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Re:	A response to a Call for Technical Proposal, http://wirelessman.org/relay/docs/80216j-06_027.pdf
Abstract	This contribution proposes an algorithm which assigns a mobile station to one of the network relays over an OFDMA sub-channel. Here, we show that this scheme significantly increases the network throughput because it uses network topology along with sub-channel gains in the decision procedure.
Purpose	FYI
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Effective Node Assignment in 2-Hop Fixed Relay Networks

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Introduction

One of the main issues in IEEE 802.16 networks using OFDMA as a multiple access mechanism is how to handle an increasing number of users. This requires effective node assignment which has a significant role, especially when relays are used in the network.
Recent proposed techniques for resource allocation in IEEE 802.16 relay networks aim to take advantage of OFDMA multi-user diversity, but the network capacity significantly increases if the opportunity of spatial multiplexing is considered in the assignment algorithm.
In the presence of relays, mobile stations (MS) are able to transmit with lower power, because they are connecting to the relay which is closer to them than the base-station (BS). Consequently, there is a chance that some nodes may transmit simultaneously on the same OFDM sub-channel, if they do not significantly interfere with each other. Note that such the spatial multiplexing should be applied only if it improves the sum rate of the network and, more importantly, the proposed algorithm should not produce a large overhead on the network signaling. To this end, typical OFDMA resource allocation algorithm should be modified for the relayed network, and nodes should be assigned to relays based on both network topology and multi-user diversity.

Resource allocation procedure

Previous research has proposed several frame structures for the relay IEEE 802.16. In general, the frame structure will have one of the following structures:

- Uplink (UL) and downlink (DL) are separated into two parts:
  - In the first part, BS sends data to associated MSs and relays.
  - In the second part, relays send their data to the MSs.
  - The same partitioning exists in the UL.

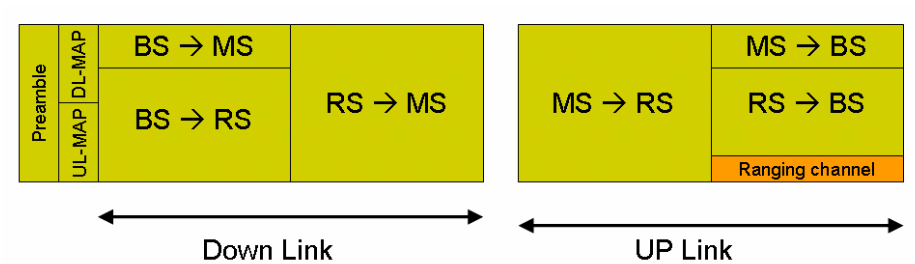


Fig .1. Frame structure

- In the second scheme, the above mentioned partitioning does not exist. So, MS and relay's sub-channels are assigned through the whole band.

Using the above frame structure and the fact that nodes' data rates depend on the sub-channel and the relay assigned to them, the network throughput defined as the following:

$$\tau_M = \sum_{n=1}^{N}\sum_{k=0}^{K}\sum_{m=1}^{M} p_{mk}^{(n)} R_{mk}^{(n)} \qquad (1)$$

Here $p_{mk}^{(n)}$ is "one" if node 'm' is connected to relay 'k' over the *nth* sub-channel and it is "zero" otherwise. Moreover, $R_{mk}^{(n)}$ is defined as the maximum data rate that the node 'm' can transmit, if it uses the *nth* OFDM sub-channel to connect to the relay 'k'. This value depends on the coding and modulation scheme which is used for transmission. In this work, it is assumed that $R_{mk}^{(n)}$ is equal to the maximum achievable data rate while the node transmits using its maximum power (P_{max}) (the achievable rate depends on the signal power and the amount of interference that exists at the receiver). Therefore, the node assignment objective function is to maximize the network throughput given in (1). For this reason, the resource allocation algorithm should know all the channel gains between users and relays and in addition, it should have information about the interference of each user on the other relays.

Although all these data are essential for assignment, their required accuracy is not the same. The first group of information, which requires high accuracy, is the one used for assigning sub-channels and setting modulation order of each user. The second group of data requires lower accuracy, and is used to find the interference zone of each relay.

To this end, there should be a flexible, extendable and distributed procedure to collect all data required for the assignment procedure. Moreover, this procedure should be designed in such a way that there is no need to change the structure and algorithm of the mobile stations, so that ordinary MSs are able to connect to relay IEEE 802.16 networks.

Given this, we are able to introduce a new table called "interference table" which will be generated and updated at each relay. Table (1) shows the structure of this table.

CID	Subchannel No.	Received Power	Type
1250	5	A	R
1440	3	B	Out
…	…	…	…
...	...	...	...

Table .1. Interference table structure

The functionality of this table is similar to the "Routing Table". Routing tables are used to model the possible connections between network nodes, and interference tables are used to model the interference structure of the network (used to find the potential simultaneous transmissions). To construct this table, each relay should run the algorithm described below.

To start, we define two zones for each relay: interference zone and receiving zone. *This algorithm is based on the fact that all relays receive the UL-Map, and hence they know which user (CID) will send on which OFDM sub-channel*. Hence, a relay scans that sub-channel and performs one of three functions:

- If the signal on that sub-channel is decoded successfully, the relay will find the channel gain of that user (CID). Thus, from reciprocality of the channel, the relay considers the user in its receiving zone and marks 'R' in the "Type" field of interference table. Moreover, the relay adds the user CID and corresponding channel gain to the table. (Accurate data)

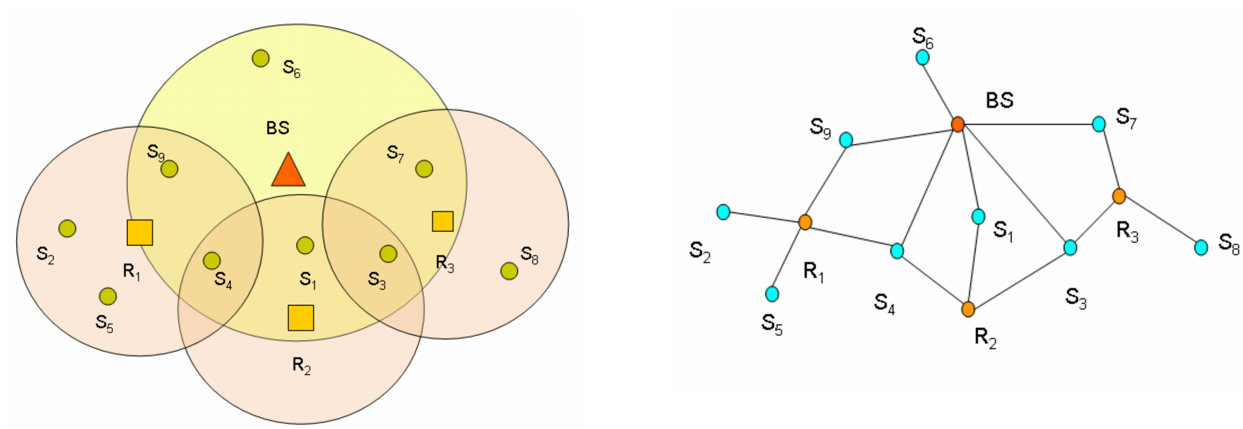
- If the relay is not able to decode the received signal, but the power of the signal is more than a certain threshold, the relay adds this user (CID) to the table with type "I" signifying that this user is in the interference zone, but not in its receiving zone. It is obvious that all nodes in the receiving zone are in the interference zone as well. Moreover, the maximum acceptable threshold is bounded by the minimum required SINR (signal to interference plus noise ratio) for successful decoding. The channel gains of these nodes are not important because these data are used only to prevent sub-channel reassignment in one relay interference zone. (Imprecise data)

- If the received power of the signal is less than the threshold, then the user (CID) is added to the interference table with type "Out". This type represents the nodes which do not cause a high level of interference on that relay.

Using the above procedure, each relay constructs its own table and updates it repeatedly. The updating of the table entries enables the network to locate the mobile users and to find the latest network topology. In fact, network topology is created after each relay feedbacks its table to the base station (BS). *Using all these tables, the BS finds the structure of the network*. Moreover, the BS creates a matrix called "interference matrix, *I*". This matrix is defined as follows:

$$I_{ij} = \begin{cases} 1 & \text{If node 'i' is in interference zone of relay 'j'} \\ & i \in \{S_1, ..., S_M\},\ j \in \{R_0, ..., R_K\} \\ 0 & \text{Otherwise} \end{cases} \qquad (2)$$

This defined matrix can be used for different purposes in both physical and upper layers, including resource allocation, scheduling and routing. For the purposes of this study, we have focused on using this matrix in the node assignment problem. For example, the following figures show a typical network and the graph representation of its interference matrix:



(a) (b)

Fig .2. (a) Typical IEEE 802.16 relay network (b) Graph representation of the interference matrix

In this figure BS and R_i represent the base station and the *ith* relays, respectively, while S_i represents the *ith* mobile station. If we consider BS as one of the relays, and permit direct node-BS assignment, then the interference graph can be assumed to be a bipartite graph. The bipartite graph representation of the above network is illustrated below:

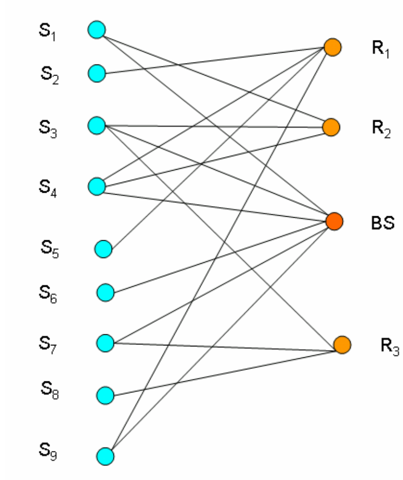


Fig .3. Bipartite representation of the interference graph

Using the interference matrix, the network interference constraints can be formulated as follows:

1. Each user must be assigned to at most one relay:

$$\forall S_m, \sum_{k=0}^{K}\sum_{n=1}^{N} p_{mk}^{(n)} \le 1, \quad m = \{1,2,...,M\} \tag{3}$$

Here it is assumed that there is 'M' nodes $\{S_1, S_2, ...S_M\}$ in the network and the number of relays and available sub-channels are respectively 'K' and 'N'. This constraint can be relaxed if it is allowed that one node is associated to more than one relay.

2. To prevent collision, sub-channel spatial reuse is not allowed in the interference zone of each relay. Thus, using above notation, we have:

$$\forall R_k, \forall n \in \{1,...,n\}, \sum_{l=1}^{M} I_{lk} \sum_{k'=0}^{K} p_{lk'}^{(n)} \le 1, \quad k = \{1,2,...,K\} \tag{4}$$

These constraints, along with the network throughput as the objective function could be described as an Integer Programming optimization problem, such that its solution describes the desirable node-relay assignment. The IP formulation is as follows:

$$\begin{aligned}
\max \quad & \tau_M = \sum_{n=1}^{N}\sum_{k=0}^{K}\sum_{m=1}^{M} p_{mk}^{(n)} R_{mk}^{(n)} \\
s.t. \quad & \forall S_m, \sum_{k=0}^{K}\sum_{n=1}^{N} p_{mk}^{(n)} \le 1, \quad m = \{1,2,...,M\} \\
& \forall R_k, \forall n \in \{1,...,N\}, \sum_{l=1}^{M} I_{lk} \sum_{k'=0}^{K} p_{lk'}^{(n)} \le 1, \qquad k = \{1,2,...,K\} \\
& p_{mk}^{(n)} = \{0,1\} \quad \forall\, m = \{1,2,...,M\}, k = \{1,2,...,K\}, n \in \{1,...,N\}
\end{aligned} \tag{5}$$

Since the integer constraints can be relaxed to a hypercube constraint with 0-1 corner points, the Integer Program can be relaxed to the following Linear Program problem and hence it can be solved with the efficient LP algorithms.

$$
\begin{aligned}
\max \quad & \tau_M = \sum_{n=1}^{N}\sum_{k=0}^{K}\sum_{m=1}^{M} p_{mk}^{(n)} R_{mk}^{(n)} \\
s.t. \quad & \forall S_m, \sum_{k=0}^{K}\sum_{n=1}^{N} p_{mk}^{(n)} \le 1, \quad m = \{1,2,\ldots,M\} \\
& \forall R_k, \forall n \in \{1,\ldots,N\}, \sum_{l=1}^{M} I_{lk} \sum_{k'=0}^{K} p_{lk'}^{(n)} \le 1, \qquad k = \{1,2,\ldots,K\} \\
& 0 \le p_{mk}^{(n)} \le 1 \qquad \forall m = \{1,2,\ldots,M\}, k = \{1,2,\ldots,K\}, n \in \{1,\ldots,N\}
\end{aligned} \tag{6}
$$

As an example, the formulation was applied to the network mentioned above. It is assumed that the network has three available OFDM sub-channels with the result shown in the following diagram:

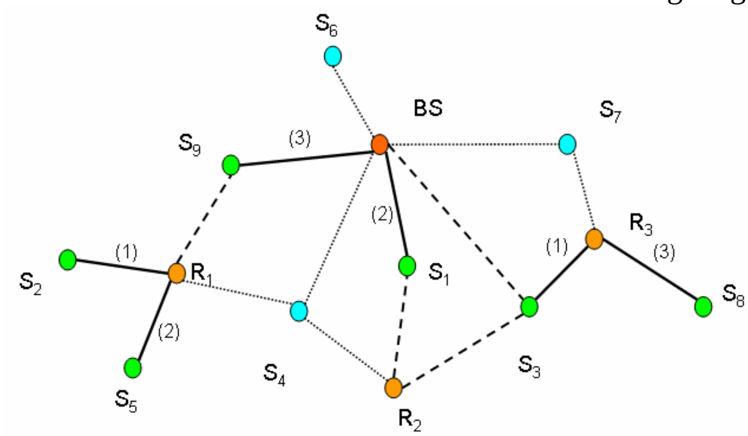


Fig .4. OFDM sub-channel assignment

In this figure, solid lines represent the mobile station association to the relay or BS while dashed lines also show the possible source of interference. The value written besides each edge shows the assigned sub-channel for that connection.

Summary and Conclusion

It can be clearly seen that these *three* sub-channels are allocated to *six* users (CID) and hence the network capacity is improved by factor of two compared to the result of other algorithms.
It is important to note that, this gain in frequency reuse is equal to or greater than one, and its value depends on the network topology and the mobile stations transmission power. For instance, if all MSs are placed inside one interference zone, then no spatial reuse is allowed and the gain factor is one. Moreover, since interference level depends on the transmission power, the node assignment algorithm which jointly optimizes node assignment and user power allocation could take advantage of both lower power consumption and higher system capacity and throughput.