Energy-efficient hybrid opportunistic cooperative protocol for single-carrier frequency division multiple access-based networks

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Abstract: In this study, a new energy-efficient hybrid opportunistic cooperative (HOC) transmission protocol is proposed for single-carrier frequency division multiple access (SC-FDMA)-based cooperative networks. The author considers a single source–destination pair and multiple relays network. The proposed protocol improves the energy efficiency of SC-FDMA-based networks by selecting the most energy-efficient cooperative transmission protocol from a set of available protocols according to the current channel state information. The protocols considered in the development of the HOC protocol are amplify-and-forward, decode-and-forward, compress-and-forward and estimate-and-forward. Computer simulation is done over four different scenarios of channel conditions. The obtained results show that the proposed HOC protocol significantly improves the delay-limited capacity and minimises the outage probability of SC-FDMA-based cooperative networks. The results also show that the minimum required average total power in the proposed HOC protocol is less than that of opportunistic decode-and-forward by 0.55 dB.

1 Introduction

The main challenge in today’s wireless broadband networks is to support high data rates while avoiding multipath effects over frequency selective fading channels. As indicated in [1, 2] the multiple-input–multiple-output (MIMO) antenna techniques are considered effective means to achieve spatial diversity and multiplexing gain in wireless networks. Unfortunately, the physical size of most mobile hardware devices limits the number of antennas that can be co-deployed because of probabilistic correlation between antennas. Cooperative communications refer to the class of techniques, where the benefits of MIMO techniques are gained via sharing information between multiple cooperating terminals in a wireless networks. Wireless relay networks that employ cooperative diversity have sometimes been referred to as virtual MIMO systems [3–7].

Single-carrier frequency division multiple access (SC-FDMA), which utilises single-carrier modulation and frequency domain equalisation is a technique that has similar performance and essentially the same overall complexity as those of orthogonal frequency division multiple access (OFDMA) system. SC-FDMA is an extension of single-carrier modulation with frequency domain equalisation (SC-FDE) to accommodate multiple-user access [8–10]. One prominent advantage over OFDMA is that the SC-FDMA signal has lower peak-to-average power ratio (PAPR) because of its inherent single-carrier structure [10]. SC-FDMA has drawn great attention as an attractive alternative to OFDMA, especially in the uplink communications where lower PAPR greatly benefits the mobile terminal in terms of power efficiency. Currently, it has been adopted for the uplink multiple access transmission in 3GPP long-term evolution (LTE) or evolved universal terrestrial radio access (E-UTRA) [11].

The performance evaluation of SC-FDMA-based cooperative communication systems was reported in many literatures [12–14]. The multiuser performance of the amplify-and-forward (AF) single-relay-assisted SC-FDMA uplink scheme was proposed in [12]. The energy-efficient channel-dependent cooperative relaying for the multiuser SC-FDMA uplink was considered in [13]. In [14], the authors proposed a space-time coding (STC) and space-frequency coding (SFC) mapping scheme, which provided good PAPR property, a capability of low-complexity frequency-domain equaliser (FDE) and full space diversity. This paper provides a comprehensive study of the energy efficiency of a single source–destination pair and N relay nodes SC-FDMA-based cooperative networks under differing assumptions about channel state knowledge and cooperative protocols.

Generally, the main contribution of this paper is to propose a new energy efficient hybrid opportunistic cooperative (HOC) transmission protocol for SC-FDMA-based cooperative networks. The proposed protocol improve the energy efficiency of SC-FDMA-based cooperative networks by selecting the most energy-efficient cooperative transmission protocol from a set of available protocols.
according to the current channel state information (CCSI). The authors in [15] proposed an opportunistic decode-and-forward (ODF) protocol, in which the terminals choose either decode-and-forward (DF) or direct transmission (DT) depending on which protocol is more energy efficient in the current channel state. In the proposed protocol, the choice is among multiple transmission protocols. These protocols are AF, DF, compress-and-forward (CF) and estimate-and-forward (EF). Therefore the proposed HOC protocol is expected to outperform the ODF protocol [15] especially when the relay is close to the destination as will be verified in the results and discussion section. The SC-FDMA-based networks with the proposed HOC transmission protocol combine the advantages of the low-complexity and the high-power efficiency of the SC-FDMA system and the performance improvements in terms of delay-limited capacity and the outage probability of the proposed HOC protocol because of the freedom of choosing among multiple transmission protocols.

2 Cooperative SC-FDMA system model

This section presents the cooperative SC-FDMA system model used in this paper. We consider a single source–destination cooperative system with multiple relay nodes \( R_i \) (\( i = 1, 2, \ldots, N \)), that is, a total of \( N + 2 \) nodes are considered in the network as shown in Fig. 1a. The relay nodes are randomly located between the source node \( S \) and the destination node \( D \). An SC-FDMA transceiver with \( K \) subcarriers is available at each node. Assume perfect time and frequency synchronisation among nodes and the inclusion of a cyclic prefix (CP) that is long enough to accommodate the delay spread of the channel. In this paper, we model the links among the network nodes as independent, quasi-static and Rayleigh flat fading channels. Denote the channel coefficients from \( S \) node to the \( D \) node, from \( S \) node to the relay node \( i \), and from relay node \( i \) to the \( D \) node as \( h_{SD} \), \( h_{SR_i} \), and \( h_{RI_D} \), respectively. In general, these coefficients include path loss, shadowing and Rayleigh flat fading. There is also additive white Gaussian noise (AWGN) with zero-mean and equal variance \( \sigma^2 \) at each receiver.

The normalised squared channel gains in the cooperative SC-FDMA system shown in Fig. 1a denoted by \( H_1 = |h_{SD}|^2 / \sigma^2 \), \( H_2 = |h_{SR_i}|^2 / \sigma^2 \) and \( H_3 = |h_{RI_D}|^2 / \sigma^2 \) are exponentially distributed random variables with means \( \mu_1 \), \( \mu_2 \) and \( \mu_3 \), respectively.

To consider the effect of the \( i \)th relay position on the performance of the SC-FDMA-based networks, we assume that the \( i \)th relay is located between the source and the destination, on the straight line connecting them as shown in Fig. 1b. The distance between the source and the destination is normalised to one. Therefore if the source to \( i \)th relay distance is \( d \), the \( i \)th relay to destination distance will be \( 1 - d \) [15, 16]. For a fixed path loss exponent, \( \alpha \), the effect of this normalisation is scaling the average power. The means of normalised squared channel coefficients will be \( \mu_1 = 1 \), \( \mu_2 = 1/d^\alpha \) and \( \mu_3 = 1/(1 - d)^\alpha \). The mean values capture the effect of path loss across the corresponding link. As in most existing schemes, each cooperation period is divided into two orthogonal phases as shown in Fig. 2.

2.1 First phase

In this phase, the source node \( S \) broadcasts the information to its intended destination \( D \) (DT) and to all potential relays as shown in Fig. 1a. The relays that have succeeded in detecting the information, that is, the relays with the highest signal-to-noise ratio (SNR) are selected to construct a relaying candidate set \( S(R) \), where \( S(R) \subseteq [1, \ldots, N] \). Let \( N_R \) represents the number of relays in this set where \( 1 \leq N_R \leq N \). The relays in \( S(R) \) can be selected by monitoring the received SNR value at each relay node and forward these values to a central node, which may be a base station or any other node. In this paper, the \( i \)th relay is selected from \( N_R \) not from all the \( N \) relays.

Fig. 2a shows the transmitter structure of SC-FDMA system. The first step is to perform a \( K \)-point discrete Fourier transform (DFT) to produce a frequency domain representation \( X_k \) of the input symbols. It then maps each of the \( K \)-DFT outputs to one of the \( M \) \((> K) \) orthogonal subcarriers that can be transmitted. There are two methods to choose the subcarriers for transmission: distributed subcarrier mapping and localised subcarrier mapping [10]. The distributed mode with equidistance between occupied subcarriers is called interleaved FDMA (IFDMA), which will be considered in this paper.

The result of the subcarrier mapping is the set \( \tilde{X}_l \) (\( l = 0, 1, 2, \ldots, M - 1 \)) of complex subcarrier amplitudes, where \( K \) of the amplitudes are non-zero. As in OFDMA, an \( M \)-point inverse DFT (IDFT) transforms the subcarrier amplitudes to a complex time-domain signal \( \tilde{x}_m \). Finally, each SC-FDMA block is preceded by a CP and then broadcasted. In the ‘first phase’, the received signal from the source at the destination, \( y_{SD} \) and at the \( i \)th relay, \( y_{SR_i} \) can be expressed as

\[
y_{SD} = \sqrt{P_S h_{SD}} x + n_{SD} \tag{1}
\]

\[
y_{SR_i} = \sqrt{P_S h_{SR_i}} x + n_{SR_i} \tag{2}
\]

where \( P_S \) is the average transmitted power of the source node, \( x \) is the transmitted data with unit power constraint, that is, \( E[|x|^2] = 1 \), where \( E[.| \] represents the expectation operator.
and $n_{\text{SD}}$ and $n_{\text{SR}}$ are the AWGN terms at $D$ and $i$th relay, respectively, with zero mean and equal variance $\sigma^2$. The proposed HOC protocol is applied at the $i$th relay as shown in Fig. 2b.

2.2 Second phase

In the ‘second phase’, the selected $i$th relay generates the relayed signal $x_r$ and transmits it to the destination $D$ using the proposed HOC protocol. The received signal at the destination from the selected $i$th relay is given by

$$y_{RD} = \sqrt{P_R h_{RD}^2} x_r + n_{RD}$$

where $P_R$ is the average transmitted power of the $i$th relay and $n_{RD}$ is the AWGN of the $R_i$ to $D$ link.

The destination node $D$ employs maximal ratio combining (MRC) to combine the received signals from the ‘first’ and ‘second’ phases. Hence, we can improve the diversity gain by selecting more than one relay from the set $S(R)$. In this case, the received signal at the destination is given by

$$y_D = \sum_{i=1}^{N_S} y_{RD}$$

The receiver transforms the received signal into the frequency domain with $M$-point DFT, de-maps the subcarriers, and then performs FDE. In this paper, we consider the minimum mean-square error (MMSE) equalisation. The equalised symbols are transformed back to the time domain via $K$-point IDFT, and detection and decoding take place in the time domain as shown in Fig. 2c.

3 Proposed HOC protocol

The protocols considered in the development of the proposed HOC protocol are AF, DF, CF and EF. The following subsections introduce and analyse these protocols in terms of delay-limited capacity and outage probability.

Consider the scenario shown in Fig. 1a, there are two transmission energies in each cooperative frame when selecting one ($i$th) relay from the set $S(R)$. We assume a half-duplex relay and normalise the time interval for each cooperative frame to one unit as in Fig. 3. Let $P(c) = (P_S(c), P_R(c), T(c))$ be a resource allocation function defined over the set of all possible channel states $c = (H_1, H_2, H_3)$, where $P_S(c)$ is the source power in the first time-slot of duration $T(c)$, $P_R(c)$ is the transmission power of the selected $i$th relay in the second time-slot of duration $1 - T(c)$, $0 < T(c) \leq 1$, $H_1$, $H_2$ and $H_3$ are the normalised squared channel gains as shown in Fig. 1a. The total transmission power $P_t = P_S + P_R$.

Define $\psi$ as the set of all possible resource allocation functions. We have

$$\psi = \{P(c): P_S(c) \geq 0, \quad P_R(c) \geq 0, \quad 0 < T(c) \leq 1\}$$

Define $F(c)$ as the probability distribution function of the channel states, $c$. Then the long-term average total transmit energy constraint can be written as [15]

$$E[P_t(c)] = \int c \left[ T(c)P_S(c) + (1 - T(c))P_R(c) \right] dF(c) \leq P_{\text{avg}}$$

Fig. 2 SC-FDMA-based cooperative network using the proposed HOC protocol

Fig. 3 First and second time-slots transmission of the proposed HOC protocol
The long-term average total transmit power constraint imposes a set of feasible resource allocation functions, \( \psi \subseteq \phi \), that is composed of power allocation functions, which satisfy the above inequality, that is

\[
\tilde{\psi} = \{ P(c): E[P(c)] \leq P_{\text{avg}}, P(c) \in \phi \}
\]  

(7)

The performance of SC-FDMA-based cooperative networks with the proposed HOC protocol is evaluated in terms of delay-limited capacity and outage probability. The delay-limited capacity is defined as the highest achievable rate that can be sustained independent of the channel state [15, 17]. The proposed HOC protocol maximises the delay-limited capacity by dynamically allocating the relay transmit time and power among the terminals, based on the CSI. Let \( C(P(c), c) \) be the instantaneous capacity of the SC-FDMA-based cooperative networks with the proposed HOC protocol using the above-defined resource allocation function, \( P(c) \) at channel state \( c \). Define \( R \) as the target rate, the delay-limited capacity maximisation problem can be represented as follows

\[
\max_{P(c) \in \tilde{\psi}} R \\
\text{such that } \Rightarrow \quad C(P(c), c) \geq R \quad \text{for all } c
\]  

(8)

Using the usual cut-set bounds (CSB) for the half-duplex relay, we find an upper bound, CSB to the delay-limited capacity. For any power and time allocation scheme, the instantaneous capacity can be upper bounded by [15] as

\[
C_{\text{CSB}}(P(c), c) = \min \{ T(c) \log (1 + (H_1 + H_2)P_S), T(c) \log (1 + H_1P_S) + (1 - T(c)) \log (1 + H_2P_\phi) \}
\]  

(9)

Solving (8)

\[
\max_{P(c) \in \tilde{\psi}} R \\
\text{such that } \Rightarrow \quad C_{\text{CSB}}(P(c), c) \geq R \quad \text{for all } c
\]  

(10)

The outage probability, \( P_{\text{out}} \), is defined as the probability that the SNR at the destination \( D \) falls below a deterministic threshold \( \rho \) [18, 19]

\[
P_{\text{out}} = \text{Prob}[\text{SNR} < \rho]
\]  

(11)

What we want is to minimise the total transmission energy subject to an outage probability constraint as follows

\[
\min_{P(c) \in \tilde{\psi}} E[P(c)] \\
\text{such that } \Rightarrow \quad P_{\text{out}} \leq p
\]  

(12)

where \( 0 \leq p \leq 1 \). Using (8), the problem of minimising the outage probability can be expressed in terms of delay-limited capacity as

\[
\min_{P(c) \in \tilde{\psi}} P_{\text{out}} = \text{Prob}[C(\min_{P(c) \in \tilde{\psi}} P(c), c) < R]
\]  

(13)

The proposed HOC protocol selects from all available protocols the most energy-efficient protocol according to

the current CSI. In this paper, we will consider ‘four’-different scenarios of CSI [6, 20, 21], as follows:

- **First scenario**

  When the source \( S \) and the selected \( i \)-th relay \( R_i \) have access to full CSI, they can dynamically allocate their transmission energies according to the instantaneous channel amplitudes in each transmission interval.

- **Second scenario**

  When the source \( S \) and the selected \( i \)-th relay \( R_i \) do not have access to the CSI, they cannot dynamically allocate their transmission energies in each transmission interval. Instead, they must select a fixed transmission energy based only on knowledge of the channel statistics.

  In the ‘first’ and the ‘second’ scenarios it is assumed that, the destination has full access to the CSI and the transmit energies of the source \( S \) and the selected relay \( R_i \) in both time-slots and uses MRC. This can be accomplished by separate low-rate feedback channels.

- **Third scenario**

  In this scenario, the source \( S \) and the selected \( i \)-th relay \( R_i \) have access to full CSI.

- **Fourth scenario**

  When the source \( S \) and the selected \( i \)-th relay \( R_i \) do not have access to the CSI.

  In the ‘third’ and the ‘fourth’ scenario, we assume that the CSI is not available at the destination; hence MRC cannot be used, however, we can use the equal gain combiner (EGC) [22]. These scenarios are summarised in Table 1. In this table, the word ‘Access’ means that the terminal has full access to CSI and ‘Not Access’ means that the terminal does not have access to full CSI.

  The following subsections introduce and analyse the AF, DF, CF and EF protocols in terms of delay-limited capacity and outage probability.

### 3.1 Direct transmission

Let us first discuss the DT that will be included for comparison. The maximum average mutual information between \( S \) and \( D \) in this case, is given by [6]

\[
I_{\text{DT}} = \log_2 (1 + g_{SD} \text{SNR})
\]  

(14)

The outage probability is given by \( I_{\text{DT}} < R \) and it can be expressed as [6]

\[
P_{\text{out}}(\text{DT}) = \text{Pr}[I_{\text{DT}} < R] = \text{Pr}
\left[
H_i < \frac{2^R - 1}{\text{SNR}}
\right]
\]

\[
= 1 - \exp\left(-\frac{2^R - 1}{H_i \text{SNR}}\right)
\]  

(15)

#### 3.2 AF protocol

In the AF protocol [20, 21] the selected \( i \)-th relay simply scales its received signal during the ‘first’ time-slot and retransmits it to the destination \( D \) in the ‘second’ time-slot. Therefore the
relayed signal, \( x_t \) in (3) can be written as follows
\[
x_t = A_F y_{SRi}
\]
where \( y_{SRi} \) is the received signal at \( R_i \) during the ‘first’ time-slot as defined in (2) and \( A_F \) is the scaling factor at the selected relay, it defined as [6, 20]
\[
A_F \leq \sqrt{\frac{P_{RI}}{|h_{SRi}|^2 P_S + \sigma^2}}
\]
(17)

- Considering the ‘first’ scenario, the resulting instantaneous SNR1 at the destination, after MRC, can be expressed as [21, 22]
\[
\text{SNR}_1(\text{AF}) = \frac{|h_{SD}|^2 P_S}{\sigma^2} + \sum_{i=1}^{N_r} \frac{|h_{SRi}|^2 P_{SD}/\sigma^2 \times |h_{RD_i}|^2 P_{RI}/\sigma^2}{1 + |h_{SRi}|^2 P_S/\sigma^2 + |h_{RD_i}|^2 P_{RI}/\sigma^2}
\]
(18)

We assume that all channels are independent Rayleigh fading channels. Substituting for \( H_1, H_2 \) and \( H_3 \) as defined in Section 2; (18) can be rewritten as
\[
\text{SNR}_1(\text{AF}) = H_1 P_S + \sum_{i=1}^{N_r} \frac{H_2 P_S H_1 P_{RI}}{1 + H_2^2 P_S + H_1 P_{RI}}
\]
(19)
where \( \bar{\gamma} = 1/\sigma^2 \) is proportional to all the transmitted and the received SNRs. Therefore it can be used as a measure of the average system SNR.

- In the ‘second’ scenario, the resulting instantaneous SNR2 at the destination, after MRC, can be expressed as
\[
\text{SNR}_2(\text{AF}) = H_1 P_S + \sum_{i=1}^{N_r} \frac{\mu_2 P_S H_1 P_{RI}}{1 + \mu_2 P_S + H_1 P_{RI}}
\]
(20)

It is clear that, in (19), the transmit powers are functions of the current channel states \( c = (H_1, H_2, H_3) \); whereas in (20), these powers are based only on the knowledge of the channel statistics, for example, \( \mu_1, \mu_2 \) and \( \mu_3 \).

- The resulting instantaneous SNR3 in the ‘third’ scenario at the destination, after EGC, can be expressed as [22] (see (21))
\[
\text{SNR}_3(\text{AF}) = \frac{H_1 P_S}{2} + \sum_{i=1}^{N_r} \frac{H_2 P_S P_R (H_2 - H_3/2) + 2P_3(H_1 H_2 H_1 P_{RI} + H_2 P_S + 1))}{2(H_2 P_S + 1) + H_2 P_{RI}}
\]
(21)

- Using (21), the resulting instantaneous SNR4 at the destination, after EGC, considering ‘fourth’ scenario can be expressed as (see (22))
\[
\text{SNR}_4(\text{AF}) = \frac{\mu_1 P_S}{2} + \sum_{i=1}^{N_r} \frac{\mu_2 P_S P_R (\mu_2 - \mu_3/2) + 2P_3(\mu_1 \mu_2 \mu_3 P_R + \mu_2 P_S + 1))}{2(\mu_2 P_S + 1) + \mu_3 P_{RI}}
\]
(22)

3.2.1 AF delay-limited capacity: Define \( P_{SD} = P_S |h_{SD}|^2 \), \( P_{SRi} = P_S |h_{SRi}|^2 \) and \( P_{RD} = P_R |h_{RD}|^2 \) as the received signal power at \( D \) from \( S \), at the \( i \)th relay \( R_i \) from \( S \), and at \( D \) from \( R_i \) relay, respectively. The maximum instantaneous mutual information achieved by AF with resource allocation \( P(c) = (P_S(c), P_R(c), 0.5) \) at channel state \( c \) can be written as follows [17, 23]
\[
I(x; y_{SD}(c)) = 0.5 \log \left( \frac{1 + \bar{\gamma} H_1 P_{SRi} P_{SD} |A_F|^2 + H_1 P_{RI} + \bar{\gamma} H_1 P_{SD} P_{RI}}{1 + |A_F|^2 H_3 + |A_F|^2 H_3} \right)
\]
(23)

In the AF protocol, the time interval for each cooperative frame is divided into two equal time slots, that is \( T(c) = 0.5 \) for all \( c \) [6, 16, 20]. The delay-limited capacity of AF can be found by solving the optimisation problem in (10), by replacing \( C(P(c), c) \) with \( C_{AF}(P(c), c) \) as
\[
C_{AF}(P(c), c) = I(x; y_{SD}(c))
\]
(24)
Equation (24) gives the delay-limited capacity of the orthogonal AF transmission protocol.

3.2.2 AF outage probability analysis: To obtain the outage probability, we should first obtain the cumulative density function (CDF) of the achieved system SNR, \( \gamma \), defined in (19)–(22). In this paper, we consider the distribution in large average SNR values. The CDF of the received system SNR can be written as follows [21]
\[
F_{AF}(\gamma) \simeq \frac{1}{N_s + 1} \left( \frac{\gamma}{\bar{\gamma}} \right)^{N_s + 1} P_{SD} \prod_{i=1}^{N_r} (P_{SRi} + P_{RD})
\]
(25)
Using (13), the outage probability can expressed as

\[ P_{\text{out}}(\text{AF}) = \Pr[C_{\text{AF}}(P(c), c) < R] \]
\[ = \Pr[\gamma < 2^{(N_s+1)R} - 1] = F_{\text{AF}}(2^{(N_s+1)R} - 1) \quad (26) \]

We can substitute for \( \gamma \) from (19) to (22) to obtain the outage probability for each of the above mentioned scenarios. It can be seen that the outage probability given in (26) is proportional to \((1/\gamma)^{2(N_s+1)}\). Thus, a cooperative diversity order of \(N_s + 1\) can be achieved.

### 3.3 DF protocol

In DF protocol [24], the source \( S \) first transmits its message to both the destination \( D \) and the \( N \) relays in the ‘first’ time-slot, the selected \( i \)th relay \( R_i \) decodes and retransmits this message to the destination in the ‘second’ time-slot. In DF protocol considered in this paper, the time allocation is not necessarily equal \((0 < T(c) \leq 1)\) [15] unlike the simple non-opportunistic fixed decode-and-forward (fDF) considered in [25].

#### 3.3.1 DF delay-limited capacity: The instantaneous capacity achieved by DF with resource allocation function \( P(c) \) can be written [26, 27]

\[ C_{\text{DF}}(P(c), c) = T(c) \log \left[ 1 + \gamma P_{SD} + \frac{\gamma P_{SRi}}{1 + \sigma_n^2} \right] + (1 - T(c)) \log (1 + H_i P_{Ri}) \]

where

\[ \sigma_n^2 = \frac{1 + \gamma P_{SD} + \gamma P_{SRi}}{(1 + \gamma P_{SD})(1 + \gamma P_{Ri})(1 - (G/3/T_{\text{DF}})) - 1) \quad (31) \]

The delay-limited capacity of DF can be found by solving the optimisation problem in (10), by replace \( C(P(c), c) \) with \( C_{\text{DF}}(P(c), c) \).

#### 3.3.2 DF outage probability analysis: In DF protocol the relay performs Wyner–Ziv coding, that is, it compresses the sequence \( y_{SRi} \) and sends a corresponding codeword \( x_i \); then the destination calculates the estimates \( \hat{y}_{SRi} \) using \( x_i \) as well as the sequence \( y_{SD} \) from the source as side information. The level of compression of \( \hat{y}_{SRi} \) is controlled by two parameters, namely the code rate \( R_i \) chosen for the forwarding on the relay-to-destination channel and the quantisation noise variance \( N_q \). Then, from \( x_i \) and \( y_{SD} \) the receivers tries to obtain \( \hat{y}_{SRi} \); the event \( D \) of correct decompression is written as [29]

\[ D: R_i \geq \log \left( 1 + \frac{1 + 2 P_{SRi}}{N_q (1 + P_{SRi})} \right) \quad (32) \]

The probability of not satisfying the rate constraint in (13), given that the destination has been able to decompress the signal from the relay

\[ P_{\text{out}}(\text{DF}) = \Pr[C_{\text{DF}}(P(c), c) < R] = 1 - \exp \left( -\gamma \left( 2^{(N_s+1)R} - 1 - \frac{P_{SRi}}{N_q} \right) \right) \quad (33) \]

Equation (33) is valid only if

\[ N_q > \frac{P_{SRi}}{2(N_s+1)R} - 1 \quad (34) \]

### Table 2 Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>modulation type</td>
<td>BPSK</td>
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<tr>
<td>subcarrier mapping scheme</td>
<td>interleaved</td>
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<td>number of subcarriers, ( K )</td>
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<tr>
<td>IDFT-size, ( M )</td>
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</tr>
<tr>
<td>target rate, ( R )</td>
<td>1 bit/s/Hz</td>
</tr>
<tr>
<td>path loss exponent, ( A )</td>
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</tr>
<tr>
<td>shadowing: log-normal</td>
<td>with standard deviation of ( \sigma_r = 3 ) dB</td>
</tr>
<tr>
<td>source to ( i )th relay distance, ( d )</td>
<td>( 0 &lt; d &lt; 1 )</td>
</tr>
<tr>
<td>number of relays</td>
<td>( 1 \leq i \leq N_s )</td>
</tr>
</tbody>
</table>

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For detailed analyses of the outage probabilities of the AF, DF and CF schemes, the reader is referred to [29].

3.5 EF protocol

Although using Wyner–Ziv compression at the $i$th relay improves the performance, it also increases the complexity of the relay encoder and the destination decoder. We also consider a simpler scheme in which the relay compresses its received signal ignoring the side information at the destination. This scheme is called EF [30].

3.5.1 EF delay-limited capacity: The instantaneous capacity of EF with energy allocation $P(c)$ at channel state $c$ can be written as follows [30]

$$C_{EF}(P(c), c) = T(c) \log \left( 1 + \gamma P_{SD} + \frac{\gamma P_{SRi}}{1 + \delta_w^2} \right) + (1 - T(c)) \log (1 + H_i P_{Ri})$$ (35)

where

$$\delta_w^2 = \frac{1 + \gamma P_{SRi}}{((1 + \gamma P_{Ri})^{(1-T(c))/(1-c)}) - 1}$$ (36)

It is clear that, $\delta_w^2 \geq \sigma_w^2$, therefore EF has a larger quantisation noise than CF [30].

3.5.2 EF outage probability analysis: The outage probability of CF protocol can be obtained according to (13) as follows

$$P_{out}(EF) = \Pr[C_{CT}(P(c), c) < R]$$ (37)

3.6 HOC protocol

The main idea of the proposed HOC protocol is, instead of using a single cooperation protocol at the selected $i$th relay, we can choose the optimal cooperation protocol along with its corresponding optimal resource allocation at the selected $i$th relay according to the current CSI.

3.6.1 HOC delay-limited capacity: To maximise the delay-limited capacity for each protocol, we find the optimal resource allocation at each CSI so that the target rate is supported. The delay-limited capacity of the HOC protocol can be maximised as follows (see (38))

$$\min_{P(c) \in \Phi} P_{out}(HOC) = \text{Prob} \left[ \min \{ C_{DT}(P(c), c), C_{AF}(P(c), c), C_{DF}(P(c), c), C_{CF}(P(c), c), C_{EF}(P(c), c) \} \right] < R$$ (39)

3.6.2 HOC outage probability analysis: The minimum required total power for HOC protocol at channel state $c$ is the minimum power among the DT and the other protocols considered in this study. The outage probability of the HOC protocol can be minimised as follows

$$\max_{P(c) \in \Phi} R \text{ such that } \Rightarrow$$

$$C_{HOC}(P(c), c) = \max \{ C_{DT}(P(c), c), C_{AF}(P(c), c), C_{DF}(P(c), c), C_{CF}(P(c), c), C_{EF}(P(c), c) \} \geq R$$ (38)
4 Numerical results and discussion

In this section, both theoretical expressions and simulations are used to test the performance of SC-FDMA-based cooperative networks with the proposed HOC protocol. The performance is measured in terms of delay-limited capacity and outage probability. The simulation parameters are summarised in Table 2.

Fig. 4 shows the delay-limited capacity of the proposed HOC protocol and for the different protocols considered in this paper as a function of the average total transmit power using \( d = 0.5 \), one relay, \( N_s = 1 \), and considering the first scenario. The CSB and ODF [15] are included for comparison. The obtained results show that the delay-limited capacity of the proposed HOC protocol is closest to the CSB case. Moreover, it is higher than the ODF protocol.

Fig. 5 shows the delay-limited capacity against \( d \) (source to \( i \)th relay distance) for HOC protocol and for the other protocols considered in this paper using average total transmit power of 10 dB, \( N_s = 1 \), and first scenario. The results show that the proposed HOC protocol achieves the higher delay-limited capacity when compared to the other protocols. It is clear also that the HOC protocol outperforms the ODF protocol especially when the \( i \)th relay is close to the destination; this is because the HOC protocol includes the CF protocol, which outperforms the DF protocol when the relay is close to the destination [28].

Fig. 6 demonstrates the delay-limited capacity as a function of average total transmit power of HOC protocol considering the different four scenarios when \( d = 0.5 \) and \( N_s = 1 \). The CSB and the DT using first scenario are also included for comparison.
It is clear that the delay-limited capacity of the proposed HOC protocol is degraded especially when the CSI is not available at the destination (third and fourth scenarios). It is also clear that, the DT case (conventional SC-FDMA) considering the first scenario outperforms HOC protocol (cooperative SC-FDMA with HOC protocol) when considering the fourth scenario. Therefore the DT is preferable in some channel states as we have a total power constraint for the source and the relay, thus the relay power cannot be utilised without cost.

Fig. 7 shows the minimum required average total power against $d$ for HOC and the other protocols using $N_s = 1$ and $P_{out} = 10^{-3}$. The obtained results show that the proposed HOC protocol is the closest protocol to the lower bound. Moreover, the proposed HOC protocol outperforms the ODF protocol when the $i$th relay is located closer to the destination. For example, when the relay is closer to the destination, $d = 0.9$, ODF has a power loss around 1.25 dB; whereas on the other hand, the proposed HOC protocol has a power loss around 0.7 dB only when compared to the lower bound case. Therefore the minimum required average total power in the proposed HOC protocol is less than that of ODF by about 0.55 dB.

Fig. 8 shows the outage probability of HOC protocol and the other protocols considered in this paper as a function of SNR using $N_s = 1$, $d = 0.5$, and the first scenario. We can observe the excellent matching between results of the closed-form expression of (39) derived in this paper and the simulation results in HOC protocol case. The obtained results show that the proposed HOC protocol outperforms all the individual protocols. For example, at an outage probability of $10^{-3}$, the proposed HOC protocol has SNR...
gain of 2.5 dB when compared with the CF protocol, which is the nearest one to HOC protocol.

Fig. 9 presents the outage probability of HOC protocol as a function of SNR using $N_s = 1$ and $d = 0.5$ considering the four scenarios. As the delay-limited capacity case, the outage probability of the proposed HOC protocol is degraded especially when the CSI is not available at the destination (third and fourth scenarios). For example, at an outage probability of $10^{-3}$, the HOC protocol using first scenario provides SNR gain of 6 dB, 15 dB and 27 dB over second, third and fourth scenarios, respectively.

Fig. 10 shows the outage probability of HOC protocol using different number of relays and $d = 0.5$. In this figure, we consider the first scenario. It can be noted that increasing the number of relays improves the outage probability for the whole range of SNR and obviously improves the diversity order. This is because the relays are selected from the set $S(R)$. We can also note the excellent matching between the results of the closed-form expression derived in this paper and the simulation results.

5 Conclusion

This paper proposed an HOC transmission protocol for SC-FDMA-based cooperative networks. The proposed protocol improves the energy efficiency of SC-FDMA-based networks by selecting the most energy-efficient cooperative transmission protocol from a set of available protocols according to the CCSI. Computer simulation was done over four different scenarios of channel conditions. It was demonstrated that the proposed HOC protocol not only improves the delay-limited capacity but also minimises the outage probability of SC-FDMA-based cooperative networks. The obtained results show that the minimum
required average total power in the proposed HOC protocol is less than that of ODF proposed in [15] by 0.55 dB. Moreover, it provides at least 2.5 dB SNR gain when compared to the other protocols considered in this paper. The obtained results also showed that the HOC protocol outage probability was further improved for the whole range of SNR by increasing the number of relays.

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