbf{A}^T \mathbf{B}) &= \text{vec}(\mathbf{A})^T \text{vec}(\mathbf{B}) \\
\text{vec}(\mathbf{AXB}) &= (\mathbf{B}^T \otimes \mathbf{A}) \text{vec}(\mathbf{X}) \\
(\mathbf{A} \otimes \mathbf{B})(\mathbf{C} \otimes \mathbf{D}) &= (\mathbf{A} \mathbf{C} \otimes \mathbf{B} \mathbf{D})
\end{align}
\]

**II. SYSTEM MODEL AND RELAYING PROTOCOLS**

We consider a cooperative MIMO relay system where a source, a relay and a destination are respectively equipped with \(N_s\), \(N_r\) and \(N_d\) antennas. The block diagram of the system is shown in Fig. 1. The source and relay do not have transmit-side CSI. The source-relay (S-R), relay-destination (R-D) and S-D MIMO channels are assumed to be flat fading spatially correlated Rayleigh channels. The relay is a coherent AF relay, operates in a half-duplex mode and follows either the standard

\(\text{Fig. 1. OSTBC based MIMO relay system}\)
The relay estimates the source signal with a linear MMSE of the source broadcasts its signal with the same target rate is a non-acknowledgment, i.e., an indication for the outage, $T_m$ order constellation, i.e., $r$ and relay. In order to make a fair comparison, we use the signal broadcasts OSTBC encoded signal. Let $\tilde{s}$ and relay. In order to make a fair comparison, we use the source transmits data using the FR protocol, the source transmits at the rate $T_m$. In the FR protocol, during the first transmission phase, the relay transmits, whereas the relay and destination receive the signals received from the relay. On the other hand, if the feedback bit is an acknowledgment, indicating that there is no outage, the source transmits the rate $r_t$ ($N_b$ bits in $T$ channel uses) using the S-D link. In the FR protocol, the destination is said to be in outage when transmissions via both the S-R-D and S-D links fail.\footnote{We consider that when the destination is not in outage, it can correctly decode the source symbol.}

In the FR protocol, during the first transmission phase, the source transmits, whereas the relay and destination receive the signal. In the second transmission phase, the relay transmits the destination combines signals received from the source and relay. In order to make a fair comparison, we use the same target rate as in the SR protocol (i.e., $r_t$) to define the outage at the destination. Because the end-to-end transmission from the source to the destination always occupies $2T$ channel uses in the FR protocol, the source transmits data using the constellation $Q_{2m}$ to maintain the rate $r_t$.

### III. Signal Model and Proposed Scheme

Theorem received by the relay and the destination are, respectively, given by

$$
Y_1 = \sqrt{P_s \mu_1} \tilde{H}_1 \mathbf{S} + V_1 \rightarrow Y_1 = H_1 \mathbf{S} + V_1
$$

$$
Y_3 = \sqrt{P_s \mu_2} \tilde{H}_3 \mathbf{S} + V_3 \rightarrow Y_3 = H_3 \mathbf{S} + V_3
$$

where $H_1 \in C_{N_L \times N_R}$ and $H_3 \in C_{N_R \times N_T}$ are the normalized S-R and S-D MIMO channels, $\mu_1$ and $\mu_2$ are the corresponding path gains, and $P_s$ is the transmit power of the source node.

$V_1 \in C_{N_L \times T}$ and $V_3 \in C_{N_R \times T}$ are due to additive Gaussian noise, where each column of the matrices is a $N_L / N_R$ column vector with correlated complex Gaussian random variables. $\mathbf{S} \in C_{N_T \times T}$ is the OSTBC formed from a set of $K$ complex symbols $\mathbf{S} = [s_1, s_2, \ldots, s_K]$, where $E[|s_k|^2] = 1$, $\forall k$ and $T$ is the number of channel uses during which the channels remain constant (also the time dimension of the OSTBC).

### III. Signal Model and Proposed Scheme

The received signal $Y_1$ is expressed in vector form as

$$
\tilde{Y}_1 = \mathbf{H}_{e, 1} \tilde{\mathbf{Y}}_1 + \mathbf{v}_1, \quad \text{where} \quad Y_1 = \sqrt{P_s} \mathbf{H}_1 \mathbf{S} + V_1
$$

$$
\tilde{Y}_3 = \sqrt{P_s} \mathbf{H}_3 \mathbf{S} + V_3
$$

where $\mathbf{H}_1 \in C_{N_L \times N_R}$ and $\mathbf{H}_3 \in C_{N_R \times N_T}$ are the normalized S-R and S-D MIMO channels, $\mu_1$ and $\mu_2$ are the corresponding path gains, and $P_s$ is the transmit power of the source node.

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$$
\mathbf{S} = \sum_{k=1}^K \mathbf{C}_k \mathbf{R}(s_k) + \mathbf{D}_k \mathbf{I}(s_k).
$$

and $\mathbf{C}_k$ and $\mathbf{D}_k$ are the dispersion matrices. Note that $\mathbf{C}_k = \mathbf{S}(e_k)$ and $\mathbf{D}_k = \mathbf{S}(j e_k)$, where $e_k$ is a vector of ones and zeros with one at the $k$th symbol in $\mathbf{S}$. For an example, in the case of Alamouti code, we have $\mathbf{C}_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\mathbf{C}_2 = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, $\mathbf{D}_1 = \begin{bmatrix} j & 0 \\ -j & 0 \end{bmatrix}$ and $\mathbf{D}_2 = \begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}$. The received signal $\tilde{Y}_1$ is expressed in vector form as

$$
\tilde{Y}_1 = \mathbf{H}_{e, 1} \tilde{\mathbf{Y}}_1 + \mathbf{v}_1, \quad \text{where} \quad Y_1 = \sqrt{P_s} \mathbf{H}_1 \mathbf{S} + V_1
$$

$$
\tilde{Y}_3 = \sqrt{P_s} \mathbf{H}_3 \mathbf{S} + V_3
$$

Note that $y_1$ and $y_3$ are of the size $2N_T \times 1$, whereas $\mathbf{H}_{e, 1}$ has a size of $2N_s \times 2K$. In a similar way, we get $\mathbf{y}_3 = \mathbf{H}_{e, 3} \tilde{\mathbf{y}}_3 + \mathbf{v}_3$. Using the properties of the dispersion matrices, $\mathbf{H}_{e, 1}^T \mathbf{H}_{e, 1}$ and $\mathbf{H}_{e, 3}^T \mathbf{H}_{e, 3}$ are expressed as in [6]-[7] as

$$
\mathbf{H}_{e, 1}^T \mathbf{H}_{e, 1} = ||\mathbf{H}_1||^2 \mathbf{I}_{2K}, \quad \mathbf{H}_{e, 3}^T \mathbf{H}_{e, 3} = ||\mathbf{H}_3||^2 \mathbf{I}_{2K}.
$$

Let $\mathbf{v}_1$ be expressed as $\mathbf{v}_1 = [\mathbf{R}(\mathbf{v}_{1, 1})^T, \ldots, \mathbf{R}(\mathbf{v}_{1, T})^T, \mathbf{I}(\mathbf{v}_{1, 1}), \ldots, \mathbf{I}(\mathbf{v}_{1, T})]^T$, where $\mathbf{v}_{1, t}$, $t = 1, \ldots, T$ is the $t$th column of $\mathbf{V}_1$. Consider that the spatial correlation matrix of noise at the relay is $\mathbf{R}_{\mathbf{v}_{1, 1}} \in C_{N_T \times N_T}$. Then, we express $\mathbf{v}_{1, t}$ as $\mathbf{v}_{1, t} = \mathbf{R}_{\mathbf{v}_{1, 1}}^{\frac{1}{2}} \mathbf{v}_{1, t}$, where the elements of $\mathbf{v}_{1, t}$ are considered to be independent and identically distributed (i.i.d.) zero-mean circularly

$$
\mathbf{R}_{\mathbf{v}_{1, 1}} = \begin{bmatrix} \mathbf{R}(\mathbf{v}_{1, 1}) & \cdots & \mathbf{R}(\mathbf{v}_{1, T}) \\ \cdots & \cdots & \cdots \\ \mathbf{I}(\mathbf{v}_{1, 1}) & \cdots & \mathbf{I}(\mathbf{v}_{1, T}) \end{bmatrix}^T.
$$

\[\text{Note that } y_1 \text{ and } y_3 \text{ are of the size } 2N_T \times 1, \text{ whereas } H_{e, 1} \text{ has a size of } 2N_s \times 2K. \]
symmetric complex Gaussian (ZMCSCG) random variables with unit variance. From (1a)-(1b), we get

\[
\begin{bmatrix}
R(\tilde{R}^*_{v,1}v_{1,t}) = [R(\tilde{R}^*_{v,1}), -I(\tilde{R}^*_{v,1})] \\
\tilde{I}(\tilde{R}^*_{v,1}v_{1,t}) = [\tilde{I}(\tilde{R}^*_{v,1}), R(\tilde{R}^*_{v,1})]
\end{bmatrix}
\]

Thus, \( v_1 \) is expressed as

\[
v_1 = \begin{bmatrix}
I_T \otimes R(\tilde{R}^*_{v,1}) \\
I_T \otimes \tilde{I}(\tilde{R}^*_{v,1}) \\
I_T \otimes R(\tilde{R}^*_{v,1}) \\
\tilde{I}(\tilde{R}^*_{v,1})
\end{bmatrix}
\]

Since \( E \{ \tilde{I}(\tilde{v}_{1,t})\tilde{I}(\tilde{v}_{1,t})^T \} = 0 \) and \( E \{ R(\tilde{v}_{1,t})\tilde{I}(\tilde{v}_{1,t})^T \} = 0 \) for \( t \neq \tilde{t} \), and \( E \{ R(\tilde{v}_{1,t})\tilde{I}(\tilde{v}_{1,t})^T \} = \frac{1}{2} I_{N_v}, \forall t \), we obtain

\[
R_{v,1} = E \{ v_1 v_1^T \} = \frac{1}{2} \begin{bmatrix}
I_T & \otimes R_d \\
I_T & \otimes R_{nd}
\end{bmatrix}
\]

where

\[
R_d = R(\tilde{R}^*_{v,1})R(\tilde{R}^*_{v,1})^T + \tilde{I}(\tilde{R}^*_{v,1})\tilde{I}(\tilde{R}^*_{v,1})^T
\]

\[
R_{nd} = I(\tilde{R}^*_{v,1})R(\tilde{R}^*_{v,1})^T - \tilde{I}(\tilde{R}^*_{v,1})I(\tilde{R}^*_{v,1})^T.
\]

The relay and destination nodes employ MMSE receivers. Consider the S-R MIMO channel. The estimated symbol is expressed as

\[
\hat{s}_r = Z_1^* y_1 = Z_1^T (H_{e,1} \hat{s} + v_1),
\]

where \( Z_1 \in \mathbb{C}^{2N_v \times 2K} \) is a linear receiver at the relay. The MMSE receiver \( Z_1 \) is given by

\[
Z_1 = (H_{e,1}R_sH_{e,1}^H + R_{v,1})^{-1} H_{e,1}^H R_s
\]

where \( R_s = E \{ s \tilde{s} \} \). Since \( E \{ |s_k|^2 \} = 1 \) and \( E \{ s_k \tilde{s}_k \} = 0, \forall k \neq \tilde{k} \), we have \( R_s = \frac{1}{2} I_{2K} \). Thus, the MMSE estimate is given by

\[
\hat{s}_r = H_{e,1}^T (H_{e,1}H_{e,1}^H + 2 R_{v,1})^{-1} (H_{e,1} \hat{s} + v_1).
\]

After using the following matrix-identity [24]

\[
(2R_{v,1} + H_{e,1} H_{e,1}^H)^{-1} H_{e,1} = \frac{1}{2} R_{v,1} H_{e,1} I + \frac{1}{2} H_{e,1}^H R_{v,1}^{-1} H_{e,1}
\]

and defining \( T \triangleq \frac{1}{2} H_{e,1} R_{v,1}^{-1} H_{e,1} \), the MMSE estimate (12) is given by

\[
\hat{s}_r = T (I + T)^{-1} \hat{s} + (I + T)^{-1} \frac{1}{2} H_{e,1}^H R_{v,1}^{-1} v_1.
\]

We show that \( T \) turns to a scaled identity matrix due to the properties of the OSTBC. This result is an extension of (7) which is a specific case with \( R_{v,1} = I_{2N_vT} \) and proved in [7] using constellation space invariance property of OSTBC. Our result for general \( R_{v,1} \) is formulated in the following proposition which in other words establishes the equivalency between the maximum-likelihood (ML) and MMSE receivers for an OSTBC-based MIMO system that is subject to correlated noise.

**Proposition 1**: The estimate \( \hat{s}_t \) of the relay is expressed in the following decoupled form as\(^7\)

\[
\hat{s}_{l,t} = \frac{\alpha_1}{1 + \alpha_1} \hat{s}_l + \frac{1}{1 + \alpha_1} \tilde{v}_l, l = 1, \ldots, 2K,
\]

\[
\alpha_1 = \text{tr} (H_3 H_3^H \tilde{R}_{v,2}^{-1}), \quad \tilde{v}_l = \frac{1}{2} (\tilde{H}_{e,1}^T R_{v,1}^{-1}) v_1.
\]

**Proof**: Please refer to Appendix A.

The destination processes the signal received from the source with the MMSE receiver. Using the result of Proposition 1, the source signal estimated by the destination is given by

\[
\hat{s}_d = \frac{\alpha_3 \hat{s}_l}{1 + \alpha_3} + \frac{1}{2} (\tilde{H}_{e,1}^T) R_{v,1}^{-1} v_3, \quad \alpha_3 = \text{tr} (H_3 H_3^H \tilde{R}_{v,2}^{-1})
\]

where \( v_3 \in \mathbb{C}^{2N_dT \times 1} \) is formed from \( V_3 \) and defined as \( v_1 \) in (5), and \( R_{v,2} = \mathbb{C}^{N_v \times N_d} \) is the correlation matrix of the destination noise. Moreover, \( R_{v,2} \in \mathbb{C}^{2N_dT \times 2N_dT} \) is the function of \( R_{v,2} \) as given by (8) for the case with \( R_{v,1} \). The SNR of the S-D link is then given by

\[
\gamma_3 = \frac{\alpha_3 \alpha_1}{1 + \alpha_3} + \frac{1}{(1 + \alpha_3)^2}.
\]

In the SR protocol, transmission via the relay takes place only when the S-D link fails to support the target rate, whereas in the FR protocol the relay is always used during the second phase of the transmission. The relay normalizes the estimated signal \( \hat{s}_{l,t} \triangleq \hat{s}_{l,t} + j \hat{s}_{l,t} + K, l = 1, \ldots, K \), encodes the normalized signal with the OSTBC and forwards the resulting signal to the destination. The power of the \( l \)th complex symbol received at the relay is given by

\[
E \{ |\hat{s}_{l,t}|^2 \} = \frac{\alpha_1^2 (\alpha_1^2 + \alpha_1 + 1)}{(1 + \alpha_1)^2}.
\]

where we use the facts that \( E \{ |\hat{s}_{l,t} + j \hat{s}_{l,t}|^2 \} = 1 \) and \( E \{ |\hat{s}_{l,t}|^2 \} = E \{ |\hat{s}_{l,t}|^2 \} = \alpha_1 \). The normalized \( l \)th complex symbol \( \overline{y}_{l,t} \) at the relay is expressed as

\[
\overline{y}_{l,t} = \sqrt{\frac{\alpha_1}{1 + \alpha_1}} (\hat{s}_{l,t} + j \hat{s}_{l,t}) + \frac{1}{\alpha_1} (\tilde{v}_l + j \tilde{v}_l + K).
\]

Let \( \overline{y}_{k,t} = [\overline{y}_{k,t}, \ldots, \overline{y}_{K,t}]^T \in \mathbb{C}^{K \times 1} \). The relay employs OSTBC which is a function of \( \overline{y}_{k,t} \) in (3) and transmits the resulting \( R_{t} \times T \) signal to the destination. The \( N_d \times T \) matrix of received signal samples at the destination is given by

\[
Y_2 = \frac{\mu}{N_r} H_2 S(\overline{y}_r) + V_2 = H_2 S(\overline{y}_r) + V_2
\]

where \( H_2 \) is the normalized \( N_d \times T \) R-D MIMO channel, \( \mu \) is the corresponding path gain, \( V_2 \) is \( N_d \times T \) matrix of

\[^7\]Notice that the proposed analysis with the MMSE receiver is general since the derivations of this proposition can be straightforwardly extended to the case where interferers employ OSTBCs and their channels are known [26].
noise signals at the destination and $S(y_t)$ is the $N_T \times T$ OSTBC formed from complex symbols $y_t$. The path gain $\mu_2$ is given by $d_2^{-\gamma}$, where $d_2$ is the R-D distance. The destination also employs MMSE receiver to decode the source signal from $Y_2$. Using Proposition 1, the estimated source signal at the destination is derived in the following proposition. This proposition in fact establishes equivalency between the ML and MMSE receivers for an OSTBC-MIMO relay system where noise at both relay and destination nodes are spatially correlated.

**Proposition 2:** The estimated source signal from $Y_2$ is given by

$$\hat{s}_{l,d} = \frac{\hat{\alpha} \hat{s}_l}{\hat{\alpha} + 1} + \left(1/2\right)[H_{l,2}^{-1}/I_l] \hat{v}, l = 1, \cdots, 2K, (22)$$

where $\hat{\alpha} = \frac{1}{\alpha_1 + \alpha_2 + 1}$ and

$$\alpha_2 = \text{tr} \left( H_{l,2} H_{l,2}^{-1} R_{l,1}^{-1} \right), H_{l,2} = \sqrt{\frac{\alpha_1}{\alpha_1 + 1}} H_{l,2},$$

$$\hat{v} = H_{l,2} \left(1/2\right) H_{l,2}^{-1} R_{l,1}^{-1} v_1 + v_2, R_{l,2} = E[\hat{v}^H \hat{v}], (23)$$

$v_2 \in R^{2N_T \times 1}$ and $H_{l,2} \in R^{2N_T \times 2K}$ are given as in (4)-(6).

**Proof:** Please refer to Appendix B. □

From Proposition 2, the SNR of the S-R-D link is given by

$$\gamma_{1-2} = \frac{\text{tr} \left( H_{1,2} H_{1,2}^{-1} R_{1,1}^{-1} \right)}{\text{tr} \left( H_{1,2} H_{1,2}^{-1} R_{1,2}^{-1} \right)} + 1. (24)$$

It is clear from (22) that the estimated source symbols at the destination do not interfere with each other. As such, application of OSTBCs at the source and relay, and the linear MMSE receivers at the relay and destination makes symbol by symbol decoding possible. Therefore, the MMSE receivers are optimal.

**IV. PERFORMANCE ANALYSIS**

In this section, exact and asymptotic expressions of the outage probability are derived for the SR protocol, whereas the asymptotic expression is derived for the FR protocol. Based on the asymptotic expressions, diversity gains are obtained for both protocols.

Using double-sided Kronecker’s correlation model [27], the MIMO channels (S-R, R-D and S-D) are given by

$$H_m = \sqrt{\eta_1} R_{e,m} H_{w,m} R_{e,m}^{-1}, m = 1, 2, 3, \eta_3 = \frac{P_3 h_1}{N_3}, \eta_2 = \frac{P_2 h_2}{N_2}, \eta_3 = \frac{P_3 h_3}{N_3}, (25)$$

where $R_{e,m}$ and $R_{v,m}$ are respectively, the receive-side and transmit-side correlation matrices for the $i$th MIMO channel. The entries of $H_{w,m}$ are assumed to be i.i.d. ZMCSG random variables. Substituting $H_m$ from (25) into $\alpha_m$ yields $\alpha_m = \eta_m^\nu \left( H_{w,m}^H R_{e,m}^{-1} R_{v,m}^{-1} H_{w,m} R_{e,m} \right), m = 1, 2$ and $\alpha_m = \eta_m^\nu \left( H_{w,m}^H R_{e,m}^{-1} R_{v,m}^{-1} H_{w,m} R_{e,m} \right), m = 3$. Using the facts that $\text{tr}(X^H A X B) = \text{vec}(X)^H \text{vec}(A X B) = \text{vec}(X)^H (B^T \otimes A) \text{vec}(X)$ [24], we get

$$\alpha_m = \eta_m \text{vec}(H_{w,m})^H \left[ R_{e,m}^{-1} \otimes \left( R_{v,m}^{-1} R_{e,m}^{-1} \right) \right] \text{vec}(H_{w,m}). (26)$$

Define $\Phi_m \triangleq R_{e,m}^{-1} \otimes (R_{v,m}^{-1} R_{e,m}^{-1})$ and let $\Phi_m = U_m \Lambda_m U_m^H$ be the eigen decomposition of $\Phi_m$, where $U_m$ are the unitary matrices and $\Lambda_m$ are the diagonal matrices with the eigenvalues. $\alpha_m$ is expressed as

$$\alpha_m = \text{vec}(H_{w,m})^H U_m (I_m \Lambda_m) (U_m^H \text{vec}(H_{w,m})) \triangleq h_m^H \Lambda_m h_m. (27)$$

where $\Lambda_m = \eta_m \Lambda_m$ and $h_m = \text{vec}(H_{w,m})^H U_m (I_m \Lambda_m)$. Since $U_m$ are unitary matrices, and the elements of $\text{vec}(H_{w,m})^H U_m (I_m \Lambda_m)$ are i.i.d. ZMCSG random variables, the entries of $h_m$ remain i.i.d. ZMCSG random. Let $\Lambda_m = \text{diag} \{ \lambda_1^{(m)}, \cdots, \lambda_{L_m}^{(m)} \}$, $\alpha_m$ is written as $\alpha_m = \sum_{i=1}^{L_m} \lambda_i^{(m)} |h_i^{(m)}|^2$, where $h_i^{(m)}$ is the $i$th element of $h_m$. Since $h_i^{(m)}$, $\forall i$, are i.i.d. ZMCSG with the unit variance, $|h_i^{(m)}|^2$ are exponentially distributed with the unit rate parameter. Consequently, $\alpha_m, \forall m$ are the weighted sum of the exponentially distributed random variables. Assuming that $\{\lambda_i^{(m)}\}$ are distinct for a given $m$\(^1\), the probability density function (PDF) of $\alpha_m$ is given by [28]

$$f_{\alpha_m}(z) = \sum_{i=1}^{L_m} a_i^{(m)} e^{-\lambda_i^{(m)}},$$

$$\text{with } a_i^{(m)} = \frac{(\lambda_i^{(m)})^{L_m-2}}{\prod_{j=1, j \neq i}^{L_m} (\lambda_i^{(m)} - \lambda_j^{(m)})}. (28)$$

**A. Outage Probability of Selection Relaying**

Note that the transmission through the relay is employed only if the direct link is in outage, i.e., when $\ln 2(1 + \gamma_3) \leq r_1$. Therefore, the destination will be in outage if the relay is selected (i.e., direct link is in outage) and corresponding transmission is in outage. The outage probability at the destination is\(^1\)

$$P_o = \text{Pr} \left\{ \frac{1}{2} \ln 2 + \gamma_1 \right\} \leq r_1, \ln 2(1 + \gamma_3) \leq r_1 \right\}$$

$$= \text{Pr} \left\{ \gamma_1 \leq 2^{r_1} - 1 \right\} \text{Pr} \left\{ \gamma_3 \leq 2^{r_1} - 1 \right\}. (29)$$

Let us define $P_{o,1} = \text{Pr} \left\{ \gamma_1 \leq 2^{r_1} \right\}$ with $\gamma_1 \leq 2^{r_1} - 1$ and $P_{o,3} = \text{Pr} \left\{ \gamma_3 \leq 2^{r_1} - 1 \right\}$ with $\gamma_3 \leq 2^{r_1} - 1$. Using\(^1\)

The assumption is made so that the difference between the SR and FR protocols can be analytically established in a comprehensive way. Nonetheless, due to the structure of eigenvalues of noise [17]-[22] and channel correlation matrices [29] in practice, the probability of having non-zero eigenvalues of multiplicity greater than one is minimum for $\Phi_m$ [24].

\(^1\)For notational clarity of the derivations, we consider full-rate OSTBC without loss of generality (w.l.o.g). Thus, the rate of the OSTBC does not appear in the expressions of performance analysis.
the PDF of $\alpha_3$, $P_{o,3}$ is expressed as

$$P_{o,3} = 1 - \sum_{i=1}^{L_3} a_i^{(3)} \lambda_i^{(3)} e^{-r_{i}^{(3)}} = 1 - \tilde{P}_{o,3}$$  \hspace{1cm} (30)$$

where we use the fact that $\sum_{i=1}^{L_3} a_i^{(3)} \lambda_i^{(3)} = 1$. We express $P_{o,1}$ as

$$P_{o,1} = \int_{1}^{\infty} \int_{1}^{r_1} \Pr \{ \alpha_3 x + 1 \} f_{o,2}(x) dx$$

$$= \int_{1}^{\infty} \int_{1}^{r_1} \Pr \{ \alpha_3 x + 1 \} f_{o,2}(x) dx$$

where the last step is due to $\Pr \{ \alpha_3 x + 1 \} = 1$ for $0 \leq x \leq r_1$. With the help of (28) and the relation $\sum_{i=1}^{L_1} a_i^{(1)} \lambda_i^{(1)} = 1$, we obtain

$$\Pr \left\{ \alpha_3 x + 1 \right\} = 1 - \sum_{i=1}^{L_1} a_i^{(1)} \lambda_i^{(1)} e^{-r_{i}^{(1)}} x^{(1)} \lambda_i^{(1)}.$$

(31) Using (31) and (28), the integral $I_2$ is expressed as

$$I_2 = \int_{1}^{\infty} \int_{1}^{r_1} f_{o,2}(x) dx = \frac{L_1}{1-x} \sum_{i=1}^{L_1} a_i^{(1)} \lambda_i^{(1)}$$

$$× \int_{1}^{\infty} e^{-r_{i}^{(1)}} x^{(1)} \lambda_i^{(1)} f_{o,2}(x) dx.$$  \hspace{1cm} (32)$$

Noting that $\int_{1}^{\infty} f_{o,2}(x) dx = \int_{1}^{\infty} f_{o,2}(x) dx = 1$, making a variable substitution $x' = x - r_1$ and applying [eq. (3.324.1), [30] ], $P_{o,1}$ is given by

$$P_{o,1} = 1 - \sum_{i=1}^{L_1} \sum_{k=1}^{L_2} a_i^{(1)} \lambda_i^{(2)} \lambda_k^{(2)} e^{-\frac{1}{\lambda_i^{(1)}} - \frac{1}{\lambda_k^{(2)}}} \beta_{i,k} K_1(\beta_{i,k}),$$

(33) where $\beta_{i,k} = 2\sqrt{r_{i}^{(1)}}(1 + \lambda_i^{(1)})$ and $K_1(\cdot)$ is the modified first-order Bessel function of the second type. Therefore, the closed-form expression for the outage probability $P_o = P_{o,1}P_{o,3} = P_{o,1} - P_{o,1}P_{o,3}$ is obtained. However, the exact expression remains complicated, and thus, sufficient metrics and the corresponding insights may not be obtained. As such, we derive a novel asymptotic expression for $P_o$. Our key contribution in this regard is to carefully identify the properties of functions of the coefficients $a_i^{(m)}$ and exploit those properties to derive the asymptotic expressions that have simplified form and do not further depend on $a_i^{(m)}$.

1. Asymptotic analysis of selection relaying: We propose an asymptotic analysis (i.e., high SNR analysis) of $P_o$. Define $\Phi_m = U_m A_m U_m^H$, where $A_m = \text{diag}(\lambda_1^{(m)}, \ldots, \lambda_{L_m}^{(m)})$ is the diagonal matrix of non-zero eigenvalues of $\Phi_m$ and $U_m$ is the matrix of columns of $U_m$ corresponding to these non-zero eigenvalues. Then, the main result is expressed in the following proposition.

Proposition 3: The outage probability of the SR protocol at high SNR is approximated as

$$P_o \approx \frac{c_2 c_3}{\eta_1^{3} \eta_3^{3} \det(\Phi_2) \det(\Phi_3)} + \frac{c_1 c_3}{\eta_1^{3} \eta_3^{3} \det(\Phi_2) \det(\Phi_3)}$$

(34)

where $c_m = \frac{r_{m+1}}{r_m}$, $r_m$ for $m = 1$, 2, and $r_2 = r_3$ for $m = 3$.

Proof: Please refer to Appendix C.

Let $\{\eta_m\}_{m=1}^{3}$ be expressed in terms of $\rho \equiv \frac{P_r}{N_0}$ as $\eta_m = \delta_m \rho, \forall m$, where $\delta_1 = \delta_4^{(-)}$, $\delta_2 = \delta_5^{(-)}$ (with $\frac{P_r}{N_0} = \delta_2 \rho, \delta_2 > 0$) and $\delta_3 = \delta_3^{(-)}$. Substituting these values into (34), we obtain

$$P_o \approx \frac{c_2 c_3}{\delta_2 \delta_3^{(-)} \det(\Phi_2) \det(\Phi_3)} + \frac{c_1 c_3}{\delta_1 \delta_3^{(-)} \det(\Phi_2) \det(\Phi_3)}$$

$$\approx \frac{c_2 c_3}{\delta_1 \delta_3^{(-)} \det(\Phi_2) \det(\Phi_3)} \rho^{-L_m + L_3}$$

where $\delta_m = \arg \min \{L_1, L_2, L_3\}$. Comparing (35) with the standard asymptotic result $P_o \approx (G_c \rho)^{-G_d}$ [33], where $G_c$ and $G_d$ are respectively the coding and diversity gains, we find that the diversity order of the SR protocol is min$(L_2 + L_3, L_1 + L_3)$. When all MIMO channels and noise are spatially uncorrelated, $L_1 = N_s N_t$, $L_2 = N_r N_t$, and $L_3 = N_s N_d$, i.e., the diversity gain of the SR protocol becomes $N_r N_t + \min(N_s N_t, N_r N_t)$ which, in fact, is the maximum diversity gain of a coherent MIMO relay system [14].

B. Asymptotic Analysis of Fixed Relaying

The FR protocol always uses the MIMO relay. In the first transmission phase, the source transmits, whereas the relay and destination listen to the source. In the second transmission phase, the relay transmits and the destination combines signals received from the source and destination. The outage probability of the FR protocol is therefore given by

$$P_{o,fr} = \Pr \left\{ \frac{1}{2} \ln_2 \left( 1 + \gamma_{l_1} + \gamma_{l_2} + \gamma_{l_3} - \gamma_{l_1} \right) \right\}.$$  \hspace{1cm} (36)$$

We derive a new asymptotic expression for $P_{o,fr}$ and determine the diversity gain of the FR protocol. Using the approximation that $\gamma_{l_1} - \gamma_{l_2} \approx \frac{\alpha_1 + \alpha_2}{\alpha_1 + \alpha_2 + 1}$, we approximate $P_{o,fr}$ as

$$P_{o,fr} \approx \int_{0}^{\infty} \int_{0}^{\infty} \Pr \{ \min(\alpha_1, \alpha_2) \leq \tilde{\gamma}_1 - \gamma \} f_{o,3}(\gamma) dy$$

$$= \int_{0}^{\infty} \int_{0}^{\infty} \Pr \{ \min(\alpha_1, \alpha_2) \geq \tilde{\gamma}_1 - \gamma \} f_{o,3}(\gamma) dy,$$  \hspace{1cm} (37)$$

where $\tilde{\gamma}_1 = \frac{\alpha_1 + \alpha_2}{\alpha_1 + \alpha_2 + 1}$.

Since $\Pr \{ \alpha_1 \leq \tilde{\gamma}_1 - \gamma \} = 1 - \sum_{i=1}^{L_1} \alpha_i^{(1)} \lambda_i^{(1)} e^{-\frac{1}{\lambda_i^{(1)}}}$ and $\Pr \{ \alpha_2 \leq \tilde{\gamma}_1 - \gamma \} = 1 - \sum_{k=1}^{L_2} \alpha_k^{(2)} \lambda_k^{(2)} e^{-\frac{1}{\lambda_k^{(2)}}}$, $P_{o,fr}$ in (37)
is expressed as
\[
P_{o,fr} \approx \int_0^{\hat{f}} \left[ 1 - \sum_{i=1}^{L_1} \sum_{k=1}^{L_2} a_1^{(1)}(\lambda_i^{(1)}) a_2^{(2)}(\lambda_k^{(2)}) e^{-\left(\frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}}\right)} \right] e^{-\left(\frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}}\right)f_{o,3}(y)} dy, \tag{38}
\]
Substituting \(f_{o,3}(y)\) into (38), \(P_{o,fr}\) is re-expressed as
\[
P_{o,fr} \approx 1 - P_{o,3} - \sum_{i=1}^{L_1} \sum_{k=1}^{L_2} \sum_{l=1}^{L_3} a_1^{(1)}(\hat{\lambda}_i^{(1)}) a_2^{(2)}(\hat{\lambda}_k^{(2)}) a_3^{(3)}(\tilde{\lambda}_{i,k,l}) e^{-\left(\frac{1}{\hat{\lambda}_i^{(1)}} + \frac{1}{\hat{\lambda}_k^{(2)}}\right)} - e^{-\left(\frac{1}{\tilde{\lambda}_{i,k,l}} + \frac{1}{\tilde{\lambda}_{i,k,l}}\right)} \tag{39}
\]
where \(\tilde{\lambda}_{i,k,l} = \frac{1}{\hat{\lambda}_i^{(1)}} + \frac{1}{\hat{\lambda}_k^{(2)}} - \frac{1}{\tilde{\lambda}_{i,k,l}}\) and \(P_{o,3} = 1 - \sum_{l=1}^{L_3} a_1^{(3)}(\hat{\lambda}_l^{(3)}) e^{-\left(\frac{1}{\hat{\lambda}_l^{(3)}}\right)}\). The final result of the asymptotic expansion for \(P_{o,fr}\) is given in the following proposition.

**Proposition 4:** For high SNR, \(P_{o,fr}\) is approximated as
\[
P_{o,fr} \approx \frac{p_{L_1+L_3}}{(L_1 + L_3)! \eta_1^{-1} \eta_3^{-1} \det(\Phi_1) \det(\Phi_3)} \left[ 1 + \frac{L_2}{(L_2 + L_3)! \eta_2^{-1} \eta_3^{-1} \det(\Phi_2) \det(\Phi_3)} \right]. \tag{40}
\]

**Proof:** Please refer to Appendix D. \(\square\)

As in the case of SR protocol, w.l.o.g., consider that \(\eta_m = \delta_m \rho, \forall m\). Then, (40) is expressed as
\[
P_{o,fr} \approx \frac{p_{L_1+L_3}}{(L_1 + L_3)! \delta_m \eta_m^{-1} \det(\Phi_m) \det(\Phi_3)} \rho^{-(L_m+L_3)} \tag{41}
\]
By comparing (41) with \(P_{o,fr} \approx (G_c \rho)^{-G_1}\), we find that the diversity order of the FR protocol is also \(\min(L_1+L_3, L_2+L_3)\). For uncorrelated channels and noise, the FR protocol achieves maximum diversity gain of \(N_s N_r + \min(N_s, N_r)\) as in the SR protocol.

V. COMPARISON OF CODING GAINS

The CGs of the SR and FR protocols can be expressed, respectively, from (35) and (41) as
\[
G_{c,1} = \left[ \frac{p_{L_1} p_{L_3}}{L_1! L_3! \det(\Phi_m) \det(\Phi_3)} \right]^{L_m + L_3},
\]
\[
G_{c,2} = \left[ \frac{p_{L_1+L_3}}{(L_m + L_3)! \det(\Phi_m) \det(\Phi_3)} \right]^{L_m + L_3}. \tag{42}
\]

\(^{14}\)The main contribution is to rigorously utilize the properties of functions of \(a^{(m)}_i\) to derive a general simplified asymptotic expression that does not further depend on \(a^{(m)}_i\). As it will be evident from Section V, the advantage of this contribution is that we are able to propose a comprehensive asymptotic analysis of the SR and FR protocols and provide important insights on their performance.

which means that the CG of the SR is better than that of the FR protocol if
\[
\frac{p_{L_1} p_{L_3}}{L_1! L_3!} \leq \frac{p_{L_1} p_{L_3}}{(L_1 + L_3)!} \Rightarrow \frac{2^{\gamma} - 1}{2^{2\gamma} - 1} \leq \left( \frac{L_m! L_3!}{(L_m + L_3)!} \right)^{\frac{1}{L_1+L_3}} \tag{43}
\]
where the last step is due to \(r_1 > 0\). It is very difficult to simplify the term on the right-hand side of (43) for general values of \(L_m\) and \(L_3\). However, important insights can be obtained by analyzing (43) for some specific cases.

A. Case A: \(L_m = 1, L_3 \geq 1\)

This is the case when one of the two-hop MIMO channels reduces to rank-one due to perfect spatial correlation or is a single-input single-output (SISO) channel. For this case, (43) simplifies to \(\frac{1}{2^{2\gamma} + 1} \leq \left( \frac{1}{L_1+L_3} \right)^{\frac{1}{L_1+L_3}}\). It can be readily shown that \(\frac{1}{2} \leq \left( \frac{1}{L_1+L_3} \right)^{\frac{1}{L_1+L_3}} \leq 1\) for any \(L_3 \geq 1\). This means that \(G_{c,1} \leq G_{c,2}\) if \(r_1 > 0\). Consequently, the CG of the SR protocol is always better than that of the FR protocol in this case, and when all nodes are single-antenna nodes.

B. Case B: \(L_m = L_3 = L > 1\)

In this case, the direct channel is as good as one of the two-hop links in terms of effective ranks. Using Stirling's approximation for a factorial of an integer (8.327.21 of [30]), \(L!\) can be lower and upper bounded as
\[
\sqrt{2\pi L} \left( \frac{L}{e_c} \right)^L \leq L! \leq e_c \sqrt{L} \left( \frac{L}{e_c} \right)^L \tag{44}
\]
where \(e_c \approx 2.718\) is Euler's number [30]. From (44), the following bounds are obtained
\[
(L!L!)^{\frac{1}{2}} \geq \left( \sqrt{2\pi L} \left( \frac{L}{e_c} \right)^L \right)^{\frac{1}{2}},
\]
\[
((2L)!)^{\frac{1}{2}} \leq e_c \sqrt{2L} \left( \frac{2L}{e_c} \right)^{2L}^{\frac{1}{2}}, \tag{45}
\]
which yield the following lower bound to \(\left( \frac{L!L!}{(2L)!} \right)^{\frac{1}{2}}\)
\[
\left( \frac{L!L!}{(2L)!} \right)^{\frac{1}{2}} \geq \frac{1}{4} \left( \frac{\sqrt{2\pi}}{e_c} \right)^{\frac{1}{2}} L^{\frac{1}{2}}. \tag{46}
\]
Let \(\tilde{y} = \frac{1}{4} L^{\frac{1}{2}} \sqrt{2\pi} \), where \(s_c \approx 1.634\). By plotting \(\tilde{y}\) for \(L \geq 1\), we easily observe that \(\tilde{y}\) is a monotonically decreasing function of \(L\). Alternatively, this can be verified from the first-order derivative of \(y\) w.r.t. \(L\). As such, the minimum value of \(\tilde{y}\) is obtained when \(L \to \infty\). It can be readily shown that \(\tilde{y} \to 1\) as \(L \to \infty\). Therefore, (46) can be further lower bounded as
\[
\left( \frac{L!L!}{(2L)!} \right)^{\frac{1}{2}} \geq \frac{1}{4}, \tag{47}
\]
Consequently, the inequality in (43) can be further tightened as
\[
\frac{1}{2^{2\gamma} + 1} \leq \frac{1}{4}. \tag{47}
\]
This means that, irrespective of the value of \( L \), the CG of the SR protocol is better than that of the FR scheme as long as \( r_t \geq \ln 2(3) \).

**C. Case C: \( L_\delta = 1 \), \( L_{\tilde{b}} > 1 \)**

This is the case when the S-D channel is in the worst-scenario when compared to the two-hop link in terms of rank. For this case, (43) simplifies to \( \frac{1}{2^{\gamma + 1}} \leq \frac{1}{L_{\tilde{b}} + 1} \). Note that \( L_{\tilde{b}} \leq \min(N_s, N_t, N_d) \), i.e., the inequality is further tightened as \( \frac{1}{2^{\gamma + 1}} \leq \frac{1}{\min(N_s, N_t, N_d) + 1} \). For the desired full-rate OSTBCs (e.g., the Alamouti code), the number of antennas at transmit-side nodes turns to \( N_t = N_s = 2 \). Since \( N_d = 1 \) is implicitly included in Case A, we obtain \( 1 - \frac{1}{2^{\gamma + 1}} \leq \frac{1}{2} \). This means that the CG of the SR protocol is better than that of the FR protocol if \( r_t \geq 2 \). With this analysis, we end this section with the following remarks.

**Remark 1:** When the effective rank of the S-D link is lower bounded by the minimum rank of the two-hop links, the SR protocol outperforms the FR protocol if the target information rate lies above zero or some small value (Cases A and B). However, when the S-D channel is in the worst-scenario (in terms of effective rank), depending on the value of \( N_t \), the SR protocol can be better than the FR only for larger values of \( r_t \). Nevertheless, if Alamouti code is employed to avoid rate reduction, the CG of the SR protocol becomes better than the FR protocol with \( r_t \geq 2 \).

**Remark 2:** It is worthwhile to perform a large scale analysis of the proposed system having a large number of antennas at the source and relay nodes (i.e., \( (N_s, N_t) \to \infty \)). Since such analysis for a general case with spatially correlated channels and noise is much more involved and beyond the scope of this manuscript, we consider a case when channels and noise are spatially uncorrelated. Due to implementation and cost constraints at the destination node, \( N_d \) is assumed to be fixed. For the uncorrelated case, the end-to-end two-hop SNR is given by

\[
\gamma_{1-2}^{u} = \frac{\eta_{1} \eta_{2} \text{tr}(H_{w,1}^H H_{w,1}) \text{tr}(H_{w,2}^H H_{w,2})}{\eta_{1} \text{tr}(H_{w,1}^H H_{w,1}) + \eta_{2} \text{tr}(H_{w,2}^H H_{w,2}) + 1} = \frac{a_{1} \text{vec}(H_{w,1}^H \text{vec}(H_{w,1})) + a_{3} \text{vec}(H_{w,2}^H \text{vec}(H_{w,2}))}{d_{2} \text{vec}(H_{w,1}^H \text{vec}(H_{w,1})) + d_{3} \text{vec}(H_{w,2}^H \text{vec}(H_{w,2})) + 1} \tag{48}
\]

where we use \( \mathbf{R}_{m} = \mathbf{R}_{m} = \mathbf{R}_{m} = \mathbf{1} \), \( \forall m, m' \), \( \text{tr}(H_{w,m} H_{w,m'}) = \text{vec}(H_{w,m})^H \text{vec}(H_{w,m}), \forall m, m' \), \( a_{1} = P_{t} P_{t} \mu_{1} \mu_{2} N_{t} N_{d} \), \( a_{2} = P_{t} \mu_{1} N_{t} \), and \( a_{3} = P_{t} \mu_{2} N_{d} \). The elements of \( \text{vec}(H_{w,m}) \) are i.i.d. random variables with zero-mean and unit-variance. Applying the law of large numbers [34], we obtain

\[
\frac{\text{vec}(H_{w,1})^H \text{vec}(H_{w,1})}{N_{t} N_{t}} \to 1, \text{ as } (N_{s}, N_{t}) \to \infty, \tag{49}
\]

\[
\frac{\text{vec}(H_{w,2})^H \text{vec}(H_{w,2})}{N_{t} N_{d}} \to 1, \text{ as } N_{t} \to \infty. \tag{49}
\]

Substituting (49) into (48), the asymptotic value of \( \gamma_{1-2}^{u} \) is given by

\[
\gamma_{1-2}^{u} \to \frac{P_{t} P_{t} \mu_{1} \mu_{2} N_{t} N_{d}}{P_{t} \mu_{1} N_{t} + P_{t} \mu_{2} N_{d} + 1} \text{ as } (N_{s}, N_{t}) \to \infty \tag{50}
\]

which after simple step reduces to

\[
\gamma_{1-2}^{u} \to P_{t} \mu_{2} N_{d} \text{ as } (N_{s}, N_{t}) \to \infty. \tag{51}
\]

Similarly, using law of large numbers in \( \gamma_{3}^{u} = \eta_{3} \text{tr}(H_{w,3}^H H_{w,3}) \) as \( N_{s} \to \infty \), \( \gamma_{3}^{u} \) is given by

\[
\gamma_{3}^{u} \to P_{t} \mu_{3} N_{d} \text{ as } N_{s} \to \infty. \tag{52}
\]

As such, for \( (N_{s}, N_{t}) \to \infty \) and fixed \( N_{d} \), the SR protocol selects the relay only when \( \ln 2(1 + P_{t} \mu_{3} N_{d}) < r_{t} \), and outage occurs if both \( \ln 2(1 + P_{t} \mu_{3} N_{d}) \) and \( \frac{1}{2} \ln 2(1 + P_{t} \mu_{2} N_{d}) \) are smaller than \( r_{t} \). However, in the FR protocol, the outage occurs if \( \frac{1}{2} \ln 2(1 + P_{t} \mu_{2} N_{d}) < r_{t} \). It is interesting to note that as \( (N_{s}, N_{t}) \to \infty \) and \( N_{d} \) is fixed, the outage depends only on \( N_{d} \).

**VI. Numerical results**

In this section, we provide Monte Carlo simulation results to assess the accuracy of the exact and asymptotic outage probability expressions. As a benchmark performance, we also show the performance of the FR protocol with the MRC receiver. The fast fading components of all MIMO channels, i.e., \( H_{w,m}, \forall m \) are taken from the entries of 2MCSG random variables with unit variances. Throughout all simulations, the S-D distance is normalized, i.e., \( d_{3} = 1 \), whereas the S-R and R-D distances are respectively taken as \( d_{1} = 0.5d_{3} \) and \( d_{2} = 1 - d_{1} \). This means that the relay is located at the midpoint between the source and destination. The path loss exponent \( \zeta \) takes the values of 2 and 3.

For all results, we take \( P_{s} = P_{r} = P, n_{s} = n_{r} = n_{d} = 2 \), and use Alamouti code. For comparing theoretical and simulation results, a common average SNR \( \rho \) is used, which is varied by changing \( P \). In all simulations, we take \( \mathbf{R}_{\nu,1} = \mathbf{R}_{\nu,2} = \begin{bmatrix} 1 & 0.5 \\ 0.5 & 1 \end{bmatrix} \) and exponential correlation models for channels, i.e., \( \mathbf{R}_{\nu,m} = \mathbf{R}_{\nu,m} = \begin{bmatrix} 1 & \nu_{m} \\ \nu_{m} & 1 \end{bmatrix} \) with \( \nu_{m} \geq 0 \).

In Figs. 2 and 3, the outage probability versus SNR is displayed for the SR protocol, and the FR protocol that employs the MMSE and MRC receivers. We take \( \nu_{m} = \nu = 0.4, \forall m \) in both figures, and \( r_{t} = 3 \) b.p.c.u and \( r_{l} = 5 \) b.p.c.u in Figs. 2 and 3, respectively. It can be observed from these figures that the SR method performs better than the FR protocol. In particular, at the outage probability of \( 10^{-2} \), the SR protocol, respectively, provides gains of around 2.5 dB and 3.5 dB.
outage probability over the FR method with the MMSE and MRC receivers when $\zeta = 2$. These gains reduce to around 2 dB and 3 dB, respectively, when $\zeta = 3$ due to the fact that the attenuations of the S-R and R-D links decrease. As the value of $r_t$ increases (e.g., from 3 to 5 b.p.c.u), the relative gain of the SR method over the FR-based methods improves further. For example, at the outage probability of $10^{-2}$, the respective gains of the SR method over the FR-based MMSE and MRC methods are around 7.5 dB and 8.4 dB when $\zeta = 2$, and around 5.7 dB and 6.8 dB when $\zeta = 3$. Fig. 4 shows the outage probability versus $r_t$ for different methods, where we fix $\rho$ to 18 dB and take $\nu_m = \nu = 0.4, \forall m$. This figure also shows that the SR protocol outperforms the methods based on FR protocol. At the outage probability of $10^{-2}$, the gains of the SR method over the FR method with the MMSE and MRC receivers are about 1.1 and 1.2 b.p.c.u, respectively, when $\zeta = 2$, and 0.9 and 1 b.p.c.u when $\zeta = 3$. This result also shows that when two-hop channel gains improve, the gain of the SR method over the FR-based schemes starts to decrease. In Fig. 5, the outage performance of different methods is depicted when the S-R and R-D channels observe much higher spatial correlation than the S-D channel. For this purpose, we take $\nu_m = 0.9, m = 1, 2$ and $\nu_3 = 0.1$. The target rate is set to $r_t = 3$ b.p.c.u. At the outage probability of $10^{-2}$, the SR method provides around 2.7 dB and 3.2 dB improvements over the FR scheme with the MMSE and MRC receivers, respectively, when $\zeta = 2$. When $\zeta = 3$, these improvements reduce to around 1.8 dB and 2.5 dB, respectively. As in previous results, it is seen that the benefit of the SR method starts to shrink when the attenuations of the two-hop channels decrease.

The SR method is compared with the FR scheme employing MMSE and MRC receivers in Fig. 6 by considering that the S-D channel observes much higher spatial correlation than the S-R and R-D channels. As such, we take $\nu_2 = 0.9$ and $\nu_1 = \nu_2 = 0.1$. In this figure, the target rate is fixed to $r_t = 5$ b.p.c.u. For the outage probability of $10^{-2}$, the respective gains of the SR method over the FR scheme with the MMSE and MRC receivers are about 4.25 dB and 5.1 dB when $\zeta = 2$, and 3.1 dB and 4.1 dB when $\zeta = 3$. As in Figs. 2-5, Fig. 6 shows that the gain of the SR method w.r.t. to the FR-based methods increase when path-loss exponent decreases from 3 to 2. In a nutshell, it can be observed from Figs. 5 and 6 that the SR method provides better performance than the FR methods in all of the considered examples. In Fig. 7, the asymptotic outage probability expressions of the SR and FR protocols are shown for $r_t = 3$ b.p.c.u and $r_t = 2$ b.p.c.u. We take $\nu_m = 0.2, \forall m$ and $\zeta = 2$ in this figure. It can be observed from Fig. 7 that
the asymptotic outage probabilities of both protocols converge
to corresponding actual outage probabilities as SNR increases.
When \( r_1 \) increases, the gap between the asymptotic and the
actual outage probabilities increases in the low SNR region.
However, it can be seen that the derived asymptotic outage
probability of the SR protocol is much tighter than that of the
FR protocol at low SNR region. Moreover, for a small value
of \( r_1 \) (e.g., \( r_1 = 0.8 \)), the FR protocol performs better than
the SR protocol. The corresponding simulation results are not
shown in this paper due to space constraints. However, all of
these results are in accordance with the theoretical results of
Section V.

We also investigate the relative performance difference
between the SR and FR protocols for different relay positions.
Although simulation results are not shown for conciseness,
we find that the SR protocol significantly outperforms the
FR-based methods for all positions of the relay, where the
best performance of all methods is obtained when the relay
is located at around the mid-point between the source and
destination.

VII. CONCLUSIONS

In this paper, selection relaying protocol is proposed for
an OSTBC-based coherent AF MIMO relay system where the
direct link between the source and the destination exists, and
the channels and noise are spatially correlated. Asymptotic
expressions of the outage probability are derived for the
selection and fixed relaying protocols. It is shown that the
performance of both protocols depends on the rank of a
composite matrix which is a function of the channel and noise
spatial correlation matrices. Moreover, both protocols achieve
the same diversity gain. However, small values of target
information rate can be sufficient for the selection relaying
protocol to have better coding gain than the fixed relaying
protocol. Simulation results show that the former protocol
significantly outperforms the latter protocol with the MMSE
and MRC receivers, especially for larger values of the target
rate. These results may justify the complexity due to one-
bit feedback requirement in the selection protocol. Moreover,
the benefits of the selection relaying approach is much more
pronounced when the attenuations of the two-hop channels
increase.

APPENDIX A: PROOF OF PROPOSITION 1

Let \( t(p,q) \) be the \((p,q)\)th element of \( T \) where \( p,q = 1, \cdots 2K \). Then, \( t(p,q) \) is expressed as
\[
t(p,q) = \frac{1}{2} \left[ \text{vec} \left( H_{1,R} \tilde{C}_p^T \right), \text{vec} \left( H_{1,I} \tilde{C}_p^T \right) \right]^T \mathbf{R}_{1,1}^{-1} \]
\[
\times \left[ \text{vec} \left( H_{1,R} \tilde{C}_q^T \right), \text{vec} \left( H_{1,I} \tilde{C}_q^T \right) \right]^T \mathbf{R}_{1,1}^{-1} \]
\[
= \frac{1}{2} \left[ \text{vec} (\tilde{C}_p^T (I_T \otimes H_{1,R}^H), \text{vec} (\tilde{C}_q^T (I_T \otimes H_{1,I}^H)) \right]\]
\[
\times \mathbf{R}_{1,1}^{-1} \left[ \text{vec} (\tilde{C}_p^T (I_T \otimes H_{1,R}^H), \text{vec} (\tilde{C}_q^T (I_T \otimes H_{1,I}^H)) \right] \]
\[
\text{where } \tilde{C}_p = \left[ \mathcal{R}(C_p)^T, \mathcal{I}(C_p)^T \right]^T, \ H_{1,R} = \mathcal{R}(H_1), \ H_{1,I} = \mathcal{I}(H_1), \ \text{and we}
\]

have used (1a)-(1b) and (1d). For a positive definite matrix
\( X \) of complex values, we know that
\[
\mathbf{R}_{1,1}^{-1} \mathbf{I} \mathbf{R}_{1,1}^{-1} = \left[ \begin{array}{cc} \mathcal{R}(X) & -\mathcal{I}(X) \\ \mathcal{I}(X) & \mathcal{R}(X) \end{array} \right]^{-1} \left[ \begin{array}{cc} \mathcal{R}(X^{-1}) & -\mathcal{I}(X^{-1}) \\ \mathcal{I}(X^{-1}) & \mathcal{R}(X^{-1}) \end{array} \right].
\]

Using (54), we express \( \mathbf{R}_{1,1}^{-1} \)
\[
\mathbf{R}_{1,1}^{-1} = \left[ \begin{array}{cc} I_T\otimes\mathcal{R}(\tilde{C}_p^T), -I_T\otimes\mathcal{I}(\tilde{C}_p^T) \\ I_T\otimes\mathcal{I}(\tilde{C}_p^T), I_T\otimes\mathcal{R}(\tilde{C}_p^T) \end{array} \right],
\]

where we use the fact that \( \tilde{C}_p = R_1 + jR_{nd} \). Substituting
\( \mathbf{R}_{1,1}^{-1} \) from (55) into (33), using (1e) and after some
simplifications, we express \( t(p,q) \) as
\[
t(p,q) = \left( \vec{C}_p^T I_T \otimes \vec{H}_1 \right) \vec{C}_q,
\]

where
\[
\vec{H}_1 = \left[ \begin{array}{c} \vec{H}_{1,R}^T, \vec{H}_{1,I}^T \end{array} \right], \quad \left[ \begin{array}{cc} \mathcal{R}(\tilde{C}_p^T), -\mathcal{I}(\tilde{C}_p^T) \\ \mathcal{I}(\tilde{C}_p^T), \mathcal{R}(\tilde{C}_p^T) \end{array} \right] \left[ \begin{array}{cc} \mathcal{R}(\tilde{C}_q^T), -\mathcal{I}(\tilde{C}_q^T) \\ \mathcal{I}(\tilde{C}_q^T), \mathcal{R}(\tilde{C}_q^T) \end{array} \right]^{-1} \left[ \begin{array}{c} \vec{H}_{1,R} \vec{H}_{1,I} \end{array} \right].
\]

Applying (1d) and (1c) to (56), \( t(p,q) \) is re-expressed as
\[
t(p,q) = \text{tr} \left( \vec{C}_p^T \vec{C}_q^T \vec{H}_1 \right) = \left\{ \begin{array}{ll}
\text{tr} (\vec{H}_1 \vec{H}_1^T \vec{R}_{1,1}^{-1}), & p = q \\
0, & p \neq q
\end{array} \right.
\]

where the last equality is due to the properties of the dispersion
matrices. The same result can be shown for \( (p,q) = K +
1, \cdots, 2K \), i.e., for the terms including \( D_{1,1} D_{1,1}^T \) and \( C_{1,1} D_{1,1}^T \).

Therefore, \( T \) reduces to the following scaled identity matrix
\[
T = \text{tr} (\vec{H}_1 \vec{H}_1^T \vec{R}_{1,1}) I_{2K}.
\]

Substituting (58) into (14), \( \tilde{s}_r \) is expressed as
\[
\tilde{s}_r = \frac{\text{tr} (\vec{H}_c \vec{H}_c^T \vec{R}_{1,1}^{-1})}{1 + \text{tr} (\vec{H}_1 \vec{H}_1^T \vec{R}_{1,1}^{-1})} \tilde{s}_i + \frac{(1/2)\vec{H}_c \vec{R}_{1,1}^{-1} \vec{v}_1}{1 + \text{tr} (\vec{H}_1 \vec{H}_1^T \vec{R}_{1,1}^{-1})},
\]

which means that the \( l \)th element \((l = 1, \cdots, 2K)\) of \( \tilde{s}_r \) is
\[
\tilde{s}_r(l) = \frac{\alpha_1}{1 + \alpha_1} \tilde{s}_i(l) + \frac{1}{1 + \alpha_1} \left( \frac{1/2}{\vec{H}_c \vec{R}_{1,1}^{-1}} \right) v_1(l),
\]

where \( \tilde{s}_i(l) \) is the \( l \)th element of \( \tilde{s} \triangleq [\tilde{s}_1, \cdots, \tilde{s}_K, \tilde{s}_{K+1}, \cdots, \tilde{s}_{2K}]^T \). This completes the proof
of Proposition 1.

\[\square\]

APPENDIX B: PROOF OF PROPOSITION 2

Using similar steps as (4)-(6) for the S-R MIMO channel,
(21) is expressed in vector form as
\[
\vec{y}_2 = H_{c,2} \vec{y}_r + \vec{v}_2, \quad \text{where}
\]
\[
\vec{y}_r = \sqrt{\frac{\alpha_1}{(1 + \alpha_1)}} \vec{s}_i + \sqrt{\frac{1}{\alpha_1(1 + \alpha_1)} \frac{1}{2}} H_{c,1}^T \vec{R}_{1,1}^{-1} \vec{v}_1,
\]

and \( \vec{y}_2 \in \mathbb{R}^{2N_d T \times 1} \) is given as in (4)-(6). Using \( \tilde{y}_r, y_2 \) in
(61) is expressed as
\[
y_2 = H_{c,2} \sqrt{\frac{\alpha_1}{(1 + \alpha_1)}} \vec{s} + \sqrt{\frac{1}{\alpha_1(1 + \alpha_1)} \frac{1}{2}} H_{c,1}^T \vec{R}_{1,1}^{-1} \vec{v}_1 + \vec{v}_2 = \vec{H}_c^2 \vec{s} + \vec{v}.
\]
Note that $R_{\tilde{v}}$ is given by
\[
R_{\tilde{v}} = \frac{1}{4\alpha_1} \tilde{H}_{e,2} \tilde{H}^T_{e,2} \tilde{R}_{e,1} \tilde{H}^T_{e,1} + \tilde{R}_{v,2}
\]
where $R_{v,2} \in \mathbb{R}^{2N(T) \times 2N(T)}$ is a function of $R_{\tilde{v},2}$ and given as in (8)-(9). Using the steps (10)-(14), the MMSE estimate of the source signal at the destination is given by
\[
\hat{s}_d = \hat{T} \left[ I + \hat{T} \right]^{-1} \tilde{s} + \left[ I + \hat{T} \right]^{-1} \frac{1}{2} \hat{H}^T_{e,2} \tilde{R}_{\tilde{v},2} \tilde{v}
\]
where $\hat{T} = \frac{1}{2} \hat{H}^T_{e,2} \tilde{R}_{e,1}^{-1} \tilde{H}_{e,2}$. Using (63) and (13), $\hat{T}$ is expressed as
\[
\hat{T} = \frac{1}{2} \hat{H}^T_{e,2} \left[ \frac{1}{2\alpha_1} \tilde{H}_{e,2} \tilde{H}^T_{e,2} + R_{v,2} \right]^{-1} \hat{H}_{e,2} = \frac{\alpha_1}{1 + \alpha_1} \frac{1}{\alpha_1 + 1} \tilde{H}_{e,2} \tilde{R}_{e,2}^{-1} \tilde{v}
\]
With the help of (53)-(57), $\frac{1}{2} \hat{H}^T_{e,2} \tilde{R}_{e,2}^{-1} \tilde{H}_{e,2}$ is expressed as
\[
\frac{1}{2} \hat{H}^T_{e,2} \tilde{R}_{e,2}^{-1} \tilde{H}_{e,2} = \text{tr} (\tilde{H}^2 \tilde{H} H^T_{\tilde{v},2}) I_{2K} \triangleq \alpha_2 I_{2K}.
\]
Therefore, we get $\hat{T} = \frac{\alpha_1}{\alpha_1 + 1} \frac{1}{\alpha_1} \tilde{h}_{e,2} = \hat{\alpha}_2 I_{2K}$. Consequently, the estimated signal at the destination is
\[
\hat{s}_d = \frac{\tilde{h}_{e,2}}{\alpha_1 + 1} \tilde{s} + \frac{1}{\alpha_1} (1/2) \hat{H}^T_{e,2} \tilde{R}_{\tilde{v},2} \tilde{v}
\]
which yields (22) with $\hat{s}_d \triangleq \left[ \tilde{s}_1, \ldots, \tilde{s}_K d \right]^T$. This completes the proof of the Proposition 2.

\textbf{APPENDIX C: PROOF OF PROPOSITION 3}

For high SNR regions, $K_1(x)$ can be approximated by $\frac{1}{2}$. Consequently, $P_{o,1}$ is expressed as
\[
P_{o,1} \approx 1 - \sum_{i=1}^{L_1} a_i^{(1)} \frac{1}{\lambda_i^{(1)}} e^{-\frac{x}{\lambda_i^{(1)}}} - \sum_{k=1}^{L_2} a_k^{(2)} \frac{1}{\lambda_k^{(2)}} e^{-\frac{x}{\lambda_k^{(2)}}}
\]
\[
= 1 - P_{o,1} \bar{P}_{o,2}
\]
where $\bar{P}_{o,1}$ and $\bar{P}_{o,2}$ are, respectively, the functions of $\lambda_i^{(1)}$ and $\lambda_k^{(2)}$. Noting that $e^{-x} = \sum_{n=0}^{\infty} \frac{(-1)^n x^n}{n!}$, $P_{o,m}$ is expressed as
\[
\bar{P}_{o,m} = \sum_{i=1}^{L_1} a_i^{(m)} \frac{1}{\lambda_i^{(m)}} - \frac{\tilde{r}}{\tilde{r}^2} 2 \tilde{r}^2 \sum_{i=1}^{L_1} a_i^{(m)} \frac{1}{\lambda_i^{(m)}}
\]
\[
= \frac{1}{6} (\tilde{r})^3 \sum_{i=1}^{L_1} a_i^{(m)} (\lambda_i^{(m)} - 1) + O \left( \frac{1}{\lambda_i^{(m)}} \right), m = 1, 2, 3, (68)
\]
where $\tilde{r} = \tilde{r}_1$ for $m = 1, 2, \tilde{r} = \tilde{r}_2$ for $m = 3$, and $O(x)$ stands for higher-order terms of $x$. Substituting $a_i^{(m)}$ from (28) into (68), and after some simple steps of derivations, we find that the first two terms (denoted by $\tilde{l} = 0, 1$) of (68) reduce to $\sum_{i=1}^{L_1} a_i^{(m)} \lambda_i^{(m)} = 1, \sum_{i=1}^{L_1} a_i^{(m)} = 0$, whereas the terms corresponding to $\tilde{l} = 2$ and $\tilde{l} = 3$ yield
\[
\sum_{i=1}^{L_1} a_i^{(m)} (\lambda_i^{(m)} - 1) = \left\{ \begin{array}{ll} 0 & \text{for } \tilde{l} < L_m \\ \frac{(-1)^{-1-1}}{n_i^{(m)}} & \text{for } \tilde{l} = L_m \end{array} \right. \]
With the help of (69), $\bar{P}_{o,m}$ is approximated at high-SNR region as
\[
\bar{P}_{o,m} \approx 1 - c_m \frac{1}{\prod_{i=1}^{L_1} \lambda_i^{(1)}} = 1 - c_m \frac{1}{\eta_m \det(\Phi_m)} \]
where $c_m = \frac{\tilde{r}_m}{\eta_m}$. Therefore, the outage probability of the SR protocol at high SNR is approximated as
\[
P_o \approx \left( 1 - \left( 1 - c_1 \frac{1}{\eta_1 \det(\Phi_1)} \right) \left( 1 - c_2 \frac{1}{\eta_2 \det(\Phi_2)} \right) \right) \times c_3 \frac{1}{\eta_3 \det(\Phi_3)}
\]
\[
= \frac{c_2 c_3}{\eta_1 \eta_2 \eta_3 \det(\Phi_1) \det(\Phi_2) \det(\Phi_3)} + \frac{c_1 c_3}{\eta_1 \eta_2 \eta_3 \det(\Phi_1) \det(\Phi_3)}
\]
\[
- \frac{3}{\eta_1 \eta_2 \eta_3 \det(\Phi_1) \det(\Phi_3)},
\]
from which (34) follows.

\textbf{APPENDIX D: PROOF OF PROPOSITION 4}

Noting that $e^{-x} = \sum_{n=0}^{\infty} \frac{(-1)^n x^n}{n!}$, we express $t \triangleq e^{-\frac{1}{\lambda_1^{(1)}}} - e^{-\frac{1}{\lambda_1^{(1)} + \frac{1}{\lambda_1^{(2)}}}}$ as
\[
t = \tilde{r}_1 \tilde{\lambda}_i, k, l - \frac{\tilde{r}_1^2}{2} \lambda_i, k, l \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} + \frac{1}{\lambda_i^{(3)}} \right)
\]
\[
+ \frac{\tilde{r}_1^2}{6} \lambda_i, k, l \left( \frac{\lambda_i^{(2)}}{\lambda_i^{(1)}} + 3 \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right) \frac{1}{\lambda_i^{(3)}} \right) - \frac{\tilde{r}_1^4}{24} \lambda_i, k, l
\]
\[
\left[ \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} + \frac{1}{\lambda_i^{(3)}} \right]^2 \left[ \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right]^2 + \frac{1}{\lambda_i^{(3)}} \right]^2 + O \left( \frac{1}{\lambda_i^{(m)}} \right).
\]
Define $t_1 \triangleq \tilde{r}_1 \tilde{\lambda}_i, k, l$ and $t_2 \triangleq \frac{\tilde{r}_1^2}{2} \lambda_i, k, l \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} + \frac{1}{\lambda_i^{(3)}} \right)$. Note that in the following steps, we often use the property
\[
\sum_{i=1}^{L_1} a_i^{(m)} = 0, \sum_{i=1}^{L_1} a_i^{(m)} \lambda_i^{(m)} = 1, \forall m.
\]
Applying (73), it can be shown that
\[
\sum_{i=1}^{L_1} \sum_{k=1}^{L_1} a_i^{(1)} \lambda_i^{(1)} a_k^{(2)} \lambda_k^{(2)} a_l^{(3)} t_{11} = 0,
\]
\[
\sum_{i=1}^{L_1} \sum_{k=1}^{L_1} a_i^{(1)} \lambda_i^{(1)} a_k^{(2)} \lambda_k^{(2)} a_l^{(3)} t_{22} = \tilde{r}_1^2 \sum_{i=1}^{L_1} \sum_{k=1}^{L_1} \sum_{l=1}^{L_1} a_i^{(1)} \lambda_i^{(1)} a_k^{(2)} \lambda_k^{(2)} a_l^{(3)} \lambda_i^{(1)} a_k^{(2)} \lambda_k^{(2)} a_l^{(3)} \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}} + \frac{1}{\lambda_l^{(3)}}.
\]
Let $t_3 \triangleq \frac{r^4}{6} \frac{1}{\lambda_{i,k,l}} \left( \frac{r^2}{\lambda_{i,k,l}} + 3 \left( \frac{1}{\lambda_{i}^{(1)}} + \frac{1}{\lambda_{k}^{(2)}} \right) \frac{1}{\lambda_{i}^{(3)}} \right)$. After some steps of derivations, we obtain

$$
\sum_{i=1}^{L_1} \sum_{k=1}^{L_2} \sum_{l=1}^{L_3} \frac{a_i^{(1)} a_k^{(2)} a_l^{(3)}}{\lambda_{i,k,l}} t_3 = \frac{r^4}{6} \sum_{i=1}^{L_1} \sum_{k=1}^{L_2} \sum_{l=1}^{L_3} a_i^{(1)} \\
\times \lambda_i^{(1)} a_k^{(2)} a_l^{(3)} \left\{ \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}} \right)^2 + \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}} \right) \frac{1}{\lambda_i^{(3)}} + \frac{1}{\lambda_k^{(3)}}^2 \right\}.
$$

(75)

With the definition

$$
\frac{r^4}{6} \frac{1}{\lambda_{i,k,l}} \left[ \frac{1}{\lambda_{i}^{(1)}} + \frac{1}{\lambda_{k}^{(2)}} + \frac{1}{\lambda_{l}^{(3)}} \right] \left[ \frac{1}{\lambda_{i}^{(1)}} + \frac{1}{\lambda_{k}^{(2)}} \right] =
$$

we get

$$
\sum_{i=1}^{L_1} \sum_{k=1}^{L_2} \sum_{l=1}^{L_3} \frac{a_i^{(1)} a_k^{(2)} a_l^{(3)}}{\lambda_{i,k,l}} t_4 = \frac{r^4}{24} \sum_{i=1}^{L_1} \sum_{k=1}^{L_2} \sum_{l=1}^{L_3} a_i^{(1)} \\
\times \lambda_i^{(1)} a_k^{(2)} a_l^{(3)} \left\{ \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}} \right)^3 + \frac{1}{\lambda_i^{(3)}} \right\} \\
\cdot \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_k^{(2)}} \right) \frac{1}{\lambda_i^{(3)}}^2 + \frac{1}{\lambda_k^{(3)}} \right\} \\
\cdot \frac{1}{\lambda_i^{(3)}} \right\} n^{-3} \right\}.
$$

(76)

On the other hand, using (73) and $e^{-x} = \sum_{n=0}^{\infty} \frac{(-1)^n x^n}{n!}$, $P_{o,3}$ is expressed as

$$
P_{o,3} = - \sum_{n=2}^{L_3} \frac{a_i^{(3)} \lambda_i^{(3)}}{n!} \sum_{n=2}^{L_3} \frac{(-1)^n r^n}{n! \lambda_i^{(3)} n}.
$$

(77)

With the help of (72)-(76) and (77), $P_{o,fr}$ is generalized to

$$
P_{o,fr} \approx \sum_{n=2}^{\infty} \frac{r^n}{n!} \frac{1}{\lambda_i^{(1)}} \frac{1}{\lambda_i^{(2)}} \frac{1}{\lambda_i^{(3)}} n^{-2} \\
\times \left\{ \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right)^{n-2} + \frac{1}{\lambda_i^{(3)}} + \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right)^{n-3} \left( \frac{1}{\lambda_i^{(3)}} \right)^2 \\
+ \ldots + \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right)^{n-3} \left( \frac{1}{\lambda_i^{(3)}} \right)^{n-3} \\
+ \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right) \frac{1}{\lambda_i^{(3)}} \right\}.
$$

(78)

In order to find the non-zero terms with the lowest order of $\frac{1}{\lambda_i^{(m)}}$, $q = (i,k,l)$, we apply (69) and (73) to (78). This means that when $L_1 = L_2 = L_12$, the non-zero terms with the lowest order of $\frac{1}{\lambda_i^{(m)}}$, $q = (i,k,l)$ are contained in

$$
t_d(n) = \left( \frac{1}{\lambda_i^{(1)}} + \frac{1}{\lambda_i^{(2)}} \right)^{n-L_3} \frac{1}{\lambda_i^{(3)}}^{L_3-1}, \quad n - L_3 = L_12
$$

(79)

whereas, for $L_1 \neq L_2$, such terms are contained in $t_d(n)$ corresponding to two different values of $n$. In particular, these values are $n_1 = L_1 + L_3$ and $n_2 = L_2 + L_3$. Furthermore, applying (69), $t_d(n)$ reduces to

$$
t_d(n_1) = \left( \frac{1}{\lambda_i^{(1)}} \right)^{L_1-1} \left( \frac{1}{\lambda_i^{(3)}} \right)^{L_3-1},
$$

(80)

Applying (80) in (78), $P_{o,fr}$ is approximated at high SNR as

$$
P_{o,fr} \approx \frac{\rho^{L_1 + L_3}}{L_1 + L_3} \sum_{i=1}^{L_3} \frac{a_i^{(1)}}{\lambda_i^{(1)}} \sum_{i=1}^{L_2} \frac{a_i^{(2)}}{\lambda_i^{(2)}} \sum_{i=1}^{L_3} \frac{a_i^{(3)}}{\lambda_i^{(3)}} \\
+ \frac{\rho^{L_2 + L_3}}{L_2 + L_3} \sum_{k=1}^{L_2} \frac{a_k^{(2)}}{\lambda_k^{(2)}} \sum_{k=1}^{L_3} \frac{a_k^{(3)}}{\lambda_k^{(3)}} \\
+ \frac{\rho^{L_1 + L_3}}{L_1 + L_3} \sum_{l=1}^{L_3} \frac{a_l^{(3)}}{\lambda_l^{(3)}}
$$

(81)

Applying (69) in (81), $P_{o,fr}$ is further expressed as

$$
P_{o,fr} \approx \frac{\rho^{L_1 + L_3}}{L_1 + L_3} \prod_{i=1}^{2} \frac{1}{\lambda_i^{(1)}} \prod_{i=1}^{2} \frac{1}{\lambda_i^{(3)}}
$$

(82)

which means that $P_{o,fr}$ is generalized as in (40). This completes the proof of the Proposition 4.

REFERENCES


