An Equivalence Principle for OFDM-Based Combined Bulk/Per-Subcarrier Relay Selection over Equally Spatially Correlated Channels

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Abstract—In this paper, we propose a novel relay selection scheme for orthogonal frequency-division multiplexing (OFDM) systems by combining conventional bulk and per-subcarrier selection schemes, and analyze its outage performance over equally spatially correlated channels. Specifically, the combined selection scheme selects only two relays at the first attempt and performs per-subcarrier selection over these two relays. We analyze the asymptotic outage performance of the combined selection scheme in the high signal-to-noise (SNR) region, and prove a generalized theorem. This theorem states that the combined selection can achieve an optimal outage probability equivalent to the per-subcarrier selection at high SNR without using the full set of available relays for selection. This unique property is termed the equivalence principle, and it holds for all correlation conditions. To explore this principle, we consider three examples: decode-and-forward (DF), fixed-gain (FG) amplify-and-forward (AF) and variable-gain (VG) AF relay systems. Furthermore, two extended applications, antenna selection and branch selection, are also considered to reveal the feasibility and the expandability of the equivalence principle. Our analysis is verified by Monte Carlo simulations. The proposed combined selection and the proved theorem provide a general and feasible solution to the trade-off between system complexity and outage performance when relay selection is applied.

Index Terms—Combined selection, relay selection, channel correlation, OFDM, asymptotic analysis.

I. INTRODUCTION

SINCE the proposal of combined bulk/per-subcarrier selection designed specifically for transmit antenna selection, combined selection has shown its excellent properties in terms of reducing system complexity and obtaining optimal outage performance [1]. Meanwhile, the cooperative network, as an important concept in the field of communication engineering, has been proposed and analytized for decades [2]–[4]. With the development of cooperative networks, the combined selection scheme is regarded as an effective method to reduce the system complexity and simultaneously obtain the optimal performance at high signal-to-noise ratio (SNR) for orthogonal frequency-division multiplexing (OFDM) relay systems [5]. By the combined bulk/per-subcarrier selection, only two out of the total available relays are selected according to a certain criterion and the per-subcarrier selection is performed over these two relays for all subcarriers individually. Its applicability in cooperative networks over independent and identically distributed (i.i.d.) channels is numerically analyzed in [9]. Also, a practical implementation scheme of combined selection is proposed in [10] and a comprehensive comparison among these three selection schemes in super dense networks are provided in [11]. To be more clear, the proposed combined selection scheme as well as the conventional bulk and per-subcarrier selection schemes are illustrated in Fig. 1.

Most previous works on combined relay selection assume i.i.d. fading channels, which are practically rare owing to the insufficient physical separations among relays [12]. The performance analysis of combined selection over spatially correlated fading channels is still an open issue. By literature review, a number of relevant correlated channel models can be considered. A comprehensive analysis of outage probability of multi-branch selection over spatially correlated fading channels was reported in [13]. A triple channel correlation scenario is considered in [14], but it cannot be applied to a general multi-branch case with an arbitrary number of parallel branches. The most useful and relevant spatially correlated channel model for our study is given in [15], in which a set of channel gains produced by equally correlated channels can be transfered to a set of conditionally independent channel gains. Employing this model, we are able to analyze the outage performance using conventional analytical tools, e.g. order statistics. Therefore, in this paper, we employ the correlation model proposed in [15] to analyze a general OFDM system applying combined relay selection.

It should be noted that we only consider the equally spatial correlation among channels within the same hop and still maintain the i.i.d. assumption between the channels in two hops, which is different from the cross-hop correlation scenario presented in [16]. This is simply because we assume all relays are physically stationary over a coherent time interval, so that the correlation produced by Doppler shift between two hops is negligible [16]. We assume a block fading model in frequency akin to systems that employ a resource block frame/packet structure (e.g. LTE), and hence the i.i.d. assumption in frequency holds. The identical distri-

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1Note that, in this paper the combined relay selection employed is different from the multi-relay selection schemes proposed in [6]–[8]. In particular, each subcarrier is only forwarded by one relay, and all transmissions corresponding to all subcarriers are carried out simultaneously.
As a compromise selection scheme 1) Combined selection: As a compromise selection scheme between bulk and per-subcarrier selections, combined selection scheme first selects two relays according to the criterion

\[ L_{\text{comb}} = \arg \max_{L_2 \subseteq M} \min_{k \in K} \max_{m \in L_2} \text{SNR}(m, k) \]  

\[ (3) \]

\(^2\)The CSI is usually estimated through pilots and feedback (e.g., [21]) and the CSI estimation without feedback may also be applied (e.g., [22]).
where $L_2$ identifies a pair of relays that can be employed to carry out per-subcarrier selection and $|L_2| = 2^3$. Obviously, we have $M(M-1)/2$ available options of $L_2$ in total.

After that, per-subcarrier selection is performed over the two relays in $L_{comb}$ in a per-subcarrier manner by

$$l_{comb}(k) = \arg \max_{l \in L_{comb}} \text{SNR}(l, k).$$

Therefore, when combined selection is employed, the a posteriori outage probability depending on selection can be defined as

$$F_{comb}(s) = \mathbb{P}\{\min_{k \in K} \max_{l \in L_{comb}} \text{SNR}(l, k) < s\}. \quad (5)$$

2) Per-subcarrier selection: Per-subcarrier selection scheme selects multiple relays (up to $K$) from $M$ relays in a per-subcarrier manner so that all subcarriers can be forwarded via their optimal relays and thus the optimal outage performance is attainable. For the $k$th subcarrier, the selection criterion is thereby

$$L_{ps}(k) = \arg \max_{m \in M} \text{SNR}(m, k).$$

Therefore, when per-subcarrier selection is employed, the a posteriori outage probability can be defined as

$$F_{ps}(s) = \mathbb{P}\{\min_{k \in K} \max_{m \in M} \text{SNR}(m, k) < s\}. \quad (7)$$

Although there exist three commonly used relay selection schemes for OFDM systems, the equivalence principle potentially exists between combined and per-subcarrier selections only [1]. Therefore, we only analyze and compare the outage performances of per-subcarrier and combined selections in the rest of this paper.

III. OUTAGE PERFORMANCE ANALYSIS

A. Conditionally independent variable transformation

As detailed in [15], we take a similar approach to transform a set of equally correlated random variables to a set of conditionally independent random variables, so that conventional analytical tools, e.g. order statistics can be applied to analyze them effectively. To do so, we first assume that two references for each subcarrier $x_{0i}(k)$ and $y_{0i}(k)$ are fixed and have $x_{0i}(k) = X_{0i}(k)$ and $y_{0i}(k) = Y_{0i}(k)$. Therefore, the conditional distribution of $h_i(m, k)$ is $CN(\sqrt{\rho_i}([X_{0i}(k) + jY_{0i}(k)]/\mu_i(1 - \rho_i))$. Consequently, given $x_{0i}(k) = X_{0i}(k)$ and $y_{0i}(k) = Y_{0i}(k)$, $|h_i(m, k)|^2 \sim \chi_2^2(\sqrt{\rho_i}X_{0i}^2(k) + Y_{0i}^2(k))/\mu_i(1 - \rho_i)$. If we denote $T_i(k) = X_{0i}^2(k) + Y_{0i}^2(k)$, the conditional probability density function (PDF) and the conditional cumulative distribution function (CDF) of $|h_i(m, k)|^2$ are given by [23]

$$f_{h_i}(s|T_i(k)) = \frac{1}{\mu_i(1 - \rho_i)} e^{-\frac{\mu_i(1 - \rho_i) s}{2\rho_i T_i(k)}} I_0 \left(\frac{2\sqrt{\rho_i T_i(k) s}}{\mu_i(1 - \rho_i)}\right), \quad (8)$$

and

$$F_{h_i}(s|T_i(k)) = 1 - Q\left(\frac{2\rho_i T_i(k)}{\mu_i(1 - \rho_i)}, \frac{2s}{\mu_i(1 - \rho_i)}\right), \quad (9)$$

where $I_0(\cdot)$ is the zero order modified Bessel function of the first kind; $Q(\cdot, \cdot)$ is the first order Marcum Q function.

Meanwhile, the PDF and CDF of $T_i(k)$ can be obtained as:

$$f_{T_i}(T_i(k)) = \frac{1}{\mu_i} e^{-\frac{T_i(k)}{\mu_i}} \Rightarrow F_{T_i}(T_i(k)) = 1 - e^{-\frac{T_i(k)}{\mu_i}}. \quad (10)$$

Denote $T_1 = \{T_1(1), T_1(2), \ldots, T_1(K)\}$ and $T_2 = \{T_2(1), T_2(2), \ldots, T_2(K)\}$. Because $\forall i \in \{1, 2\}$ and $k \in K$, $T_1(k)$ are mutually independent, we thereby can derive the joint PDF corresponding to $T_1$ and $T_2$ by

$$f_T(T_1, T_2) = \left(\frac{1}{\mu_1 \mu_2}\right)^K \prod_{k=1}^{K} \left(\frac{e^{-\frac{T_1(k)}{\mu_1}} - e^{-\frac{T_2(k)}{\mu_2}}}{\mu_1 - \mu_2}\right). \quad (11)$$

Accordingly, we can denote the conditional a priori outage probability as $F(s|T_1(k), T_2(k))$. We can also denote the conditional a posteriori outage probabilities for combined selection and per-subcarrier selection as $F_{comb}(s|T_1, T_2)$ and $F_{ps}(s|T_1, T_2)$ respectively.

B. Asymptotic outage performance: main results

We present the all-important contribution of this paper here. A generalized equivalence principle can be stated as follows.

Theorem 1: If the conditional CDF of the end-to-end SNR, $F(s|T_1(k), T_2(k))$, can be expanded in the variable $\frac{\gamma}{\bar{\gamma}} = \frac{T_1}{N_0}$ as

$$F(s|T_1(k), T_2(k)) = \sum_{i=0}^{\infty} c_i(s|T_1(k), T_2(k)) \left(\frac{1}{\gamma}\right)^{\frac{i}{\bar{\gamma}}} \frac{1}{\bar{\gamma}} \ln (\frac{\bar{\gamma}}{\gamma})^\gamma,$$

where $i_0$ is an integer given by $i_0 = \arg \min_{n \in \mathbb{N}} \{c_i(s|T_1(k), T_2(k)) \neq 0\}$; $\theta$ is a nonzero natural number; $c_i(s|T_1(k), T_2(k))$ represents a series of functions of $s$, given $T_1(k), T_2(k)$; $r \in \mathbb{N}$, then combined selection is able to achieve an outage probability equivalent to conventional per-subcarrier selection as $\gamma \to \infty$.

Proof: This is a powerful theorem not only suiting two-hop relay selection, but also applying to transmit antenna selection and multi-hop branch selection by a slight modification (See Section V). We will show the proof of this theorem step by step in the following subsections.

1) Combined selection: Similar to Lemma 1 proposed in [1], we here propose and prove a genocenic lemma for the a posteriori outage performance of combined selection in the high SNR region for relay systems, which is also valid over correlated channels.

Lemma 1: Consider a generic two-hop OFDM system performing combined selection over $K$ orthogonal subcarriers and $M$ relays. By applying combined relay selection scheme, the worst possible end-to-end SNR has at least the $M$th smallest value out of the total $MK$ end-to-end SNRs.
Proof: We can take exactly the same step as given in [1] for the proof of the first part of Lemma 1 in that paper, but only vary the term ‘channel gain’ considered in multiple-input and multiple-output (MIMO) systems to ‘end-to-end SNR’ considered in two-hop cooperative systems. The validity of the proof still holds for this congeneric lemma, because the internal logic of this lemma does not change when considering different diversity systems.

From Lemma 1, it is clear that once an outage event occurs, there must exist at least one subcarrier on which all M end-to-end SNRs via M relays drop below the outage threshold. Also, it is well known that the outage event is dominated by the deepest fade at high SNR and is asymptotic to the case where only one subcarrier on which all M end-to-end SNRs via M relays drop below the outage threshold at high SNR [24]. Consequently, we have

\[ F_{\text{comb}}(s|T_1, T_2) = \sum_{k=1}^{K} \left[ F(s|T_1(k), T_2(k)) \right]^{M} + O \left( (F(s|T_1(k), T_2(k)))^{M+1} \right). \]  \hfill (13)

Therefore, according to (12), the asymptotic expression for \( F_{\text{comb}}(s|T_1, T_2) \) at \( \bar{\gamma} \to \infty \) can be determined by

\[ F_{\text{comb}}(s|T_1, T_2) \sim \sum_{k=1}^{K} \left\{ c_{i_0}(s|T_1(k), T_2(k)) \left( \frac{1}{\bar{\gamma}} \right)^{\psi_2} \left[ \ln (\bar{\gamma}) \right]^r \right\}^M. \]  \hfill (14)

2) Per-subcarrier selection: Similar to the derivation performed for combined selection, according to (7), the conditional outage probability of per-subcarrier selection can be asymptotically expressed by [25]

\[ F_{ps}(s|T_1, T_2) = 1 - K \sum_{k=1}^{K} \left\{ 1 - F(s|T_1(k), T_2(k)) \right\}^{M} \]

\[ \sim \sum_{k=1}^{K} \left\{ c_{i_0}(s|T_1(k), T_2(k)) \left( \frac{1}{\bar{\gamma}} \right)^{\psi_2} \left[ \ln (\bar{\gamma}) \right]^r \right\}^M. \]  \hfill (15)

3) Unconditional outage performance: Comparing the same asymptotic expressions given in (14) and (15), it is clear that when both multiply (11) and are integrated by \( T_1 \) and \( T_2 \) from zero to infinity, they will produce the same asymptotic outage performance as

\[ \{ F_{\text{comb}}(s), F_{ps}(s) \} \sim K \left( \frac{1}{\mu_1 \mu_2} \right) \left\{ \left( \frac{1}{\bar{\gamma}} \right)^{\psi_2} \left[ \ln (\bar{\gamma}) \right]^r \right\}^M \]

\[ \times \int_{0}^{\infty} \int_{0}^{\infty} \{ c_{i_0}(s|T_1, T_2) \}^{M} (e^{-\frac{T_1}{\psi_1}} e^{-\frac{T_2}{\psi_2}}) dT_1 dT_2. \]  \hfill (16)

By (16), Theorem 1 is proved.

IV. ASYMPTOTIC OUTAGE PERFORMANCE ANALYSIS WITH RELAY SELECTION

A. DF relay selection

According to [26], the equivalent instantaneous end-to-end SNR corresponding to the kth subcarrier and the mth relay using a DF protocol can be expressed as

\[ \text{SNR}(m, k) = \frac{P_t}{N_0} \min \left( |h_1(m, k)|^2, |h_2(m, k)|^2 \right). \]  \hfill (17)

For brevity, denote \( \psi_1 = \mu_k(1 - \rho_1)/2 \) and \( \gamma_k = |h_k(m, k)|^2 \). By series expansion, we can determine the asymptotic expression for the conditional CDF of the equivalent instantaneous end-to-end SNR for the kth subcarrier at high SNR:

\[ F(s|T_1(k), T_2(k)) \sim \left( \frac{s}{2} \left( e^{-\frac{\psi_1 T_1(k)}{2\psi_1}} + e^{-\frac{\psi_2 T_2(k)}{2\psi_2}} \right) \right) \frac{1}{\gamma_k}. \]  \hfill (18)

Proof: See Appendix A.

Hence, by (12), \( c_{i_0}(s|T_1(k), T_2(k)) \) can be determined by

\[ c_{i_0}(s|T_1(k), T_2(k)) = \frac{s}{2} \left( e^{-\frac{\psi_1 T_1(k)}{2\psi_1}} + e^{-\frac{\psi_2 T_2(k)}{2\psi_2}} \right). \]  \hfill (19)

Then, by (16), the unconditional outage probabilities for both selection schemes are determined by

\[ \{ F_{\text{comb}}(s), F_{ps}(s) \} \sim K(1 - \rho_1)(1 - \rho_2) \left( \frac{s}{2\gamma} \right)^M \sum_{m=0}^{M} \left( \frac{M}{m} \right) \left( \frac{1}{\psi_1} \right)^{M-m} \left( \frac{1}{\psi_2} \right)^m \]

\[ \times \left[ 1 + \rho_1(M - m - 1) + \rho_2(m - 1) \right]. \]  \hfill (20)

B. FG AF relay selection

It is also well known that for FG AF relay system, the instantaneous end-to-end SNR can be expressed as [27]

\[ \text{SNR}(m, k) = \frac{|h_1(m, k)|^2 |h_2(m, k)|^2 P_t^2}{(\mu_k P_t + |h_2(m, k)|^2 P_t + N_0)N_0}. \]  \hfill (21)

By (8) and (9), we can derive the asymptotic expression for the conditional CDF at \( \bar{\gamma} \to \infty \) by

\[ F(s|T_1(k), T_2(k)) \sim \left( \frac{M}{4\psi_1 \psi_2} e^{-\frac{\psi_1 T_1(k)}{2\psi_1}} e^{-\frac{\psi_2 T_2(k)}{2\psi_2}} \right) \ln (\bar{\gamma}) \]. \hfill (22)

Proof: See Appendix B.

Consequently, \( c_{i_0}(s|T_1(k), T_2(k)) \) is given by

\[ c_{i_0}(s|T_1(k), T_2(k)) = \frac{\mu_k s}{4\psi_1 \psi_2} e^{-\frac{\psi_1 T_1(k)}{2\psi_1}} e^{-\frac{\psi_2 T_2(k)}{2\psi_2}}. \]  \hfill (23)

Therefore, according to (16), we have

\[ \{ F_{\text{comb}}(s), F_{ps}(s) \} \sim \left( \frac{k(1 - \rho_1)(1 - \rho_2)}{1 + \rho_1(M - 1) + \rho_2(M - 1)} \right) \left( \frac{M}{4\psi_1 \psi_2} \right) \ln (\bar{\gamma}) \]. \hfill (24)

4In fact, an outage in DF relaying networks depends on the minimum channel coefficient among the source-relay and the relay-destination links. Hence, we can employ the minimum channel coefficient as the equivalent channel quality indicator here.
C. VG AF relay selection

Similarly, the instantaneous end-to-end SNR for VG AF case can be given by [27]

\[ \text{SNR}(m, k) = \frac{|h_1(m, k)|^2|h_2(m, k)|^2P_i^2}{(|h_1(m, k)|^2P_i + |h_2(m, k)|^2P_i + N_0)N_0}. \]  

(25)

Again, performing series expansion at \( \gamma \rightarrow \infty \) yields the asymptotic expression for \( F(s|T_1(k), T_2(k)) \) for VG AF relay systems

\[ F(s|T_1(k), T_2(k)) \sim \left[ \frac{s}{2} \left( e^{-\frac{\bar{\gamma}T_1(k)}{\psi_1}}/\psi_1 + e^{-\frac{\bar{\gamma}T_2(k)}{\psi_2}}/\psi_2 \right) \right] \frac{1}{\bar{\gamma}}. \]  

(26)

Proof: See Appendix C.

Obviously, \( c_{io}(s|T_1(k), T_2(k)) \) for VG AF relay system is exactly the same as given in (19). Likewise, by (16), the unconditional outage probability in VG AF relaying network can be determined by

\[ \{F_{comb}(s), F_{ps}(s)\} \sim K(1 - \rho_1)(1 - \rho_2) \left( \frac{s}{2\bar{\gamma}} \right)^M \sum_{m=0}^{M} \left( \begin{array}{c} M \\ m \end{array} \right) \left( \frac{1}{\sqrt{s}} \right)^{M-m} \left( \frac{1}{\psi_2} \right)^m \left( 1 + \rho_1(M - m - 1) \right)^{1 + \rho_1(m - 1)} \left( 1 + \rho_2(m - 1) \right)^{1 + \rho_2(m - 1)}. \]  

(27)

Note, the unconditional outage probability of VG AF relay systems (c.f. (27)) is exactly the same as that given in DF relay systems (c.f. (20)), which aligns with the numerical results presented in [28]. Also, by the definition of the diversity gain

\[ d_o = -\lim_{\bar{\gamma} \rightarrow \infty} \frac{\log F_{comb}(s)}{\log \bar{\gamma}}, \]  

(28)

we can see that for all three kinds of relays, the diversity gain is the same value given by the number of relays \( M \). That is, the diversity advantage of combined selection will not be shadowed by different forwarding protocols and channel correlations and is only related to the number of available relays.

V. ASYMPTOTIC OUTAGE PERFORMANCE ANALYSIS WITH OTHER SELECTIONS

As we analyzed in the previous section, combined relay selection is powerful in terms of its outstanding outage performance and is able to reduce the system complexity\(^5\). Furthermore, the equivalence principle can be applied to other selection scenarios with a slight modification of the proposed theorem, e.g. transmit antenna selection and multi-hop branch selection. In this section, two examples are presented to illustrate the feasibility and the expandability of combined selection in other scenarios.

\(^5\)To be more specific, the system complexity referred here is related to the number of selected relays, because this number is closely related to the selection and synchronization processes [10]. In addition, combined selection will reduce the number of relays that are accessed for transmission compared to per-subcarrier selection, which will bring an extra system-level efficiency improvement [11].

A. Transmit antenna selection with selection combining

In this subsection, combined transmit antenna selection is analyzed. Before analyzing, it should be clarified that although combined transmit antenna selection has been analyzed in [1], it does not consider channel correlation. Therefore, the combined transmit antenna selection with selection combining over spatially correlated channels is first analyzed in our paper.

A typical MIMO system with combined transmit antenna selection can be illustrated in Fig. 2. Here, \( M \) transmit antennas and \( N \) receive antennas are considered. Also, the received signal is produced by selection combining at the receiver for each subcarrier. For the convenience purpose, we assume the physical separation among receive antennas is large enough, so that channel correlation only exists at the transmitter. Therefore, we can assume the channel from the \( m \)th transmit antenna to the \( n \)th receive antenna for the \( k \)th subcarrier is organized by

\[ h(m, k, n) = \left[ \sqrt{1 - \rho x(m, k, n)} + \sqrt{\rho x_0(k)} \right] + j\left[ \sqrt{1 - \rho y(m, k, n)} + \sqrt{\rho y_0(k)} \right], \]  

(29)

where \( x(m, k, n), y(m, k, n), x_0(k) \) and \( y_0(k) \) are i.i.d. as \( N(0, \mu/2) \); \( \rho \) is the cross-correlation coefficient. Again, we can fix \( x_0(k) \) and \( y_0(k) \) and denote \( T(k) = X_0^2(k) + Y_0^2(k) \), so that \( h(m, k, n)^2 \sim \chi^2(\sqrt{\rho T(k)}, \mu(1 - \rho)) \).

Therefore, the average SNR from the \( mn \)th transmit antenna to the \( kn \)th subcarrier after selection combining at the receiver is

\[ \text{SNR}(m, k) = \frac{P_i}{N_0} \max_{1 \leq n \leq N} |h(m, k, n)|^2. \]  

(30)

Hence, we can determine the CDF by

\[ F(s|T(k)) = \left[ 1 - Q\left( \sqrt{\frac{\rho T(k)}{\psi}}, \sqrt{\frac{s}{\sqrt{\psi}}} \right) \right]^N \sim \left( \frac{s}{2\psi} \right)^N e^{-\frac{\psi(x+1)}{2\psi}} \left( \frac{1}{\sqrt{\gamma}} \right)^N, \]  

(31)

where \( \psi = \mu(1 - \rho)/2 \).

By the combined selection criterion given in (3), we can perform the similar derivation process for MIMO systems to derive

\[ \{F_{comb}(s), F_{ps}(s)\} \sim K(1 - \rho)(1 + \rho(M - 1)) \left( \frac{s}{2\psi\gamma} \right)^M. \]  

(32)

Also, by (28) we can obtain the diversity gain in this scenario is \( MN \).

B. Multi-hop DF branch selection

As shown in Fig. 3, a multi-hop DF relay system with branch selection can be illustrated, in which \( W \) hops are considered [29]. For the \( w \)th hop given \( w \in W = \{1, 2, \ldots, W\} \), we can extend the system model constructed for two-hop DF relay system and obtain the conditional distribution of \( h_w(m, k) \) in terms of \( \rho_{w}, \mu_w \) and \( T_w(k) \). Meanwhile, because the outage event in a multi-hop DF system is dominated by the worst channel condition among all hops, we can define the
Verifying our analysis in Section III and Section IV, we employ Monte Carlo simulation methods to numerically study the outage performances of OFDM systems employing per-subcarrier and combined selection schemes with three forwarding protocols. Meanwhile, the asymptotic outage performance at high SNR is also taken into account in our simulations. In particular, we let \( K = 8 \), \( s = 1 \) (i.e., 0 dB), \( \mu_1 = \mu_2 = 2 \), for all simulations. Meanwhile, we vary \( M \in \{3,5\} \) and \( \rho_1 = \rho_2 \in \{0,0.8\} \) to observe the effects of \( M \) and \( \rho_1 \) on the outage performance. The simulation results corresponding to the three relay protocols are presented in Fig. 5.

**VI. NUMERICAL RESULTS**

First, to verify our analysis in Section III and Section IV, we employ Monte Carlo simulation methods to numerically study the outage performances of OFDM systems employing per-subcarrier and combined selection schemes with three forwarding protocols. Meanwhile, the asymptotic outage performance at high SNR is also taken into account in our simulations. In particular, we let \( K = 8 \), \( s = 1 \) (i.e., 0 dB), \( \mu_1 = \mu_2 = 2 \), for all simulations. Meanwhile, we vary \( M \in \{3,5\} \) and \( \rho_1 = \rho_2 \in \{0,0.8\} \) to observe the effects of \( M \) and \( \rho_1 \) on the outage performance. The simulation results corresponding to the three relay protocols are presented in Fig. 5.
not indicate that the number of utilized relays increases for the combined selection system since \( |L_{comb}| = 2 \), whereas only the range of selection is enlarged. As for channel correlation, it is apparent that the diversity advantage of cooperative systems brought by relay selection will not be shadowed by channel correlation, as long as \( \rho_1 \rho_2 \neq 1 \). On the other hand, a higher cross-correlation coefficient, whichever in the first hop or second hop, will result in a higher outage probability. In other words, channel correlation has a detrimental impact on the coding gain of a cooperative network. Although we mainly analyze the outage performance in the high SNR region, some important features of combined selection in the low SNR region can also be observed from these figures. First, there exists a gap between combined and per-subcarrier selections, which is caused by the difference in the numbers of selected relays and the fact that fading at low SNR is not dominated by the worst channel. Therefore, a smaller \( M \) will lead to a smaller gap at low SNR, and in particular it is expected that the gap will be eliminated when \( M = 2 \). Also, there is not an evident impact by choosing different \( \rho_i \) on the performance gap at low SNR, because channel correlation does not affect the number of selected relays and thus equivalent to both selection schemes.

In comparison with the outage performances shown in these three figures, we can also have a rough insight into the merits and drawbacks corresponding to three types of relays. First, the outage performances given by DF and VG AF relays are close to each other at high SNR, which aligns with our expectation, because both have the same asymptotic outage performance (c.f. (20) and (27)). And both outage performances are better than the outage performance given by FG AF case. On the other hand, the superiority in outage performance is paid by a higher system complexity. The former needs to decode received signals at relay nodes, and the latter needs to estimate the channel in the first hop by a real-time manner. While the FG AF relay system is relatively simple and retransmits all received signals by a specified and fixed mechanism,
which only needs to estimate the average channel gain in the first hop once. Therefore, there exists a trade-off between outage performance and system complexity among all three types of relays, which should be considered carefully when implementing cooperative networks. To clearly illustrate the outage performances of these three relays, we also simulate the case $\rho_1 = \rho_2 = 0.4$ for all three types of relays and plot the results in Fig. 7.

Meanwhile, to reveal the effects of different $s$ on the outage performance, we can take the DF relay case as an example with fixed $M = 3$ and $\rho_1 = \rho_2 = 0.4$. Then, we vary $s \in \{1, 2, 4, 8\}$ and plot the outage performance in Fig. 8. As expected, a larger $s$ will lead to a worse outage performance. In addition, $s$ has an obvious impact on the convergence rate of combined selection to per-subcarrier selection; a larger $s$ indicates a higher $\bar{\gamma}$ is required in order to obtain the equivalent performance.

Furthermore, another two extended cases as analyzed in Section V are also numerically simulated, and the results are given in Fig. 9 and Fig. 10 respectively. For the case of antenna selection, we keep all configurations as the same as for relay selection, but vary $\rho \in \{0.4, 0.8\}$ and let $N = 1$.

Meanwhile, for the case of branch-selection, we let $W = 3$ and vary $\rho_1 = \rho_2 = \rho_3 \in \{0.4, 0.8\}$. From these two figures, the feasibility and the expandability of the equivalence principle is verified. It is obvious that combined selection is not exclusive for antenna selection or relay selection, rather, it is a generic selection algorithm. The equivalence principle can be constructed as long as an OFDM system is given, regardless of the selection nature and channel fading condition. Besides, comparing Fig. 4 and Fig. 10, it is obvious that the increase in the number of hops will yield a poorer performance, since an outage event is a union of the outage in each hop for DF systems.

VII. CONCLUSION

In conclusion, we proposed a novel relay selection scheme for OFDM systems by combining conventional bulk and per-subcarrier selection schemes, and analyzed its outage performance over spatially correlated channels. Specifically, we carried out the asymptotic outage performance analysis of the combined selection scheme in the high SNR region, and proved a generalized theorem stating that if the conditional CDF of the end-to-end SNR, $F(s|T_1(k), T_2(k))$, can be expanded as a certain series in the variable $\bar{\gamma}$, combined selection is able to achieve an outage probability equivalent to conventional per-subcarrier selection in the high SNR region. To specify the generalized theorem, we also took three examples of DF, FG AF and VG AF relay systems to analyze and obtained their asymptotic outage probabilities. By Monte Carlo simulations, our analysis was verified by numerical results. The proposed combined relay selection and the proved theorem in this paper provide a general and feasible solution to the trade-off between system complexity and outage performance when relay selection is applied, so that the optimal outage probability can be achievable at high SNR without using the full set of available relays for selection. Moreover, as shown by two extended applications, the proposed theorem and the generic asymptotic expression for outage probability presented in this paper can also be easily extended to other selections or under other channel fading scenarios, as long as their CDFs of end-to-end SNR is obtainable. In particular, the extension of this theorem to a multi-hop relay selection scenario is still an open issue and is worth investigating comprehensively as a future work.
APPENDIX A

DERIVATION OF ASYMPTOTIC OUTAGE PROBABILITY OF DF NETWORKS

According to (17), we can approximate $F(s|T_1(k), T_2(k))$ at high SNR by

$$F(s|T_1(k), T_2(k)) = P \left\{ \frac{P_t}{N_0} \min (\gamma_1, \gamma_2) < s \right\} = 1 - \left[ 1 - F_{h_1} \left( \frac{s}{\gamma} T_1(k) \right) \right] \left[ 1 - F_{h_2} \left( \frac{s}{\gamma} T_2(k) \right) \right] \approx F_{h_1} \left( \frac{s}{\gamma} T_1(k) \right) + F_{h_2} \left( \frac{s}{\gamma} T_2(k) \right). \quad (37)$$

By (9), we can further obtain

$$F(s|T_1(k), T_2(k)) = \sum_{i=1}^{2} \left[ 1 - Q \left( \sqrt{\frac{\rho_i T_i(k)}{\psi_i}}, \sqrt{\frac{s}{(\psi_i \gamma)^2}} \right) \right]. \quad (38)$$

Also, we can express $Q \left( \sqrt{\frac{\rho_i T_i(k)}{\psi_i}}, \sqrt{\frac{s}{(\psi_i \gamma)^2}} \right)$ by [23]

$$Q \left( \sqrt{\frac{\rho_i T_i(k)}{\psi_i}}, \sqrt{\frac{s}{(\psi_i \gamma)^2}} \right) = e^{-\frac{\rho_i T_i(k)}{\psi_i}} - \frac{\rho_i T_i(k)}{\psi_i} \sum_{p=0}^{\infty} \left( \frac{\rho_i T_i(k)}{s} \right)^p \left( \frac{1}{\psi_i} \right) \Gamma \left( \frac{p}{\psi_i \gamma} \right). \quad (39)$$

Also, we can expand the $p$th order modified Bessel function of the first kind by [23]

$$I_p \left( \frac{1}{\psi_i} \sqrt{\frac{\rho_i T_i(k) s}{\gamma}} \right) = \left( \frac{1}{2 \psi_i} \right)^p \sum_{q=0}^{\infty} \left( \frac{\rho_i T_i(k) s}{4 \psi_i^2 \gamma} \right)^q \frac{1}{\Gamma(q+p+1)}, \quad (40)$$

where $\Gamma(\cdot)$ is the Gamma function.

Therefore, the summation part can be alternatively expressed by

$$\sum_{p=0}^{\infty} \left( \frac{\rho_i T_i(k) s}{s} \right)^p I_p \left( \frac{1}{\psi_i} \sqrt{\frac{\rho_i T_i(k) s}{\gamma}} \right) = \sum_{q=0}^{\infty} \left( \frac{\rho_i T_i(k) s}{4 \psi_i^2 \gamma} \right)^q \frac{1}{\Gamma(q+p+1)}. \quad (41)$$

Meanwhile, $e^{-\frac{\rho_i T_i(k)}{\psi_i}}$ can also be expanded in terms of $\gamma$ by [30]

$$e^{-\frac{\rho_i T_i(k)}{\psi_i}} = \sum_{p=0}^{\infty} \frac{1}{p!} \left( -\frac{s}{2 \psi_i \gamma} \right)^p. \quad (42)$$

Therefore, substituting (41) and (42) into (39) yields

$$Q \left( \sqrt{\frac{\rho_i T_i(k)}{\psi_i}}, \sqrt{\frac{s}{\psi_i \gamma}} \right) = e^{-\frac{\rho_i T_i(k)}{2 \psi_i}} \sum_{p=0}^{\infty} \frac{1}{p!} \left( -\frac{s}{2 \psi_i \gamma} \right)^p \times \sum_{q=0}^{\infty} \sum_{p=0}^{\infty} \left( \frac{\rho_i T_i(k)}{4 \psi_i^2 \gamma} \right)^q q! \Gamma(q+p+1) \approx 1 - e^{-\frac{\rho_i T_i(k)}{2 \psi_i}} \frac{s}{2 \psi_i \gamma}. \quad (43)$$

Subsequently, substituting (43) into (38) yields the asymptotic expression for $F(s|T_1(k), T_2(k))$ at $\gamma \to \infty$

$$F(s|T_1(k), T_2(k)) \sim \left[ \frac{s}{2} \left( e^{-\frac{\rho_i T_i(k)}{2 \psi_i}} / \psi_1 + e^{-\frac{\rho_i T_i(k)}{2 \psi_i}} / \psi_2 \right) \right] \frac{1}{\gamma}. \quad (44)$$

APPENDIX B

DERIVATION OF ASYMPTOTIC OUTAGE PROBABILITY OF FG AF NETWORKS

We can adopt a similar method as proposed in [31] to derive the CDF of end-to-end SNR over correlated channels and determine $F(s|T_1(k), T_2(k))$ by

$$F(s|T_1(k), T_2(k)) = P \left\{ \frac{\gamma_1 \gamma_2 P_t^2}{(\mu_1 P_t + \gamma_2 P_t + N_0)N_0} < s \right\} = P \left\{ \frac{s}{\gamma_1} < \frac{\mu_1 + \gamma_2 + \frac{1}{\gamma_2}}{\gamma_1} \right\} \approx \int_{0}^{\infty} F_{h_1} \left( s \left( \frac{\mu_1 + \gamma_2 + \frac{1}{\gamma_2}}{\gamma_2} \right) \left| T_1(k) \right. \right) f_{h_2} \left( \gamma_2 \left| T_2(k) \right. \right) d\gamma_2. \quad (45)$$

Considering $\gamma \to \infty$, we can approximate the outage condition by omitting the higher order terms corresponding to $1/\gamma$ and obtain

$$s \left( \frac{\mu_1 + \gamma_2 + \frac{1}{\gamma_2}}{\gamma_2} \right) \approx s \left( \frac{\mu_1 + \gamma_2}{\gamma_2} \right), \quad (46)$$

and thereby have

$$F(s|T_1(k), T_2(k)) \approx \int_{0}^{\infty} F_{h_1} \left( s (\mu_1 + \gamma_2) \left| T_1(k) \right. \right) f_{h_2} \left( \gamma_2 \left| T_2(k) \right. \right) d\gamma_2. \quad (47)$$

Now, let us take a close look at the conditional CDF $F_{h_1} \left( \frac{s(\gamma_2 + \mu_1)}{\gamma_2 \gamma} \left| T_1(k) \right. \right)$. Again, by (9), we can express this conditional CDF by

$$F_{h_1} \left( \frac{s(\gamma_2 + \mu_1)}{\gamma_2 \gamma} \left| T_1(k) \right. \right) = 1 - Q \left( \sqrt{\frac{\rho_i T_i(k)}{\psi_i}}, \sqrt{\frac{s(\gamma_2 + \mu_1)}{\psi_1 \gamma_2 \gamma}} \right). \quad (48)$$
Therefore, we can perform the similar derivation as we do for DF case and the Marcum Q function can be alternatively expressed as

\[
\begin{aligned}
Q &\left( \sqrt{\frac{\rho_1 T_1(k)}{\psi_1} \sqrt{\frac{s(\gamma_2 + \mu_1)}{\psi_1^2 \gamma_2^2}} \right) \\
&= e^{-s \frac{\rho_1 T_1(k)}{2 \psi_1}} \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{\rho_1 T_1(k)}{4 \psi_1^2} \frac{s(\gamma_2 + \mu_1)}{\psi_1^2 \gamma_2^2}^p q! \Gamma(q + p + 1) \\
&\times \left[ \frac{s(\gamma_2 + \mu_1)}{\gamma_2^2} \right]^q \left( \frac{1}{\gamma_2} \right)^q e^{-s \frac{(\gamma_2 + \mu_1)}{2 \psi_1 \gamma_2^2}}.
\end{aligned}
\]

(49)

Meanwhile, we can also expand \(f_{h_2}(\gamma_2 | T_2(k))\) by [23]

\[
f_{h_2}(\gamma_2 | T_2(k)) = \frac{1}{2 \psi_2} e^{-\frac{\rho_2 T_2(k)}{2 \psi_2}} e^{-\frac{\gamma_2}{2 \psi_2}} \sum_{u=0}^{\infty} \frac{\rho_2 T_2(k)}{2 \psi_2} u (u!)^2.
\]

(50)

Therefore, we can obtain

\[
\begin{aligned}
\int_0^\infty Q &\left( \sqrt{\frac{\rho_1 T_1(k)}{\psi_1} \sqrt{\frac{s(\gamma_2 + \mu_1)}{\psi_1^2 \gamma_2^2}} \right) f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2 \\
&= \frac{1}{2 \psi_2} \sum_{q=0}^{\infty} \sum_{p=0}^{\infty} \sum_{u=0}^{\infty} C(q, p, u) \mathcal{H}(q, u),
\end{aligned}
\]

(51)

where

\[
C(q, p, u) = \frac{\rho_1 T_1(k)}{2 \psi_1} \frac{\rho_2 T_2(k)}{2 \psi_2} u (u!)^2.
\]

(52)

and

\[
\mathcal{H}(q, u) = \int_0^\infty \left[ \frac{s(\gamma_2 + \mu_1)}{2 \psi_2 \gamma_2^2} \right]^q \left( \frac{\gamma_2}{2 \psi_2} \right)^u e^{-s \frac{(\gamma_2 + \mu_1)}{2 \psi_1 \gamma_2^2}} e^{-\frac{\gamma_2}{2 \psi_2}} d\gamma_2.
\]

(53)

Because we are only interested in the high SNR region, i.e. \(\bar{\gamma} \to \infty\), we can approximate (51) by considering \(q = 0\) and \(q = 1\) only:

\[
\begin{aligned}
\int_0^\infty Q &\left( \sqrt{\frac{\rho_1 T_1(k)}{\psi_1} \sqrt{\frac{s(\gamma_2 + \mu_1)}{\psi_1^2 \gamma_2^2}} \right) f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2 \\
&\approx \frac{1}{2 \psi_2} e^{-\frac{\rho_1 T_1(k)}{2 \psi_1}} e^{-\frac{\rho_2 T_2(k)}{2 \psi_2}} \sum_{u=0}^{\infty} \sum_{p=0}^{\infty} C(0, p, u) \mathcal{H}(0, u) \\
&+ \frac{1}{2 \psi_2} e^{-\frac{\rho_1 T_1(k)}{2 \psi_1}} e^{-\frac{\rho_2 T_2(k)}{2 \psi_2}} \sum_{u=0}^{\infty} \sum_{p=0}^{\infty} C(1, p, u) \mathcal{H}(1, u)
\end{aligned}
\]

(54)

Then, the closed-form expressions for \(\mathcal{H}(0, u)\) and \(\mathcal{H}(1, u)\) are now obtainable and given by

\[
\begin{aligned}
\mathcal{H}(0, u) &= 4 \psi_2 e^{-\frac{\mu_1 T_1(k)}{2 \psi_1 \gamma_2^2}} \mathcal{H}_{u+1} \left( \sqrt{\frac{\mu_1 T_1(k)}{\psi_1 \gamma_2^2}} \right), \\
\mathcal{H}(1, u) &= 2 \psi_2 e^{-\frac{\mu_1 T_1(k)}{2 \psi_1 \gamma_2^2}} \mathcal{H}_{u+1} \left( \sqrt{\frac{\mu_1 T_1(k)}{\psi_1 \gamma_2^2}} \right) + e^{-\frac{\mu_1 T_1(k)}{2 \psi_1 \gamma_2^2}} \mathcal{H}_{u+1} \left( \sqrt{\frac{\mu_1 T_1(k)}{\psi_1 \gamma_2^2}} \right).
\end{aligned}
\]

(55a)

(56)

where \(\mathcal{H}(\cdot)\) is the \(u\)th order modified Bessel function of the second kind.

Meanwhile, we can also obtain

\[
\sum_{p=0}^{\infty} C(0, p, u) = \frac{\rho_2 T_2(k)}{2 \psi_2} e^{\frac{\rho_1 T_1(k)}{2 \psi_1 \gamma_2^2} - 1}.
\]

(57)

Now, we can perform series expansion at \(\bar{\gamma} \to \infty\) and obtain the asymptotic expressions for (51) by

\[
\int_0^\infty Q &\left( \sqrt{\frac{\rho_1 T_1(k)}{\psi_1} \sqrt{\frac{s(\gamma_2 + \mu_1)}{\psi_1^2 \gamma_2^2}} \right) f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2 \\
&\sim 1 - \left( \frac{\mu_1 s}{4 \psi_1 \psi_2} e^{-\frac{\rho_1 T_1(k)}{2 \psi_1 \gamma_2^2}} e^{-\frac{\rho_2 T_2(k)}{2 \psi_2}} \right) \ln \left( \frac{\gamma}{\bar{\gamma}} \right).
\]

(59)

Also, due to the property of a PDF, it is obvious that \(\int_0^\infty f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2 = 1\). As a result, by (48) and (59) the asymptotic expression for (47) can be given by

\[
F(s | T_1(k), T_2(k)) \sim \left( \frac{\mu_1 s}{4 \psi_1 \psi_2} e^{-\frac{\rho_1 T_1(k)}{2 \psi_1 \gamma_2^2}} e^{-\frac{\rho_2 T_2(k)}{2 \psi_2}} \right) \ln \left( \frac{\gamma}{\bar{\gamma}} \right).
\]

(60)

### APPENDIX C

#### DERIVATION OF ASYMPTOTIC OUTAGE PROBABILITY OF VG AF NETWORKS

Similar to the analysis of the FG AF case, we can express \(F(s | T_1(k), T_2(k))\) by

\[
F(s | T_1(k), T_2(k)) = \mathbb{P} \left\{ \frac{\gamma_1 \gamma_2 P_1^2}{(\gamma_1 P_1 + \gamma_2 P_1 + N_0) N_0} < s \right\}
\]

\[
= \mathbb{P} \left\{ \gamma_1 < \frac{s(\gamma_2 \gamma + \frac{1}{2})}{\gamma_2 \gamma - s} \gamma_2 > \frac{s}{\gamma} \right\}
\]

\[
+ \mathbb{P} \left\{ \gamma_1 > \frac{s(\gamma_2 \gamma + \frac{1}{2})}{\gamma_2 \gamma - s} \gamma_2 < \frac{s}{\gamma} \right\}
\]

\[
= \int_\gamma^\infty \frac{s(\gamma_2 \gamma + \frac{1}{2})}{\gamma_2 \gamma - s} F_{h_1} \left( \frac{\gamma_1 P_1 + \gamma_2 P_1 + N_0}{N_0} \right) f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2
\]

\[
+ \int_0^\gamma \left[ 1 - F_{h_1} \left( \frac{s(\gamma_2 \gamma + \frac{1}{2})}{\gamma_2 \gamma - s} \right) \right] T_1(k) \right) f_{h_2}(\gamma_2 | T_2(k)) d\gamma_2.
\]

(61)
Again, we first need to expand $s(\gamma_2 + 1/\bar{\gamma})/(\gamma_2 \bar{\gamma} - s)$ at $\bar{\gamma} \to \infty$ in order to derive the asymptotic expression. Here we have

$$
\frac{s(\gamma_2 + \frac{1}{\bar{\gamma}})}{\gamma_2 \bar{\gamma} - s} \approx \frac{s}{\bar{\gamma}}.
$$

(62)

Therefore, we can approximate $F(s|T_1(k), T_2(k))$ at high SNR by

$$
F(s|T_1(k), T_2(k)) \approx \int_0^\infty F_{h_1}(\frac{s}{\bar{\gamma}} T_1(k)) f_{h_2}(\frac{s}{\bar{\gamma}} T_2(k)) d\gamma_2
$$

$$
+ \int_{\frac{s}{\bar{\gamma}}}^\infty \left[ 1 - F_{h_1}(\frac{s}{\bar{\gamma}} T_1(k)) \right] f_{h_2}(\frac{s}{\bar{\gamma}} T_2(k)) d\gamma_2
$$

$$
= F_{h_1}(\frac{s}{\bar{\gamma}} T_1(k)) + F_{h_2}(\frac{s}{\bar{\gamma}} T_1(k))
$$

$$
- 2F_{h_1}(\frac{s}{\bar{\gamma}} T_1(k)) F_{h_2}(\frac{s}{\bar{\gamma}} T_1(k))
$$

$$
\approx F_{h_1}(\frac{s}{\bar{\gamma}} T_1(k)) + F_{h_2}(\frac{s}{\bar{\gamma}} T_1(k)).
$$

(63)

Then, all analysis follows the case derived for DF relay and the asymptotic expression is given by the same one in (44).

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