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Exploiting Sparsity in Amplify-and-Forward Broadband Multiple Relay Selection

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ABSTRACT Cooperative communication has attracted significant attention in the last decade due to its ability to increase the spatial diversity order with only single-antenna nodes. However, most of the techniques in the literature are not suitable for large cooperative networks such as device-to-device and wireless sensor networks that are composed of a massive number of active devices, which significantly increases the relay selection complexity. Therefore, to solve this problem and enhance the spatial and frequency diversity orders of large amplify and forward cooperative communication networks, in this paper, we develop three multiple relay selection and distributed beamforming techniques that exploit sparse signal recovery theory to process the subcarriers using the low complexity orthogonal matching pursuit algorithm (OMP). In particular, by separating all the subcarriers or some subcarrier groups from each other and by optimizing the selection and beamforming vector(s) using OMP algorithm, a higher level of frequency diversity can be achieved. This increased diversity order allows the proposed techniques to outperform existing techniques in terms of bit error rate at a lower computation complexity. A detailed performance-complexity tradeoff, as well as Monte Carlo simulations, are presented to quantify the performance and efficiency of the proposed techniques.

INDEX TERMS Beamforming, relaying, AF, optimization, MSE, OMP.

I. INTRODUCTION

In the last few years, 5G communication networks have captured a lot of interest since their impact is expected to be revolutionary in the sense of reshaping industries and transforming our world [1]. In particular, it is expected that the amount of wireless IP data will increase by more than 100 times in just few years. Moreover, according to Cisco, ''An incremental approach will not come close to meeting the demands that networks will face by 2020'' [1].

Cooperative communication architectures have been proposed to improve the quality of emerging wireless communication systems, where the resources of multiple nodes are shared to exploit the available spatial diversity [1], [2]. There is a variety of cooperative protocols in the literature, however, most of them select only a single relay for the transmission [3]. For example, the relay with the highest expected Signal Noise Ratio (SNR) is selected in [4].

Nearest neighbor relay selection is also investigated in [5], [6]. However, the nearest relay is not always the best one in terms of Bit Error Rate (BER) since it may have a lower channel gain at a particular time. In [6], [7], the relay that maximizes the worst channel gain between the two hops is selected.

While selecting only one relay can provide performance improvements, it might still not be enough to exploit all of the available spatial diversity. Thus, in [8], the concept of single relay selection was first generalized to multiple relay selection based on the Amplify and Forward (AF) protocol. In [8], [9], multiple relay selection is performed but without gain optimization i.e. the relays either cooperate with full power or do not cooperate.

In [8] and [10], multiple relays are selected in AF relaying networks based on relay ordering. In [11], a hybrid full-duplex and alternate multiple relay selection and

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beamforming technique was proposed to alleviate the effect of residual self interference on the selection in dual hop network with single carrier transmission. In [12], [13] the authors also proposed different schemes of multiple relay selections. However, when selecting k out of N_R relays, there are $\binom{N_R}{k}$ possibilities which are almost equal to $(N_R)^K$ when $N_R >> K$ compared to only N_R possibilities when only one relay is selected. Hence, although using multiple relay selection improves the communication quality, it may also require higher computation complexity. To address this challenge, [14] proposed to exploit Sparse Signal Recovery (SSR) theory to design a multiple relay selection technique for Multiple Input Multiple Output (MIMO) cooperative systems that improves the BER performance with a low complexity selection protocol. However, the selection technique in [14] is limited to single-carrier networks and does not apply to broadband multi-carrier communications. SSR theory has been also applied recently to the design of relay selection techniques based on compressive-sensing for multi-cast networks [15] and full-duplex relay-aided multi-user networks [16].

The authors in [17] were the first to introduce an Orthogonal Frequency Division Multiplexing (OFDM)-based selection technique over frequency-selective fading channels with a per-subcarrier basis selection for each hop which improved the system performance. This technique was further studied in [18] where the performance gain was investigated.

In [4], [12], [19]–[21] many OFDM-based relay selection techniques were proposed and their achievable diversity orders were also investigated. Among those techniques was the Basic Selective OFDM technique where all the subcarriers have to follow the same path through the relay that maximizes the worst channel response. Subcarrier grouping selection and selective OFDMA were investigated in [12], [19] where the subcarriers can be separated from each other depending on the channel quality. In addition, The authors analyzed in [4] the outage performance of Bulk and PerSubcarrier selection techniques in AF OFDM relaying networks and showed that OFDM-based relay selection techniques can dramatically enhance the spatial and frequency diversity orders [4], [19].

In this paper, we propose and investigate three AF relay selection and distributed beamforming techniques that exploit SSR theory to improve the communication performance using low-complexity protocols by processing the subcarriers to increase the diversity order of the transmission. In particular, the proposed techniques exploit both the spatial and frequency diversity of the network to enhance the communication quality while using only the low complexity Orthogonal Matching Pursuit (OMP) algorithm. In addition, a compromise between the computation complexity and the BER performance is investigated for the three proposed techniques.

Notations: The following notations are adopted in the sequel. Unless stated otherwise, upper and lower cases bold letters denote matrices and vectors, respectively.

The operators $E\{.\}$, $|.|$ and $(.)^*$ represent the expectation, absolute value and conjugate operations, respectively. For vectors and matrices, the operators $(.)^T$ and $(.)^H$ denote the transpose and the conjugate-transpose, respectively. For matrices, the operator diag(.) denotes the diagonal elements selection operations. For a vector $\boldsymbol{v}$, $||\boldsymbol{v}||_p$, card($\boldsymbol{v}$) and diag($\boldsymbol{v}$) denote the p-norm, the cardinality operator (number of non zero elements of the vector) and the corresponding diagonal matrix, whose elements along the diagonal are the elements of the vector $\boldsymbol{v}$, respectively.

In addition, "$OMP(\boldsymbol{A}, \boldsymbol{b}, k$ iterations)" denotes the output of the OMP algorithm by using $\boldsymbol{A}$ as a dictionary matrix and $\boldsymbol{b}$ as the signal to be approximated after k iterations [14]. Also, we denote by "$\min_{\boldsymbol{x}} f(\boldsymbol{x})$, s. t. $g(\boldsymbol{x})$" the optimization problem corresponding to minimizing the function $f(\boldsymbol{x})$ over $\boldsymbol{x}$ subject to $g(\boldsymbol{x})$.

Paper Organization: The rest of this paper is organized as follows. Section II presents the system model. Sections III, IV and V investigate the three proposed relay selection techniques. A computation complexity comparison is conducted in Section VI. In Section VII, the simulation results of the investigated techniques are presented and discussed.

II. SYSTEM MODEL

In this paper, the multiple relay selection and distributed beamforming optimization issues are investigated in dual-hop broadband communication scenarios using OFDM with N_S subcarriers. The channel coefficients are assumed to follow independent and identically distributed (i.i.d.) complex Gaussian distributions and the Channel State Information (CSI) is assumed to be perfectly known by the source [8], [20], [22], [23]. In addition, the Inter Carrier Interference (ICI) between the OFDM subcarriers is assumed to be canceled using a Cyclic Prefix (CP) longer than the maximum channel's delay spread.

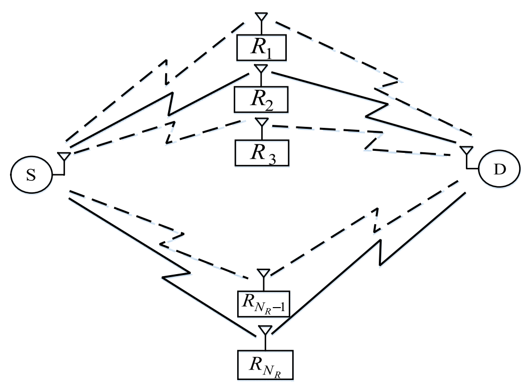

FIGURE 1. Dual-hop relaying model.

As depicted in Fig. (1), we consider a cooperative communication network composed of a source node (S), a destination node (D) and N_R relays that operate in half-duplex mode denoted by $R_1..R_{N_R}$. Different techniques are proposed and investigated in this paper to select k relays that amplify the received signal from the source node (S), multiply it by

TABLE 1. Key variables and their definitions.

Parameter	Definition
P_0	Transmission power.
σ_v^2	Variance of the noise at the destination.
σ_r^2	Variance of the noise at the relays.
N_R	Total number of relays.
k	Number of relays to be selected.
N_S	Total number of subcarriers.
x^m	Transmitted data at subcarrier m.
h_i^m	The channel coefficients for the link $S \to R_i$ and subcarrier m.
g_i^m	The channel coefficients for the link $R_i \to D$ and subcarrier m.
n_i^m	AWGN samples for the m^{th} subcarrier at the relay R_i.
v^m	AWGN samples for the m^{th} subcarrier at the node D.
$\boldsymbol{h^m}$	The channel coefficients vector for subcarrier m at the first hop.
$\boldsymbol{g^m}$	The channel coefficients vector for subcarrier m at the second hop.
$\boldsymbol{n^m}$	The relays AWGN vector for subcarrier m.
$\boldsymbol{a^m}$	Equivalent channel vector for subcarrier m.
$\boldsymbol{a}$	Equivalent aggregated channel vector.
$\boldsymbol{w}$	Beamforming and selection vector for all subcarriers.
MSE	MSE expression for all subcarriers.
$\boldsymbol{\tilde{a}^m}$	Equivalent aggregated channel vector for subcarrier m.
$\boldsymbol{w^m}$	Beamforming and selection vector for subcarrier m.
MSE^m	MSE expression for subcarrier m.
$\boldsymbol{\tilde{a}^G}$	Equivalent aggregated channel vector for a group of subcarriers G.
$\boldsymbol{w^G}$	Beamforming and selection vector for a group of subcarriers G.
MSE^G	MSE expression for a group of subcarriers G.

optimized beamforming coefficients and forward it to the destination (D). The key variables are listed in Table 1.

We denote by h_i^m and g_i^m the complex Gaussian channel coefficients for the subcarrier m at the link passing through the relay R_i in the first and the second hops, respectively. In addition, P_0 and x^m denote the transmission power and transmitted data at subcarrier m, respectively. Furthermore, let n_i^m and v^m denote the Additive-White-Gaussian Noise (AWGN) samples for the m^{th} subcarrier at R_i and D, respectively.

Next, we describe in detail below three proposed techniques to select the relays and optimize their beamforming transmission coefficients, namely:

- Sparsity Aware Selective OFDM (SA-S-OFDM): Select k relays to amplify and forward the entire OFDM block.
- Sparsity Aware Selective OFDMA (SA-S-OFDMA): Select k relays for each one of the OFDM subcarriers.
- Sparsity Aware Selective OFDM with Subcarriers Grouping (SA-S-OFDM-SG): Select k relays for each group of contiguous OFDM subcarriers.

III. SPARSITY AWARE SELECTIVE OFDM (SA-S-OFDM)

A. MOTIVATION

In this section, all the subcarriers are assumed to follow the same path(s) (see Fig. 2). In particular, we propose the

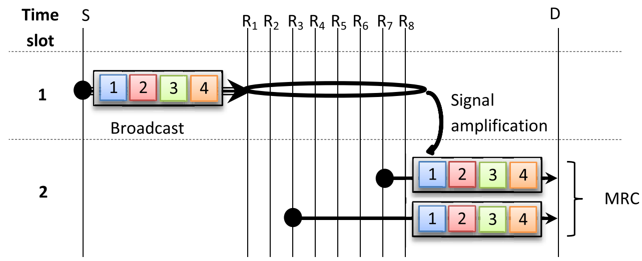

FIGURE 2. SA-S-OFDM transmission model.

SA-S-OFDM technique where k relays are selected to forward the entire OFDM symbol to the destination.

For example, it can be seen in Fig. 2 that the destination receives two copies ($k = 2$) of the data transmitted by the source without separating the subcarriers from each other. Based on the collected CSI and using our proposed selection technique below, the relays R_3 and R_7, for example, are selected to forward the data to the destination which will combine them to decode the original data using the Maximum Ratio Combining (MRC) technique.

As proven in [14], performing the selection based on the Mean-Square Error (MSE) minimization provides better BER performance compared to SNR maximization techniques. Hence, in this paper, the proposed relay selection techniques are designed to minimize the MSE at the destination.

By neglecting the ICI effect [19], [24], the received signal for each subcarrier m at the destination is given by

$$\begin{aligned} y^m &= \boldsymbol{w}^H \left(\sqrt{P_0}(\boldsymbol{h^m} \circ \boldsymbol{g^m})x^m + \boldsymbol{h^m n^m}\right) + v^m \\ &= \boldsymbol{w}^H \left(\sqrt{P_0}\boldsymbol{a^m} x^m + \boldsymbol{\tilde{n}^m}\right) + v^m, \end{aligned} \tag{1}$$

where

$$\boldsymbol{h^m} = [h_1^m,\ h_2^m,\ \dots\ h_{N_R}^m]^T \tag{2}$$
$$\boldsymbol{g^m} = [g_1^m,\ g_2^m,\ \dots\ g_{N_R}^m]^T \tag{3}$$
$$\boldsymbol{n^m} = [n_1^m,\ n_2^m,\ \dots\ n_{N_R}^m]^T \tag{4}$$
$$\boldsymbol{a^m} = \boldsymbol{h^m} \circ \boldsymbol{g^m} \tag{5}$$
$$\boldsymbol{\tilde{n}^m} = \boldsymbol{g^m} \circ \boldsymbol{n^m}. \tag{6}$$

B. RELAY SELECTION

Assume that each relay R_i performs beamforming of the received signal by multiplying it with the coefficient w_i. The selection and distributed beamforming vector $\boldsymbol{w}$ is defined as $\boldsymbol{w} = [w_1,\ w_2,\ \dots\ w_{N_R}]^T$. By using the same beamforming vector for all the subcarriers, we deduce from Eq. (1) that the error signal for subcarrier m when using the SA-S-OFDM technique is given by

$$\begin{aligned} e^m &= x^m - y^m \\ &= x^m - \boldsymbol{w}^H \left(\sqrt{P_0}\,\boldsymbol{a^m} x^m + \boldsymbol{\tilde{n}^m}\right) - v^m. \end{aligned} \tag{7}$$

Hence, the MSE at the destination for subcarrier m can be written as

$$\begin{aligned} E(|e^m|^2) = P_0 - \boldsymbol{w}^H \boldsymbol{\tilde{a}}^m - (\boldsymbol{\tilde{a}}^m)^H \boldsymbol{w} \\ + \boldsymbol{w}^H \left(P_0\, \boldsymbol{a^m}(\boldsymbol{a^m})^H + \boldsymbol{R^m_{\tilde{n}}}\right)\boldsymbol{w} + \sigma_v^2, \end{aligned} \tag{8}$$

where

$$\boldsymbol{R}^{\boldsymbol{m}}_{\tilde{\boldsymbol{n}}} = E\big(\tilde{\boldsymbol{n}}^{\boldsymbol{m}}(\tilde{\boldsymbol{n}}^{\boldsymbol{m}})\big) = \sigma_r^2 \operatorname{diag}(|\boldsymbol{g}^{\boldsymbol{m}}|^2), \quad (9)$$

$$\tilde{\boldsymbol{a}}^{\boldsymbol{m}} = \sqrt{P_0}\boldsymbol{a}^{\boldsymbol{m}}. \quad (10)$$

Also, $\sigma_r^2 = E(|n^m|^2)$ and $\sigma_v^2 = E(|v^m|^2)$ denote the variance of the noise at the relays and the destination, respectively.

Consequently, the average MSE for all the subcarriers is given by

$$\begin{aligned} E(|e|^2) &= \frac{1}{N_s}\sum_{m=1}^{N_s} E(|e^m|^2) \\ &= P_0 + \sigma_v^2 - \boldsymbol{w}^H \frac{1}{N_s}\sum_{m=1}^{N_s}(\tilde{\boldsymbol{a}}^{\boldsymbol{m}}) - \frac{1}{N_s}\sum_{m=1}^{N_s}((\tilde{\boldsymbol{a}}^m)^H)\boldsymbol{w} \\ &\quad + \frac{1}{N_s}\boldsymbol{w}^H \sum_{m=1}^{N_s}\big(P_0\boldsymbol{a}^{\boldsymbol{m}}(\boldsymbol{a}^{\boldsymbol{m}})^H + \boldsymbol{R}^{\boldsymbol{m}}_{\tilde{\boldsymbol{n}}}\big)\boldsymbol{w} \\ &= P_0 + \sigma_v^2 - \boldsymbol{w}^H\boldsymbol{a} - \boldsymbol{a}\boldsymbol{w}^H + \boldsymbol{w}^H\boldsymbol{R}\boldsymbol{w}, \end{aligned} \quad (11)$$

where

$$\boldsymbol{a} = \frac{1}{N_s}\sum_{m=1}^{N_s}(\tilde{\boldsymbol{a}^{\boldsymbol{m}}}) \quad (12)$$

$$\boldsymbol{R} = \frac{1}{N_s}\sum_{m=1}^{N_s}(P_0\,\boldsymbol{a}^{\boldsymbol{m}}(\boldsymbol{a}^{\boldsymbol{m}})^H + \boldsymbol{R}^{\boldsymbol{m}}_{\tilde{\boldsymbol{n}}}). \quad (13)$$

By definition, $\boldsymbol{a}^{\boldsymbol{m}}(\boldsymbol{a}^{\boldsymbol{m}})^H$ is a positive-definite matrix. Since $\boldsymbol{R}^{\boldsymbol{m}}_{\tilde{\boldsymbol{n}}}$ is a diagonal matrix, it follows that $\boldsymbol{R}$ is also positive-definite. Hence, by performing the Cholesky factorization of the positive-definite matrix $\boldsymbol{R} = \boldsymbol{L}\boldsymbol{L}^H$ where $\boldsymbol{L}$ is an $N_R \times N_R$ lower-triangular matrix, we can rewrite Eq. (11) as follows

$$MSE = P_0 - \boldsymbol{w}^H\boldsymbol{L}\boldsymbol{L}^{-1}\boldsymbol{a} - \boldsymbol{a}^H\boldsymbol{L}^{-H}\boldsymbol{L}^H\boldsymbol{w} + \boldsymbol{w}^H\boldsymbol{L}\boldsymbol{L}^H\boldsymbol{w} + \sigma_v^2. \quad (14)$$

By completing the square in Eq. (14), we get

$$MS = P_0 - \boldsymbol{a}^H\boldsymbol{L}^{-H}\boldsymbol{L}^{-1}\boldsymbol{a} + \sigma_v^2 + ||\boldsymbol{L}^H\boldsymbol{w} - \boldsymbol{L}^{-1}\boldsymbol{a}||_2^2. \quad (15)$$

Note that not all the terms in Eq. (15) depend on $\boldsymbol{w}$. Hence, to simplify the optimization problem, the MSE expression is divided into the following two terms

$$\begin{aligned} MSE_{min} &= P_0 - \boldsymbol{a}^H\boldsymbol{L}^{-H}\boldsymbol{L}^{-1}\boldsymbol{a} + \sigma_v^2, \\ MSE_{excess} &= ||\boldsymbol{L}^H\boldsymbol{w} - \boldsymbol{L}^{-1}\boldsymbol{a}||_2^2. \end{aligned} \quad (16)$$

Since only MSE_{excess} depends on $\boldsymbol{w}$, the MSE is minimized by minimizing the term MSE_{excess}. Consequently, the relay selection process becomes equivalent to

$$\min_{\boldsymbol{w}} ||\boldsymbol{L}^H\boldsymbol{w} - \boldsymbol{L}^{-1}\boldsymbol{a}||_2^2, \quad (17a)$$

$$\text{s. t. } \operatorname{card}(w) = k. \quad (17b)$$

Because of the non-convex cardinality constraint, the problem in Eq. (17a) is Non-deterministic Polynomial-time Hard (NP-hard). Consequently, its optimal solution can be found by solving the problem using Exhaustive Search (ES) over all the possible sets of selected relays (i.e. searching over $\binom{N_R}{k}$ possibilities) [25], [26]. However, the computation complexity of ES even without power control tends to grow very quickly with N_R especially when k approaches $\frac{N_R}{2}$ (central binomial coefficient). In particular, ES without power control corresponds to optimally identifying only which relays to be used without any information about the transmission power or the beamforming coefficients. Therefore, ES cannot be used in practical problems which motivates us to propose a quasi-optimal technique with an affordable computation complexity based on the OMP algorithm which we adopted for its simplicity.

Note that the relay selection and beamforming in this section are done under a total transmission power constraint. Hence, without loss of generality, the unconstrained optimization problem is considered (where the cardinality is used as a stopping criteria), and the obtained optimal vector $\boldsymbol{w}$ is normalized to meet the total transmission power constraint. In particular, since the optimization is unconstrained, the OMP algorithm can be used with the stopping criterion defined as the desired number of selected relays k as follows

$$\boldsymbol{w} = OMP(\boldsymbol{L}^H, \boldsymbol{L}^{-1}\boldsymbol{a}, k \text{ iterations}). \quad (18)$$

In each of the k OMP iterations, the relay that minimizes MSE_{excess} is selected until finally selecting k relays. As in [14], OMP is used to solve the optimization problem in Eq. (15). In particular, the most correlated column of $\boldsymbol{L}^H$ with the residual error vector is selected at each iteration. Then, the residual error is updated to be used in the next selection iteration. This process is repeated until the stopping criterion is satisfied which, in our case, corresponds to having exactly k non-zero elements in $\boldsymbol{w}$.

IV. SPARSITY AWARE SELECTIVE OFDMA (SA-S-OFDMA)

A. MOTIVATION

The use of SA-S-OFDM in relay selection and distributed beamforming allows us to apply SSR theory to reduce the selection complexity and improve the communication quality. However, similar to [27]–[29] OFDM is only used as an underlying transmission technology and the frequency diversity is not fully exploited since the entire OFDM block is forwarded and, therefore, all the subcarriers follow the same path (see Fig. 2).

Hence, we propose in this section to separate the OFDM subcarriers from each other to achieve full frequency diversity, improve the BER performance of the cooperative system, and provide an appreciable power gain compared with selective OFDM as shown in [17]–[19].

In SA-S-OFDMA, we assume that different paths can be selected independently for the different subcarriers (see Fig. 3). In particular, k relays are selected to amplify and forward the received signal from the source to the destination after multiplying it by an optimized beamforming coefficient. Then, the destination node uses MRC to combine the k copies of the received signals through different paths.

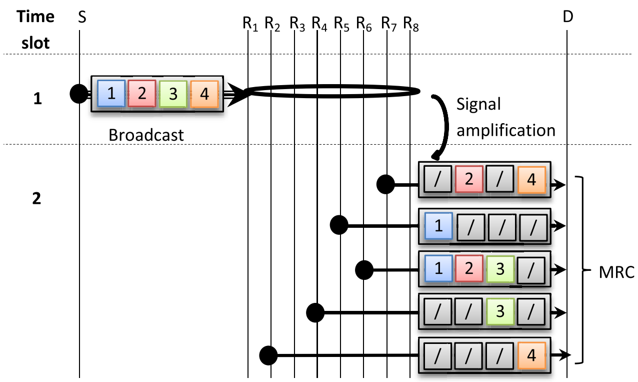

FIGURE 3. SA-S-OFDMA transmission model.

As shown in [19], [30], relay selection should be performed jointly for the two hops to avoid losing the selection diversity. In particular, the selection process should be based on the channel realizations in the first and second hops for maximum diversity exploitation.

B. RELAY SELECTION

In this section, k relays are selected independently for each OFDM subcarrier. In particular, instead of optimizing one vector $\boldsymbol{w}$ that minimizes the average MSE, N_s separate selection vectors are optimized independently for each subcarrier. Without loss of generality, we denote the selection vector for subcarrier m by $\boldsymbol{w^m}$. In SA-S-OFDMA, the vector $\boldsymbol{w^m}$ is selected so that the m^{th} subcarrier's MSE in Eq. (8) is minimized.

From Eq. (8) and similar to Eq. (15), we conclude that the m^{th} subcarrier's MSE is given by

$$MSE^m = P_0 - (\tilde{\boldsymbol{a}}^m)^H (\boldsymbol{L^m})^{-H} (L^m)^{-1} \boldsymbol{a} + \sigma_v^2 + ||(\boldsymbol{L^m})^H \boldsymbol{w^m} - (\boldsymbol{L^m})^{-1} \tilde{\boldsymbol{a}}^m||_2^2, \quad (19)$$

where

$$R^m = P_0\, \boldsymbol{a^m} (\boldsymbol{a^m})^H + \boldsymbol{R^m_{\tilde{n}}}), \quad (20)$$

and $\boldsymbol{L^m}$ is obtained by Cholesky factorization from $\boldsymbol{R^m}$ as

$$\boldsymbol{R^m} = \boldsymbol{L^m} (\boldsymbol{L^m})^H. \quad (21)$$

Consequently, for each subcarrier m the joint relay selection and beamforming optimization problem becomes equivalent to

$$\min_{\boldsymbol{w^m}} ||(\boldsymbol{L^m})^H \boldsymbol{w^m} - (\boldsymbol{L^m})^{-1} \tilde{\boldsymbol{a}}^m||_2^2, \quad (22a)$$
$$\text{s. t. card}(\boldsymbol{w^m}) = k. \quad (22b)$$

Similar to SA-S-OFDM, the OMP algorithm with a cardinality stopping criteria is used to optimize the beamforming selection vector $\boldsymbol{w^m}$ for each subcarrier m by replacing $\boldsymbol{a}$,$\boldsymbol{w}$ and $\boldsymbol{L}$ with $\tilde{\boldsymbol{a}}^m$, $\boldsymbol{w^m}$ and $\boldsymbol{L^m}$, respectively.

$$\boldsymbol{w^m} = OMP\Big((\boldsymbol{L^m})^H, (\boldsymbol{L^m})^{-1} \tilde{\boldsymbol{a}}^m, k \text{ iterations}\Big). \quad (23)$$

For example, when the number of subcarriers is $N_s = 4$, the number of relays is $N_R = 8$ and the number of selected relays is $k = 2$, Fig. 3 presents a selection example where the output of the N_s optimizations in Eq. 22a for some particular channel realizations resulted in allocating a set of subcarriers to be forwarded using each relay. Note that since the selection is performed independently for each subcarrier, each relay can be used to forward one or multiple subcarriers and can also be selected not to forward any signal. For example, it can be seen in Fig. 3 that the destination receives two copies ($k = 2$) of the data transmitted on each subcarrier. Each subcarrier can take a different path; the data on Subcarrier 1, for example, is transmitted through the relays R_5 and R_6 while the data on Subcarrier 2 is transmitted through the relays R_6 and R_7. All the received data is then combined at the destination to decode the original data.

Note that separating the subcarriers from each other may result in several implementation challenges such as relays synchronization, subcarriers orthogonality and interference issues. However, the separation of subcarriers to exploit the frequency diversity and using different paths for the different OFDM subcarriers has been recognized as a powerful technique that can achieve an appreciable performance gain [17]–[19] and hence merits investigation even with the increased network complexity. Therefore, in this paper, we assume perfect synchronization between all the nodes [4], [18], [24], [31] and the problems of out of band distortion and interference are left for future work. In fact, the main focus of this paper is to highlight the effectiveness of sparse signal recovery theory in OFDM based relay selection applications.

V. SPARSITY AWARE SELECTIVE OFDM WITH SUBCARRIER GROUPING (SA-S-OFDM-SG)

A. MOTIVATION

When the relay selection and distributed beamforming are performed using SA-S-OFDMA, each subcarrier is routed independently though a different path which enhances the selection diversity and the communication quality compared to SA-S-OFDM.

However, this performance enhancement comes at the cost of increased implementation challenges. In particular, routing the subcarriers independently increases the selection complexity and may cause other challenges such as synchronization, subcarrier orthogonality and receive-signal combining issues.

To alleviate these communication problems while guaranteeing adequate selection diversity, we propose the SA-S-OFDM-SG technique which allows only N_G groups of contiguous subcarriers to follow different paths instead of all N_S subcarriers as in SA-S-OFDMA.

B. RELAY SELECTION

As shown in Fig. 4, the communication bandwidth is divided into N_G groups of n_{spg} contiguous subcarriers.

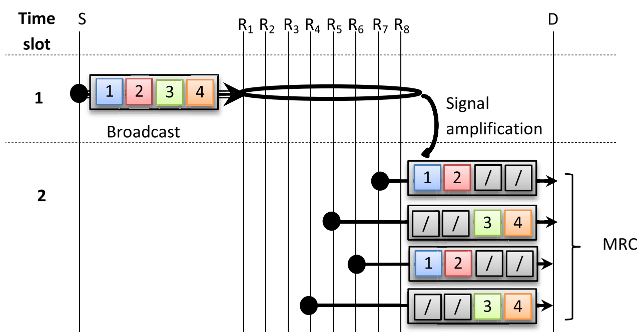

FIGURE 4. SA-S-OFDM-SG transmission model.

The subcarriers of the same group are assumed to follow the same paths and to use the same beamforming coefficients. Consequently, the selection process in each set of grouped subcarriers becomes equivalent to SA-S-OFDM.

In particular, for each group of subcarriers G, and similar to the SA-S-OFDM system, the average MSE at the destination is given by

$$MSE^G = P_0 - (\tilde{\boldsymbol{a}}^G)^H \boldsymbol{L}^{-H} (\boldsymbol{L}^{\boldsymbol{G}})^{-1} \tilde{\boldsymbol{a}}^G + \sigma_v^2 + ||(\boldsymbol{L}^{\boldsymbol{G}})^H \boldsymbol{w}^{\boldsymbol{G}} - (\boldsymbol{L}^{\boldsymbol{G}})^{-1} \tilde{\boldsymbol{a}}^G||_2^2, \quad (24)$$

where $\boldsymbol{w}^{\boldsymbol{G}}$ denotes the selection and beamforming vector for all the subcarriers in group G,

$$\tilde{\boldsymbol{a}}^G = \frac{1}{N_{spg}} \sum_{m \in G} \tilde{\boldsymbol{a}}^m \quad (25)$$

$$\tilde{\boldsymbol{R}}^G = \frac{1}{N_{spg}} \sum_{m \in G} P_0\, \tilde{\boldsymbol{a}}^m (\tilde{\boldsymbol{a}}^m)^H + \boldsymbol{R}_{\boldsymbol{n}}^{\boldsymbol{m}}). \quad (26)$$

Furthermore, $\boldsymbol{L}^{\boldsymbol{G}}$ is obtained from the Cholesky factorization of $\tilde{\boldsymbol{R}}^G$ as

$$\tilde{\boldsymbol{R}}^G = \boldsymbol{L}^{\boldsymbol{G}} (\boldsymbol{L}^{\boldsymbol{G}})^H. \quad (27)$$

Consequently, the distributed beamforming process becomes equivalent to minimizing $||(\boldsymbol{L}^{\boldsymbol{G}})^H \boldsymbol{w}^{\boldsymbol{G}} - (\boldsymbol{L}^{\boldsymbol{G}})^{-1} \tilde{\boldsymbol{a}}^G||_2^2$ independently for each one of the N_G subcarrier groups. Equivalently, for each group G, the MSE minimization based selection becomes equivalent to

$$\min_{\boldsymbol{w}^G} ||(\boldsymbol{L}^{\boldsymbol{G}})^H \boldsymbol{w}^{\boldsymbol{G}} - (\boldsymbol{L}^{\boldsymbol{G}})^{-1} \tilde{\boldsymbol{a}}^G||_2^2, \quad (28a)$$

$$\text{s. t. card}(\boldsymbol{w}^{\boldsymbol{G}}) = k. \quad (28b)$$

Hence, and similar to the SA-S-OFDM selection technique, the OMP algorithm is used to compute the selection vector for each group of subcarriers G by replacing $\boldsymbol{a}$, $\boldsymbol{w}$ and $\boldsymbol{L}$ with $\tilde{\boldsymbol{a}}^G$, $\boldsymbol{w}^{\boldsymbol{G}}$ and $\boldsymbol{L}^{\boldsymbol{G}}$, respectively. i.e.

$$\boldsymbol{w}^{\boldsymbol{G}} = OMP\Big((\boldsymbol{L}^{\boldsymbol{G}})^H, (\boldsymbol{L}^{\boldsymbol{G}})^{-1} \tilde{\boldsymbol{a}}^G, k \text{ iterations}\Big). \quad (29)$$

Fig. (4) presents an example of a relay selection decision based on SA-S-OFDM-SG where the four subcarriers ($N_S = 4$) are divided into to two groups ($N_G = 2$) with two contiguous subcarriers in each ($N_{spg} = 2$). Based on the channel realizations and the selection technique detailed below, the relays R_6 and R_7 are selected for example to forward the first two subcarriers while the relays R_4 and R_5 are selected to forward the data in subcarriers 3 and 4. At the destination, the two signal copies are combined using MRC.

VI. COMPUTATION COMPLEXITY COMPARISON

A. INTRODUCTION

In order to compare the computational complexity of the different investigated techniques, we present in this subsection a summary of the selection procedure for SA-S-OFDM, SA-S-OFDM-SG and SA-S-OFDMA. As shown in Fig. (5), the source starts always by collecting all the CSI required for the selection and by computing the equivalent channel vector a^m for each subcarrier m (See Eq. (5)).

When the SA-S-OFDMA selection technique is used, the vectors a^m are used to compute the dictionary matrix $(L^m)^H$ for each subcarrier m (See Eq. (20) and Eq. (21)). Both a^m and $(L^m)^H$ are used by the OMP algorithm to generate the selection and beamforming vector w^m for each subcarrier m.

When the SA-S-OFDM technique is used, instead of using a^m and $(L^m)^H$ as inputs for the OMP algorithm, the intermediate aggregated channel vector a (see Eq. (12)) and aggregated dictionary matrix L^H (see Eq. (13)) are computed and used to generate only one selection and beamforming vector for all the subcarriers.

When the SA-S-OFDM-SG technique is used, the intermediate aggregated channel vectors $\tilde{a}^G$ (see Eq. (25)) and aggregated dictionary matrix $(L^G)^H$ (see Eq. (26) and Eq. (27)) are computed independently for each a group of joint subcarriers G in order to generate a different Selection and beamforming vector for each group G.

B. SELECTIVE OFDM

In this subsection, the computational complexity of the relays selection and distributed beamforming is investigated for the case where all the subcarriers are routed through the same paths. The complexity is analyzed when the selection is performed by using the three techniques described below

- Exhaustive search: The selection is done by comparing all the possible selection combinations without performing any beamforming i.e. the selection vector $\boldsymbol{w}$ is binary [8].
- Basic Selective OFDM: The k relays that maximize the worst channel gain are selected [19], [30].
- Sparsity-Aware Selective OFDM: k relays are selected for all the subcarriers as detailed in Eq. (18).

First, the optimal k relays selection (without beamforming) can be obtained using ES [8] where there are $\binom{N_{Paths}}{k} = O({N_R}^k)$ possibilities. Consequently, the complexity of the exhaustive search becomes

$$C_{S-OFDM}^{ES} = O({N_R}^k). \quad (30)$$

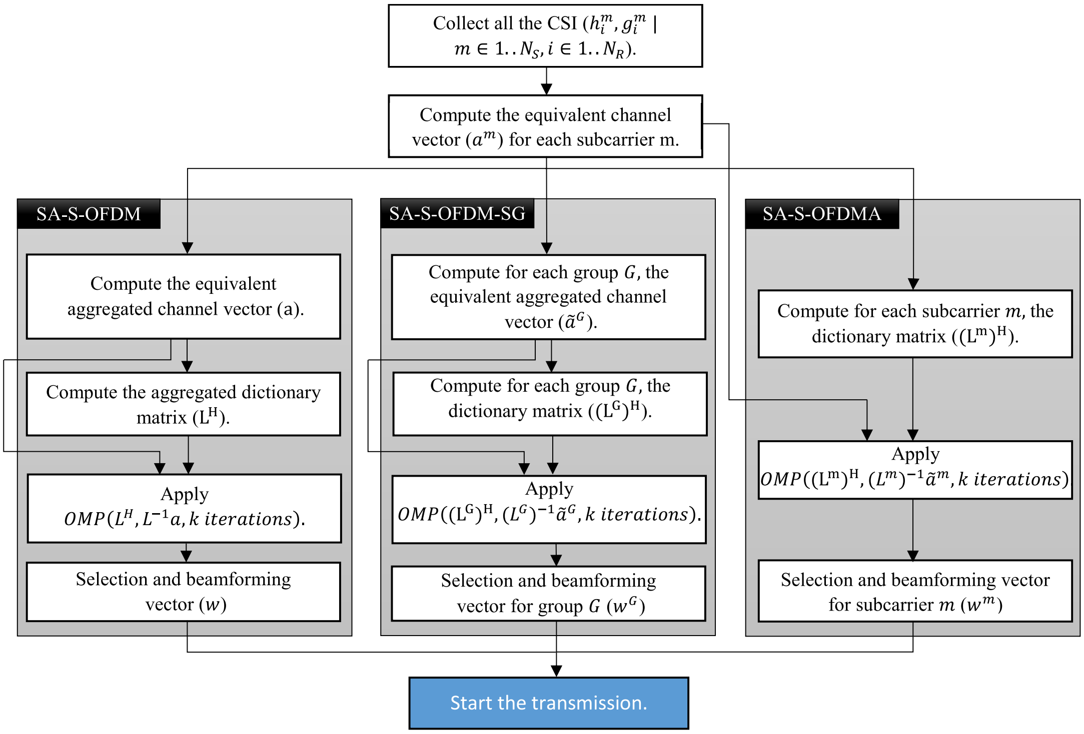

FIGURE 5. **Flow chart of the different proposed selection techniques.**

When the SA-S-OFDM technique is used to select the k relays, k iterations of the OMP algorithm have to be performed to compute a sparse vector of length N_R with exactly k non-zero elements. Consequently, the computation complexity is drastically reduced compared to ES by exploiting SSR theory and is given by [14]

$$C^{SA}_{S-OFDM} = O(k^2 N_R). \tag{31}$$

The selection process in Selective OFDM (S-OFDM) [19], [30] is done simply by sorting the worst channel gains and selecting the highest k. Thus, the selection complexity is the lowest compared to the ES and the SA techniques and is equal to

$$C^{B}_{S-OFDM} = O(N_R). \tag{32}$$

C. SELECTIVE OFDMA

In this subsection, we compare the computational complexity of selecting one path for each subcarrier using ES, B-S-OFDMA [19], [30] or by the proposed SA-S-OFDMA as detailed in Eq. (23). Compared to the selective OFDM techniques, the complexity is multiplied by N_S since the selection is performed independently for each OFDM subcarrier. Consequently, the computation complexities are given by

$$C^{ES}_{S-OFDMA} = O(N_S\, {N_R}^k). \tag{33}$$
$$C^{SA}_{S-OFDMA} = O(N_S\, k^2 N_R). \tag{34}$$
$$C^{B}_{S-OFDMA} = O(N_S\, N_R). \tag{35}$$

D. SUBCARRIER GROUPING

When the relays selection is performed separately for each group of OFDM subcarriers, the selection process is repeated N_G times and the computation complexity is multiplied by N_G compared to the different selective OFDM techniques as shown in [19], [30]. Consequently, the computation complexities are given by

$$C^{ES}_{S-OFDM-SG} = O(N_G\, {N_R}^k). \tag{36}$$
$$C^{SA}_{S-OFDM-SG} = O(N_G\, k^2 N_R). \tag{37}$$
$$C^{B}_{S-OFDM-SG} = O(N_G\, N_R). \tag{38}$$

E. SUMMARY

Table 2 presents a summary of the computational complexity of the relays selection process based on ES, worst channel maximization and the proposed SA techniques.

Note that ES selection complexity is always a multiple of $O(N_R^k)$ which is extremely high and is difficult to implement in practice especially in large relay networks. However, the complexity of the proposed SA techniques is reduced to multiples of $O(k^2\ N_R)$ by exploiting the sparse nature of the selection vector and by using the low complexity OMP algorithm. In addition, the worst channel maximization techniques can further reduce these complexities to multiples of $O(N_R)$ but without computing any beamforming coefficient.

Note also that the diversity enhancement of the selective OFDMA techniques compared to the selective OFDM techniques comes at the cost of a multiplication of the complexity

TABLE 2. Computational complexity comparison.

	Exhaustive Search	Sparsity Aware	Basic (worst channel gain maximization) [20], [33]
Selective OFDM	$O\left({N_R}^k\right)$	$O\left(k^2 N_R\right)$	$O\left(N_R\right)$
Selective OFDMA	$O\left(N_S\, {N_R}^k\right)$	$O\left(N_S\, k^2 N_R\right)$	$O\left(N_S\, N_R\right)$
Selective OFDM with Subcarrier Grouping	$O\left(N_G\, {N_R}^k\right)$	$O\left(N_G\, k^2 N_R\right)$	$O\left(N_G\, N_R\right)$

by a factor of N_S. This factor can be reduced to N_G for the subcarrier grouping techniques creating a compromise between selection complexity and performance.

VII. SIMULATION RESULTS

In this section, the simulated results of SA-S-OFDM, SA-S-OFDM-SG and SA-S-OFDMA are presented and compared with the binary exhaustive search techniques (ES) and Least-Square ES (LS-ES). The proposed techniques are also compared with the Bulk and PerSubcarrier selection techniques investigated in [4]. In particular, in the Bulk selection technique, the source only selects one out of N_R relays for all the subcarriers in order to maximize the capacity. While in PerSubcarrier selection technique, a relay is selected independently for each subcarrier. The performance is evaluated in terms of the end-to-end BER using extensive Monte-Carlo simulations.

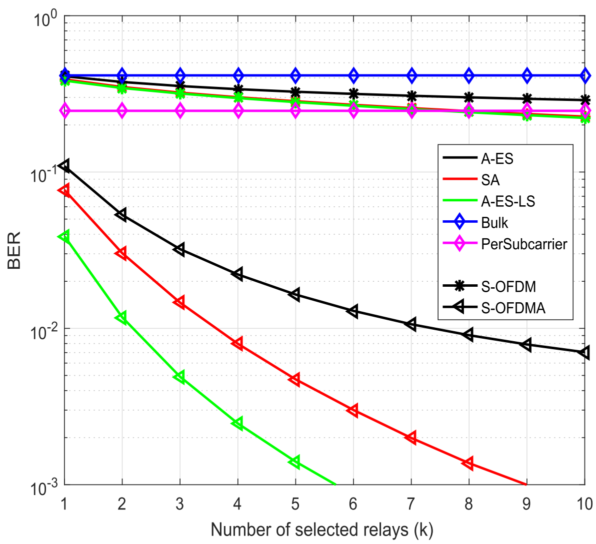

FIGURE 6. BER performance of PerSubcarrier and Bulk as well as the SA, A-ES and A-ES-LS techniques applied to the S-OFDM and S-OFDMA techniques.

As shown in Section VI, all the proposed Sparsity Aware (SA) selection techniques have lower complexities compared to the exhaustive search technique. In addition, it has been shown that SA-S-OFDMA has a higher computation complexity compared to SA-S-OFDM. In terms of BER, Fig. (6) compares the performances of the proposed SA-S-OFDMA and the SA-S-OFDM techniques with both the Boolean and the Least Squares (LS) optimized ES techniques and investigates whether the reduction in complexity is associated or not with BER performance loss. The SNR level is fixed at −2 dB and the network is assumed to be composed of 100 relays. First, it can be seen that compared to the Boolean ES technique, the proposed SA selection technique performs better in terms of BER with only limited-complexity processing whether the S-OFDM or the Selective OFDMA (S-OFDMA) techniques are used. It can be seen also that the SA selection techniques performance loss (in terms of BER increase) is small and acceptable compared to the Accelerated Exhaustive Search with Least Square (AES-LS) techniques thanks to the big reduction in computational complexity.

Note also that thanks to the separation of the subcarriers and to the exploited spatial and frequency diversities, the SA-S-OFDMA technique performs much better than the SA-S-OFDM technique and has a higher diversity order at the price of an increased complexity by a factor of N_S. This gap between the SA-S-OFDM and the SA-S-OFDMA techniques in performance and complexity motivated us to investigate the SA-S-OFDM-SG technique to create a compromise between BER and complexity. Furthermore, note that compared to SA-S-OFDM and Bulk selection techniques, the PerSubcarrier selection technique reduces the BER by exploiting the frequency diversity. However, the BER performance of the PerSubcarrier selection technique remains lower than those of the S-OFDMA techniques (ES, A-ES-LS and SA) especially when increasing k. In particular, this performance gap is caused mainly by the fact that the PerSubcarrier selection technique selects only one relay while k relays are selected by the S-OFDMA techniques, in addition to the beamforming coefficients optimized by the proposed SA selection techniques using the OMP algorithm. However, the Bulk selection technique achieves almost the same BER performance as that of the S-OFDM techniques (ES, A-ES-LS and SA) when only one relay is selected but the S-OFDM techniques outperform it when a higher number of relays is selected.

Fig. (7), presents the effect of the number of selected relays on the BER performance of the different SA selection techniques for OFDM systems with $N_R = 20$ potential relays operating over $N_S = 128$ subcarriers when subcarrier grouping is applied. First, note that the BER reduces with the number of groups for the different investigated relay selection techniques. Since the computation complexity also increases

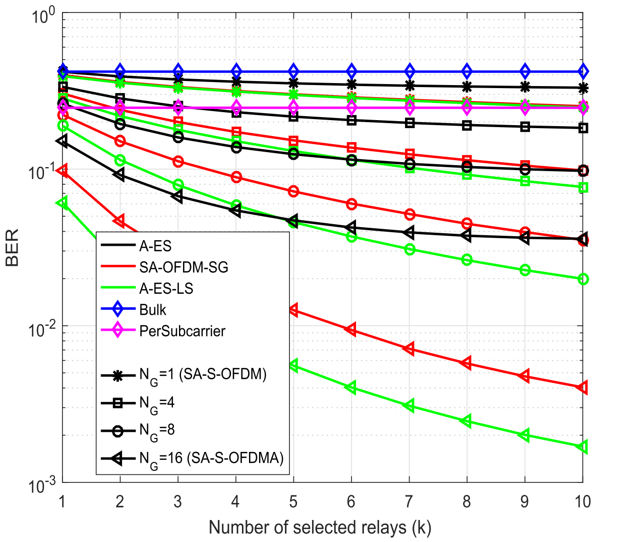

FIGURE 7. Effect of k on the BER performance of PerSubcarrier, Bulk and the SA, A-ES and A-ES-LS techniques when used with subcarrier grouping.

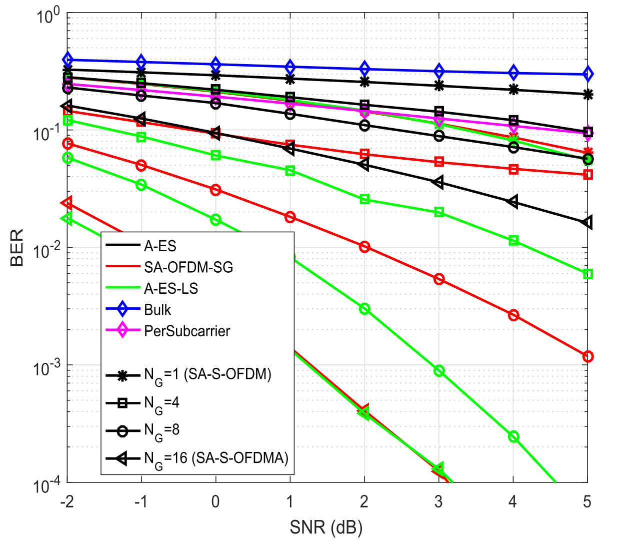

FIGURE 8. Effect of the SNR on the BER performance of PerSubcarrier, Bulk and the SA, A-ES and A-ES-LS techniques when used with subcarrier grouping.

linearly with the number of groups for these techniques, a compromise is made between the BER performance and the computation complexity. Thus, dividing the OFDM bandwidth into independent subcarriers allows SA-S-OFDMA to reap much more selection gain compared to SA-S-OFDM. Furthermore, it can be seen that independently from the number of groups, the proposed SA selection techniques (SA-S-OFDM, SA-S-OFDM-SG and SA-S-OFDMA) outperform the binary Accelerated Exhaustive Search (A-ES) technique (which also outperforms S-OFDM, Selective OFDM with Subcarrier Grouping (S-OFDM) and S-OFDMA [19], [30]) while also drastically reducing the selection complexity compared to the ES technique and the S-OFDM, S-OFDM and S-OFDMA selection techniques. The performances of the proposed techniques are also compared with AES-LS, where the beamforming parameters are optimized using LS for all the possible combinations of relays. It can be seen that SA-S-OFDM provides a near-optimal performance compared with AES-LS. However, when increasing the number of groups, a small BER gap appears between the SA techniques and AES-LS. However, in spite of providing a lower BER, the AES-LS techniques are still outperformed by SA-S-OFDM-SG in terms of computation complexity especially when the LS computational complexity is combined with the ES technique. In addition, as shown in Fig. (6), the Bulk selection technique loses its performance gain against the S-OFDM techniques when a high number of relays is selected. In addition, when only one relay is selected, SA-OFDM-SG with only 8 groups has almost the same BER performance as that of the PerSubcarrier selection technique while dividing the subcarriers into 8 groups instead of 16 and the performance gap between these techniques increases by increasing the number of relays thanks to the optimized beamforming coefficients by the proposed SA selection techniques.

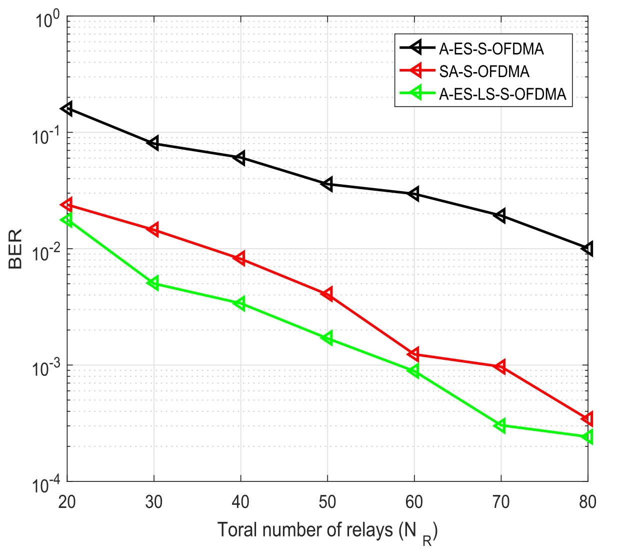

FIGURE 9. BER performances of SA-S-OFDM, ES-S-OFDM and S-OFDM.

Fig. (8) presents the effect of the SNR on the BER performance of the SA and the basic selection techniques when 10 out of 100 relays are selected ($k = 10$, $N_R = 100$). It can be seen that the performance gain (in terms of BER) of the proposed techniques compared to the A-ES selection techniques increases with the SNR. Equivalently, using the SA techniques reduces both the computational complexity and BER compared to A-ES. Furthermore, the performance gap compared with the optimal AES-LS solution remains acceptable even when increasing the SNR given the amount of complexity reduction. It can be seen also that the BER of the proposed SA selection techniques decreases faster with the SNR compared to the PerSubcarrier and the Bulk selection techniques. This is done thanks to the selection of multiple relays and to the use of optimized beamforming coefficients for the SA selection techniques which increases the diversity order compared to the PerSubcarrier and the Bulk selection techniques where only a single relay is selected towards maximizing the capacity.

In Fig. (9), k relays are selected to forward the data when the SNR level is fixed at -2 dB. To investigate the efficiency of the proposed SA-S-OFDMA technique in small and large relay networks, the total number of relays is varied from 20 to 80 relays. It can be seen that, by using only the low complexity OMP algorithm, the SA-S-OFDMA technique achieves much better performance (a BER reduction of more than 10 dB) than the optimal Boolean selection technique (A-ES-S-OFDMA) near-optimal performance (around 2 dB BER loss compared to the A-ES-LS-S-OFDMA) independently from the size of the network which demonstrates the potential for the proposed techniques to be implemented in large IoT/D2D and cooperative vehicular networks.

CONCLUSION

In large IoT/D2D and wireless networks, the relay selection complexity as well as the efficiency of the data forwarding protocols are critical metrics to the regular functioning of the network. Therefore, we investigated in this paper the problem of multiple relay selection and beamforming in dual-hop large AF networks using OFDM transmissions. In particular, the proposed SA selection techniques were shown to enhance the communication quality in dual-hop AF networks by minimizing the MSE at the destination which is formulated in this paper so that the low-complexity OMP algorithm can be used to perform joint relay selection and distributed beamforming. In addition, three techniques were proposed and investigated in the paper to minimize the MSE with limited-complexity algorithms. First, the SA-S-OFDM allows the source to select the same set of relays and their corresponding beamforming coefficients for all the subcarriers, i.e. the subcarriers are not separated from each other. Second, by optimizing the set of selected relays and their beamforming coefficients independently for each subcarrier, the proposed SA-S-OFDMA technique can achieve a higher diversity order and better BER performance compared to SA-S-OFDM but at the price of increased implementation challenges and computation complexity. Therefore, a third technique named SA-S-OFDM-SG was suggested to create a performance-complexity tradeoff between the SA-S-OFDM and SA-S-OFDMA techniques. Simulation results show that these techniques provide better performances compared to state-of-the-art techniques from the literature and a near-optimal performance with a reduced computation complexity compared to the ES technique. Finally, a detailed performance-complexity tradeoff analysis was presented to compare the different studied techniques.

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