Abstract—In this paper, we are planning to introduce a new method for relay selection and resource allocation in OFDM-based cooperative networks. Up to now, there have been relatively few works clearly concentrating on the combination of relay selection and resource allocation in such networks. In our work, a network with a single transmitter, a single receiver and a group of relays is considered. Relays work on Amplify and Forward (AF) method and there is no direct link between the transmitter and the receiver. The optimization problem is to maximize the throughput of the receiver with constraints on the amounts of the power of the transmitter and relays, and subcarriers. We will introduce an algorithm to select the best relay for each subcarrier. Eventually, we will compare our results to the optimum results and see how our proposed scheme, while being simple, performs very close to the optimum one.

I. INTRODUCTION

Cooperative communications has become an attractive topic in wireless communications and many researches has been done about it. Cooperative communications is offered to solve wireless channel problems, especially to mitigate the fading effects of the wireless channel by creating a “virtual antenna array” [1]. Through cooperation of single-antenna users in a wireless network, both capacity and reliability of the overall system will increase. This is because different users “share” their antennas, creating a distributed MIMO system [2]. The intermediate nodes, called “relays”, can adopt three main protocols for the purpose of relaying: Amplify and Forward (AF), Decode and Forward (DF), and Compress and Forward (CF).

On the other hand, Orthogonal Frequency Division Multiplexing (OFDM) has been used in the fourth generation of wireless networks. Subcarrier and power allocation in an OFDM system is a challenging problem and a lot of works have been done about it [3]. In [4] the authors have reviewed the resource allocation problem in Relay-Enhanced OFDMA-Based Networks. However, there are few works about synthesis of relay selection and resource allocation in cooperative networks.

In [5], the authors have discussed relay selection in an Amplify and Forward (AF) dual-hop network. They considered a network with a single transmitter-receiver pair and \( K \) relays. Their model was based on one shared channel between all nodes. They proved that by selecting one relay among \( K \) relays, full diversity can be achieved. They also generalized their method to a multi-relay selection scheme, discussed different criteria of relay selection and compared their efficiencies.

In [6], the problem of resource allocation in a non-cooperative network is investigated. The goal of this paper was introducing a new fairness algorithm to allocate resources in a network, in order to increase the minimum throughput of each user. In [7], the authors discussed resource allocation in a cooperative network and presented a subcarrier allocation algorithm. They considered a receiver, a transmitter, and \( K \) relays between them and \( N \) subcarriers. They suggested a fairness algorithm to allocate the subcarriers. Although they had multiple relays in their network, they did not propose a method to select the relays and just discussed the subcarrier allocation problem. The problem of power allocation in a cooperative network based on OFDM is investigated in [8]. The authors have found a power allocation method in order to minimize the total power of the system with a constraint on the throughput of each user. They also specified where and when the users should cooperate.

So far, the works about resource allocation in cooperative networks based on OFDM have been concentrated on maximizing the throughput of the system with a trade-off between throughput of the overall system and fairness between all users, or minimizing the total power with constraints on throughput of each user. However, in this paper our goal is to maximize the throughput with constraint on the total power.

In this paper, we are going to introduce a new combined relay selection and subcarrier allocation method in a cooperative network. We assume that we have a transmitter, a receiver and \( K \) relays between them. Relays just receive the message from the transmitter, amplify, and forward it to the receiver. Thus, the relays are of AF type. There is also no direct link between the transmitter and the receiver and all the channels have Rayleigh fading. For data on each subcarrier on the first hop, we will select the best relay and allocate the best subcarrier in the second hop.

The remainder of this paper is organized as follows. In section II, we present the system model and specify the signals that the receiver and the relays receive on different subcarriers.
Section III defines the optimization problem and specifies the constraints. The purpose is to maximize the total throughput of the overall system with constraints on the total power and the use of subcarriers. It means that the amount of the total power should be less than a fixed value and each subcarrier should be used just once in each hop. The suboptimal solution to this optimization problem is also introduced in section IV. In section V, we present our simulation results which show that our suboptimal solution performs finely close to the optimum solution. Finally, section VI presents our concluding remarks.

II. SYSTEM MODEL

In our model, there exists a transmitter-receiver pair with $K$ AF relays between them. We have an OFDM-based dual-hop network with $N$ subcarriers. There is no direct link between the transmitter and the receiver. First, the transmitter sends its data on all the $N$ subcarriers and all of the relays listen to it. Then, one relay is selected in order to receive the data from the transmitter on the $i_{th}$ subcarrier, and then amplify and forward it to the receiver on the $j_{th}$ subcarrier. For every specific relay, we suppose that the channels of all subcarriers for that relay are independent from one another. Also, the relays are far enough in order to have independent channels. We have also considered that all the channels have Rayleigh fading. Therefore, all channel gains will be modeled as complex Gaussian random variables with zero mean and unit variance. The channel between the transmitter and the $k_{th}$ relay on the $i_{th}$ subcarrier is shown as $f_{k,i}$. The channel between the $k_{th}$ relay and the receiver on the $j_{th}$ subcarrier is shown as $h_{k,j}$.

The set $S1$ shows the set of subcarriers between the transmitter and relays and $S2$ is the set of subcarriers between the relays and the receiver. Figure 1 clearly illustrates this model.

If $x_i$ is the signal that the transmitter intends to transmit on the $i_{th}$ subcarrier, and its power is equal to one, the received signal at the $k_{th}$ relay and on the $i_{th}$ subcarrier will be:

$$r_{k,i} = \sqrt{p_i}x_i f_{k,i} + n_{k,i}$$  \hspace{1cm} (1)$$

where $p_i$ is the power of transmitter on the $i_{th}$ subcarrier and $n_{k,i}$ is the noise at the $k_{th}$ relay on the $i_{th}$ subcarrier and $n_{k,i} \sim CN(0, 1)$; i.e. $n_{k,i}$ is a complex Gaussian random variable with zero mean and unit variance.

If the $k_{th}$ relay is chosen to amplify and forward the signal on the $j_{th}$ subcarrier, the received signal at the receiver will be:

$$y_{i,k,j} = \frac{\sqrt{p_{k,j}}h_{k,j}n_{k,i}}{\sqrt{p_i|f_{k,i}|^2 + 1}} + \frac{\sqrt{p_{k,j}}h_{k,j}^2n_{k,i}}{\sqrt{p_i|f_{k,i}|^2 + 1}} + w_{k,j}$$ \hspace{1cm} (2)$$

where $y_{i,k,j}$ is the signal which arrives at the receiver on the $j_{th}$ subcarrier and $p_{k,j}$ is the power that the $k_{th}$ relay allocates to transmit the received signal on the $j_{th}$ subcarrier. $h_{k,j}$ is the channel between the $k_{th}$ relay and the receiver on the $j_{th}$ subcarrier. $w_{k,j}$ is also the noise at the receiver on the $j_{th}$ subcarrier and $w_{k,j} \sim CN(0, 1)$. It is obvious that the $k_{th}$ relay has normalized the power of its received signal and then amplified and retransmitted it. Consequently, the SNR of the signal arriving at the receiver on the $j_{th}$ subcarrier is equal to:

$$\Gamma_{i,k,j} = \frac{p_i|f_{k,i}|^2|h_{k,j}|^2p_{k,j}}{p_{k,j}^2|h_{k,j}|^2 + p_i|f_{k,i}|^2 + 1}$$ \hspace{1cm} (3)$$

$\Gamma_{i,k,j}$ shows the SNR of the received signal $y_{i,k,j}$. The source has transmitted the signal $x_i$ on the $i_{th}$ subcarrier and then the $k_{th}$ relay amplified and forwarded this signal on the $j_{th}$ subcarrier. Thus, the throughput of this transmission is equal to:

$$R_{i,k,j} = \frac{1}{2}\log_2 (1 + \Gamma_{i,k,j})$$ \hspace{1cm} (4)$$

As a result, the total throughput of the system is:

$$R = \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{N} \rho_{i,k,j} R_{i,k,j}$$ \hspace{1cm} (5)$$

Where $\rho_{i,k,j}$ would be equal to 1 if the $k_{th}$ relay receives the signal of the transmitter on the $i_{th}$ subcarrier and retransmits it on the $j_{th}$ subcarrier and equal to 0 otherwise.

III. OPTIMIZATION PROBLEM

In this section, we are going to present the optimization problem. This problem can be solved by a suboptimal algorithm that we will introduce in the next section and whose performance is very close to the optimal solution, while it does not need a high amount of calculation.

Assume that the amount of the total transmit power of the system is $P_T$. Our goal is to maximize the total throughput of the system with constraints on the amount of the total power of the transmitter and the relays and on the use of the subcarriers:

$$\max_{p_i,p_{k,j}} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{N} \rho_{i,k,j} R_{i,k,j}$$ \hspace{1cm} (6)$$

subject to:
IV. Suboptimal Solution of the Problem

In this section, we present a new algorithm for the aforementioned optimization problem. In [5], the authors presented a relay selection method for such a system. They used the criterion of harmonic mean to select the best relay in order to amplify and forward the data from the source to the destination. In our solution, we are going to use the harmonic mean criterion in order to select the best relay for each pair of subcarriers. The amount of power of each subcarrier in both the transmitter and the relays are equal; i.e. in the first hop:

\[ \forall i \in S1 : p_i = \frac{P_T}{2N} \]

and if \( \rho_{i,k,j} = 1 \), then in the second hop

\[ p'_{k,j} = \frac{P_T}{2N} \]

Contrary to the optimal problem, we divide the total amount of power equally between all subcarriers in our suboptimal algorithm and by using this method, we will show that our results are close to those of the optimum solution.

To complete the algorithm, we define \( C(f_{k,i}, h_{k,j}) \) as:

\[ C(f_{k,i}, h_{k,j}) = \frac{1}{2} \log_2 \left( 1 + \frac{(\frac{P_T}{2N})^2 |h_{k,j}|^2}{|f_{k,i}|^2 + \frac{P_T}{2N} |f_{k,i}|^2 + 1} \right) \]

Finally, our proposed algorithm in order to allocate the subcarriers and select the relays is presented in Figure 2:

In the pseudocode of Figure 2, the first four lines represent the initializations. \( R_k \) denotes the rate of the \( k_{th} \) relay. Therefore, the loop in lines 1-3 sets the rates of all the relays to zero. Moreover, \( S1 \) and \( S2 \) denote the sets of the currently unused subcarriers of the first and second hops, respectively.

In line 4, these sets are initialized to include all subcarriers 1, 2, ..., \( N \). The main part of the algorithm starts from line 5. For every subcarrier of the first hop, i.e. \( i = 1, 2, ..., N \), we first set the harmonic mean \( H \) to zero in line 6. Then, in lines 7-15, we search over all the \( K \) relays and the remaining subcarriers of the second hop, i.e. \( j \in S2 \), to find the subcarrier-relay pair with the largest harmonic mean. After the best pair is found, the rate of the selected relay, \( R_{relay_i} \) is updated in line 16. Furthermore, the sets \( S1 \) and \( S2 \) are updated in lines 17 and 18, where the subcarriers \( i \) and \( sub \) are removed from the unused subcarriers of the first and second hops, respectively. This trend continues until all the subcarriers of the first hop are processed, or in other words, until \( S1 \) reaches Ø. Finally, in line 20, the rates of all the \( K \) relays are added together to yield the total throughput of the system.

This suboptimal algorithm can be implemented easily and does not deal with the huge complexity of the optimal solution. In this algorithm, besides selecting the best relay based on a harmonic mean metric, the best subcarrier for the second hop of the transmission is selected, either. This joint relay selection and subcarrier allocation vastly improves the performance of our suboptimal algorithm to achieve results very close to the optimal solution. This is further discussed in the next section.
For $k = 1:K$ do
  
  $R_k = 0$

end

$S1 = S2 = \{1,2,\ldots,N\}$

For $i = 1:N$ do
  
  $H = 0$

  For $k = 1:K$ do
    
    For $j = 1:N$ do
      
      If $H \leq \frac{1}{|f_{k,j}|^2 + |h_{k,j}|^2}$ and $j \in S2$ then
        
        $H = \frac{1}{|f_{k,j}|^2 + |h_{k,j}|^2}$

        sub = $j$

        relay = $k$

      end

    end

    $R_{relay} = R_{relay} + C \{ f_{relay,j}, h_{relay,sub} \}$

  end

  $S1 = S1 - \{i\}$

  $S2 = S2 - \{sub\}$

end

$R_T = \sum_{k=1}^{K} R_k$

Fig. 2. Pseudocode for the proposed suboptimal relay selection and subcarrier allocation algorithm

**V. Simulation Results**

In this section, we will compare our suboptimal algorithm with the optimum solution. In order to obtain the optimum result, we have used the Genetic Algorithms. We have considered that there is no direct link between the transmitter and the receiver. Furthermore, all the channels between the source and the relays, and between the relays and the receiver are modeled as Rayleigh fading channels; i.e. they are assumed to be complex Gaussian random variables with zero mean and unit variance. Consequently, we will have $N \times K$ independent channels in each hop.

In our first simulation, we have considered two scenarios: in the first scenario, the system includes 4 relays and 64 subcarriers and in the second one, the system consists of 8 relays and 64 subcarriers. Figure 3 shows the total throughput versus the overall power. It can be clearly seen that our result is tightly near to the optimum result. Moreover, it is important to notice that as the amount of the total transmit power of the transmitter and the relays increase, the distance between the two results becomes smaller.

In the second simulation, we have considered a system with 64 subcarriers and a total transmit power of 10. The number of the relays varies within the range of 2 to 12. Figure 4 shows that as the number of the relays increases, the distance between our result and the optimum result decreases.

**VI. Conclusion**

In this paper, we presented a new relay selection and resource allocation method in an OFDM-based cooperative network. The most obvious difference between our work and previous works is that the previous ones were based on relay selection in the case of single-channel networks or resource allocation in the case of non-cooperative networks. Our proposed suboptimal algorithm, combining the techniques for the selection of the relays and the allocation of the subcarriers, was shown to perform nearly similar to the optimal solution, and it considerably reduces the amount of calculations compared to the optimal solution.

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