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Relay Selection Fairness and Resource Allocation for OFDMA Networks

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Abstract

In this paper, resource allocation for a relay-based multi-user Orthogonal Frequency-Division Multiple Access (OFDMA) uplink system is studied. All the relays adopt the decode-and-forward protocol and assist the transmission from the source to destination. In current wireless networks, the terminal depends more on battery power. Given that, battery life is limited, prolonging the service life of equipment is a key problem in ensuring the information transmission and in reducing the financial burden of the batteries. We aim to maximize the survival time of the relay system and to reduce the rate of loss. Therefore, we formulate the problem in which the subcarriers select the optimal relay based on both the channel gain and the residual capacity of the relays. We also consider a weighting factor that reflects the residual capacity of different relays. Simulation results show that the proposed algorithms can achieve longer survival time of the relay systems.

Keywords: *OFDMA, relay selection, fairness, residual capacity, survival time, optimization*

1. Introduction

Orthogonal Frequency-Division Multiple Access (OFDMA) technology can overcome frequency-selective fading, improve spectrum efficiency, and enlarge system capacity. Thus, it is widely used in next-generation wireless communication. Combining OFDMA with relay technology can provide high data-rate communication and increase the wireless system coverage [1-2].

Several cooperation mechanisms have been proposed for OFDMA systems, including amplify-and-forward (AF) and decode-and-forward (DF). Optimal resource allocation is a critical issue in relay-assisted OFDMA systems. The authors in [3-4] analyzed the subcarrier-to-relay assignment problem in multi-relay orthogonal frequency-division multiplexing (OFDM) systems with single users, whereas those in [5] considered multiple users. Power allocation with total and individual power constraints was considered for the OFDM DF relaying systems in [6] but multiple users were not studied. The QoS requirements of users were considered in several works [7-8]. In [9], QoS-aware optimal joint relay selection and resource allocation under a total power constraint were proposed. However, the fairness of the relays was not considered in the above works, where the subcarrier was allocated to the optimal relay according only to the better channel conditions. When we consider sum-rate maximization under normal circumstances, the terminal provides maximum transmit power. Thus we may not minimize the relay power if we want to prolong the service life of equipment. However, in wireless communication, we often prefer cell phones as relays. Reducing the financial burden of the batteries is a key problem. Hence, the residual capacities of mobile phone batteries should be considered. We can extend the survival time of relays to improve relay system life. Fairness among the mobile phone relays when selected will be further studied in the following section.

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We consider the DF relaying systems for two users without a source-to-destination (SD) link. When the subcarriers select the optimal relay in the first time slot, we introduce the weighted sum rate subjected to the residual capacity of the relays. Weighting factor (w) refers to the residual capacity proportion of two relays. We aim to maximize the weighted transmission rate to achieve sum-rate maximization of the system, as well as to consider relay fairness. To reflect the actual situation, individual power constraints for users and relays, as well as the minimum data-rate constraint for each user, are applied.

2. System Model

An OFDMA uplink system with two users and two relays is considered. Figure. 1 shows a two-hop DF relay system consisting of one source, one relay, and one destination. The source nodes communicate with the destination node via the help relay nodes. We only consider the cooperative scenario. Each frame transmission is divided into two time slots. In the first slot, the source transmits to the destination that is overhead by the selected relay. In the second slot, the source remains silent while the selected relay forwards to the destination.

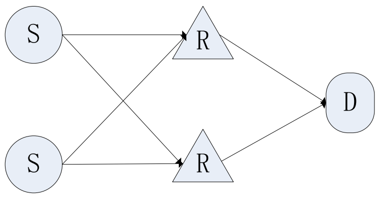

Figure. 1. Two Relay Assisted Cooperative OFDMA System Model

However, in the first slot, we consider the weighted rate (in bps/Hz), which is used to select the relay. The weighted rate of the cooperative transmission for the user *k* in the *mth* subcarrier assisted by relay *n* is calculated as follows:

$$R_{k,n}^{m} = \frac{w_n}{2}\min[\log_2(1+P_k^m\alpha_{k,n}^m), \log_2(1+P_n^m\alpha_{n,d}^m)] \tag{1}$$

The channel coefficients between *kth* source and destination, *kth* source and *nth* relay and *nth* relay and destination in the *mth* subcarrier are $\left|h_{k,d}^m\right|^2$,$\left|h_{k,n}^m\right|^2$ and $\left|h_{n,d}^m\right|^2$, and $\alpha_{k,d}^m = \frac{\left|h_{k,d}^m\right|^2}{\sigma_{k,d}^2}$, $\alpha_{k,n}^m = \frac{\left|h_{k,n}^m\right|^2}{\sigma_{k,n}^2}$, $\alpha_{n,d}^m = \frac{\left|h_{n,d}^m\right|^2}{\sigma_{n,d}^2}$ respectively.

3. Problem Formulation

The problem is formulated as a maximization of the optimal weighted sum rate under a set of constrains as follows. Denote that $\rho_{k,n}^m \in \{0,1\}$ takes 1 if the *kth* user selects the *nth* relay in the *mth* subcarrier, and 0 if otherwise.

The total power for user *k* in subcarrier *m* is $P_{t,k}^m = P_k^m + P_n^m$ [10-11]. In the current study, we only consider the DF relaying mode without the SD link. From (1), the sum rate is maximized as follows:

$$P_k^m\alpha_{k,d}^m = P_n^m\alpha_{n,d}^m \tag{2}$$

where we can obtain the source power allocation:

$$P_k^m = \frac{\alpha_{n,d}^m}{\alpha_{k,n}^m + \alpha_{n,d}^{m'}}P_{t,k}^m \tag{3}$$

and the relay power allocation:

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$$P_n^m = \frac{\alpha_{k,n}^m}{\alpha_{k,n}^m + \alpha_{n.d}^{m'}} P_{t,k}^m \tag{4}$$

Denote $\alpha_{k,eq}^m$ as the equivalent channel gain as follows:

$$\alpha_{k,eq}^m = \frac{\alpha_{k,n}^m \alpha_{n,d}^m}{\alpha_{k,n}^m + \alpha_{n,d}^{m'}} \tag{5}$$

Thus, the weighted rate can be unified as

$$R_{k,n}^m = \frac{w_n}{2}\left[\log_2(1 + P_{t,k}^m \alpha_{k,eq}^m)\right] \tag{6}$$

Subsequently, the weighted rate optimization problem can be formulated as

$$\max_{P,\rho} \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} \rho_{k,n}^m R_{k,n}^m \tag{7}$$

S.t.

$$c1: \rho_{k,n}^m \in \{0,1\}, \forall k,m,n$$

$$c2: \sum_{k=1}^{K}\sum_{n=1}^{N} \rho_{k,n}^m = 1, \forall m$$

$$c3: \sum_{m=1}^{M} P_k^m \le P_{S,k}, \forall k$$

$$c4: \sum_{m=1}^{M} P_n^m \le P_{R,k}, \forall$$

$$c5: R_k \ge Q_k, \forall k$$

$$c6: P_k^m \ge 0, \forall k,m$$

$$c7: P_n^m \ge 0, \forall k,m$$

Constrains c1 and c2 satisfy the definition of OFDMA, which states that each subcarrier is allocated to one user and one relay. Constrain c3 and c4 are the source and relay power constraints respectively. Constrain c5 applies the minimum QoS requirement

A. Solution of the Dual Function

By dualizing the constrains, we obtain the generated dual function as follows:

$$\begin{aligned}
L(p,\rho,t,\lambda,\mu,\beta) &= \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} \rho_{k,n}^m w_n R_{k,n}^m + \sum_{k=1}^{K}\lambda_k\Big(\sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^m R_{k,n}^m - Q_k\Big) \\
&+ \sum_{k=1}^{K}\beta_k\Big(P_{S,k} - \sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^m P_k^m\Big) + \sum_{k=1}^{K}\mu_k\Big(P_{R,k} - \sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^m P_n^m\Big) \\
&= \sum_{m=1}^{M}\Big[\sum_{k=1}^{K}\sum_{n=1}^{N} w_n R_{k,n}^m + \sum_{k=1}^{K}\lambda_k\sum_{n=1}^{N}\rho_{k,n}^m R_{k,n}^m - \sum_{k=1}^{K}\mu_k\sum_{n=1}^{N}\rho_{k,n}^m P_{t,k}^m \\
&- \sum_{k=1}^{K}\beta_k\sum_{n=1}^{N}\rho_{k,n}^m \frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m} P_{t,k}^m\Big] - \sum_{k=1}^{K}\lambda_k Q_k + \sum_{k=1}^{K}\mu_k P_{R,k} + \sum_{k=1}^{K}\beta_k P_{S,k}
\end{aligned} \tag{8}$$

where $\mu \ge 0$, $\lambda = (\lambda_1, \lambda_2 ......\lambda_k) \ge 0$ and $\beta = (\beta_1, \beta_2 ......\beta_k) \ge 0$ are dual variables. Lagrangian dual function of problem (7) can then be expressed as follows:

$$g(\lambda,\mu,\beta) = \max_{p,\rho,t} L(p,\rho,t,\lambda,\mu,\beta) \tag{9}$$

S.t

$$\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}^m = 1, \forall m$$

$$0 \le \rho_{k,n}^m \le 1 \quad , \quad P_{t,k}^m \ge 0$$

Therefore, as described in [12-13], we relax $\rho_{k,n}^m$ to obtain any real value between 0 and 1 during the time sharing of each subcarrier.

The dual optimization problem is expressed as:

$$\min_{\lambda,\mu,\beta} g(\lambda,\mu,\beta) \tag{10}$$

The subproblem at subcarrier m is calculated as follows:

$$\max_{p,\rho,t} L(p^m,\rho^{m,}) = \max_{p,\rho,t} \sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}^m w_n R_{k,n}^m + \sum_{k=1}^{K}\lambda_k \sum_{n=1}^{N}\rho_{k,n}^m R_{k,n}^m$$
$$-\sum_{k=1}^{K}\beta_k \sum_{n=1}^{N}\rho_{k,n}^m \frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m} P_{t,k}^m - \sum_{k=1}^{K}\mu_k \sum_{n=1}^{N}\rho_{k,n}^m (1-\frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m}) P_{t,k}^m \quad (11)$$

S.t

$$\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}^m = 1, \forall m$$

$$0 \le \rho_{k,n}^m \le 1 \;,\; P_{t,k}^m \ge 0 \;,\; \forall k,n$$

Considering the convex optimization problem in (10), the subgradient of $g(\lambda,\mu,\beta)$ can be derived using a similar method described in [14]:

$$\Delta\lambda_k = \sum_{m'=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^{m*} R_{k,n}^m - Q_k, \forall k$$

$$\Delta\mu_k = P_{R,k} - \sum\nolimits_{k=1}^{K}\sum\nolimits_{m=1}^{M}\sum\nolimits_{n=1}^{N}\rho_{k,n}^{m*}(1-\frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m})P_{t,k}^{m*}, \forall k$$

$$\Delta\beta_k = P_{S,k} - \sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^{m*}\frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m}P_{t,k}^{m*}, \forall k$$

B. Optimal Power Allocation for a Given Relay Assignment

When subcarrier *m* is assigned to user *k* and relay *n*, $\rho_{k,n}^m = 1$.The optimal power allocation and relay assignment can be determined by solving the following problem:

$$\max_{P_{t,k}^{m,m'}} L_m, \forall k,n \quad (12)$$

S.t. $\quad P_{t,k}^m \ge 0.$

Moreover L_m is a concave function of $P_{t,k}^m$. By applying Karush-Kuhn-Tucker conditions [15], we can obtain the optimal power allocation as follows:

$$P_{t,k}^m = \left[\frac{w_n+\lambda_k}{\left[\beta_k \bullet \frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m} + \mu_k \bullet (1-\frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m})\right]\times 2\ln 2} - \frac{1}{\alpha_{k,eq}^m}\right]^+ \quad (13)$$

Where $[x]^+ = \max[x,0]$

C. Optimal Relay Selection

By eliminating the optimal power variables in (12) and then substituting these into (8), we can obtain an alternative expression of the dual function as

$$g(\lambda,\mu,\beta) = \max_{\rho,t}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{k,n}^{m*}H_{k,n}^m(\lambda,\mu,\beta) - \sum_{k=1}^{K}\lambda_k Q_k + \sum_{k=1}^{K}\mu_k P_{R,k} + \sum_{k=1}^{K}\beta_k P_{S,k}, \quad (14)$$

where the function is expressed as

$$H_{k,n}^m = \frac{1}{2}(w_n+\lambda_k)\left[\log_2(1+P_{t,k}^{m*}\alpha_{k,eq}^m)\right] - (\mu_k \bullet (1-\frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m}) + \beta_k \bullet \frac{\alpha_{k,eq}^m}{\alpha_{k,n}^m})P_{t,k}^{m*} \quad (15)$$

This formula also plays an important role in relay selection.

$H = \left[H_{k,n}^m\right]$ can be interpreted as a $K \times N$ profit matrix. The optimal relay n should be selected to use k in this subcarrier pair and to achieve the maximum value of $H_{k,n}^m$ in (15).

$$\rho_{n,k}^m = \begin{cases} 1, (n^*,k^*) = \arg\max_{n,k} H_{k,n}^m \\ 0, otherwise \end{cases} \quad (16)$$

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In the above analysis, optimal power allocation is computed using (13), which is then used to compute $H_{k,n}^{m}$ in (15). Subsequently, we can use (16) to determine the use and relay in the subcarrier.

4. Simulation Results

The simulation results of survival time for each relay are shown. The corresponding capacities of the two relays are C1=4 Wh, C2=2 Wh. The two relay power constraints are both equal to 1. Thus, P1 = P2 = 1. The residual capacity proportion of the two relays of the whole relay system is [2/3 1/3]. The weighted rate parameters are set at w1 = [0.5 0.5] and w2 = [2/3 1/3]. Obviously, w1 indicates that the residual capacity of the two relays is insignificant when selected. When w= [0.5 0.5], the two relays are supplied with a maximum power because of rate maximization. Simultaneously, the corresponding survival time of the two relays are T1 = C1/P1, and T2 = C2/P2. However, w = [2/3 1/3], Thus, w is set according to the proportion of the residual capacity. Given that the channel parameters of the two simulations are the same, the number of subcarriers in relay1 increases while that in relay 2 decreases compared with the equal probability situation. However, the minimum survival time of the whole relay system can be prolonged, thereby improving the relay system life. A problem implies that two relays provide maximum power when maximizing sum rate. However, considering the actual situation, when w2 = [2/3 1/3], the number of subcarriers in relay2 can be reduced, whereas the power of the subcarriers increases compared with w1 = [0.5 0.5]. We calculate the current power of subcarriers based on the previous power. Thus, T1' = C1/P1 and T2' = C2/P'. Subsequently, we set w = [0.75 0.25], [0.85 0.15], correspondingly.

In the simulation, we consider quasi-static frequency-selective Rayleigh fading channels with a six-tap equal-gain equal-space delay profile. Gaussian random variables are assumed to have zero mean and a variance of one. The number of subcarriers is 48. We also assume that the channel variance of RD link is 0 dB. The minimum rate requirement of the two users is considered to be the same at 0.5 bps/Hz.

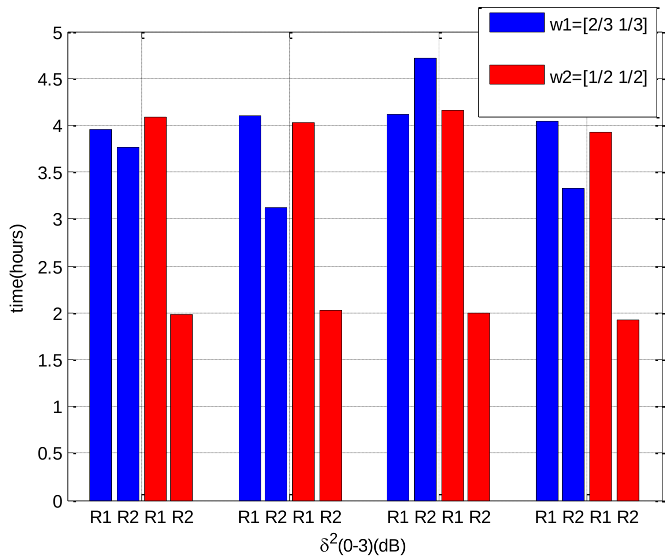

Figure 2. Survival Time for w = [2/3 1/3] and [0.5 0.5] with Different Channel Variances of SR Link

The survival time of the two relays are w = [2/3 1/3] and [0.5 0.5] with the channel variance of SR link 0-3 (dB) (Figure. 2). When w is set according to the proportion of the residual capacity, the minimum survival time of the relay system can be larger than when

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w is set equally. The survival time interval between relay1 and relay2 is insignificant. This finding is attributed to the equal probability of w, in which the relay is freely selected only because the channel gain ignores the influence of the residual capacity. When w = [2/3 1/3], the number of subcarriers that distributes relay 2 relatively decreases more than the equal probability. However, the power of the current subcarriers allocated to relay2 is calculated in the same way as w = [0.5 0.5]. Hence, the power provided by relay2 is smaller， and the survival time is longer. Under this condition, the number of subcarriers in relay1 increases, though relay1 still provides maximum power. Thus, the time of relay1 is unchanged.

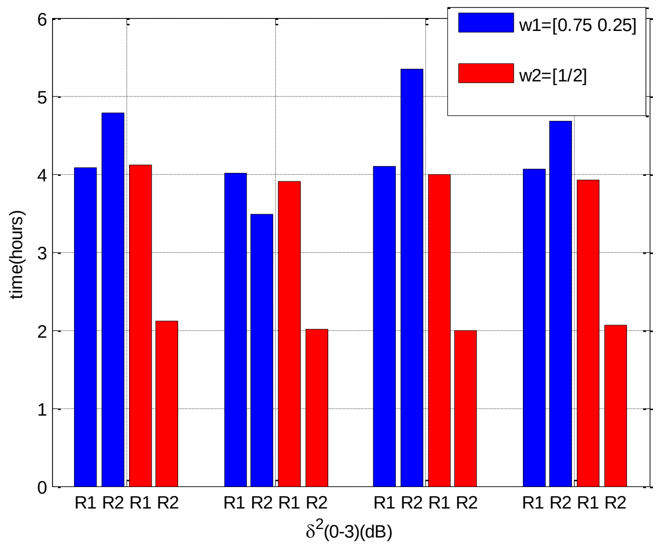

Figure 3. Survival Time for w = [0.75 0.25] and [0.5 0.5] with Different Channel Variances of SR Link

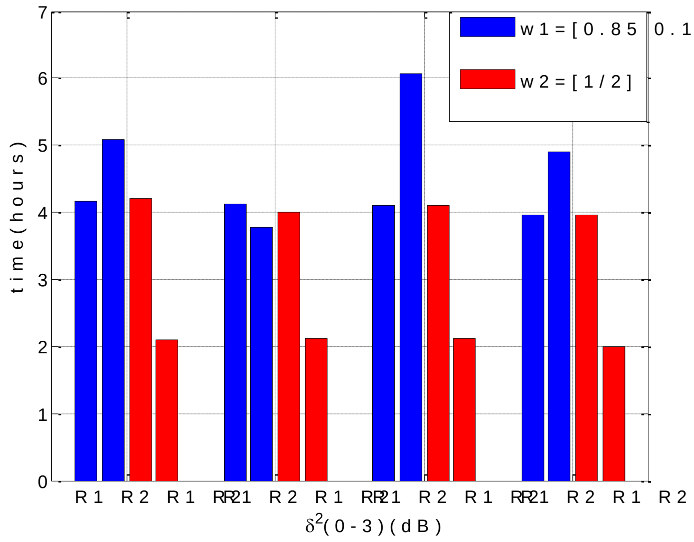

Figure 4. Survival Time for w = [0.85 0.15] and [0.5 0.5] with Different Channel Variances of SR Link

Figures 3 and 4 illustrate the survival time for w = [0.75 0.25] and [0.85 0.15] with channel variances of SR link equal to 0-3 (dB). The difference in survival time between the two relays is larger than w = [2/3 1/3]. The difference is also the smallest when w is set according to the proportion of the residual capacity. In this case, the survival time is

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prolonged depending on relay 1. However, the survival time is reduced for more rate losses (Figure. 5).

Figure 5 shows the average rate per user for the systems with different w. In the first slot, subcarriers prefer the optimal relay with w equal to [0.5 0.5], [2/3 1/3], [0.75 0.25], and [0.85 0.15]. Second, we optimize the weighted sum rate. Thus, the relay can be selected according to its residual capacity and the channel gain. Third, when we consider the actual situation, we optimize the unweighted sum rate to calculate the actual optimal power and distribute it to the relevant subcarriers. Finally, the actual total system throughput can be calculated.

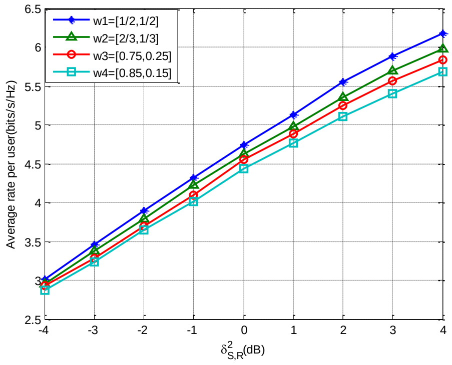

Figure. 5. Average Rate for w Set to Different Values

The largest system rate can be achieved when w is set to [0.5 0.5] (Figure. 5). The rate from high to low in the order is also obtained when w = [2/3 1/3], [0.75 0.25], [0.85 0.15]. This finding implies that the subcarriers can freely select the relay only in line with channel gains with equal probability. Nevertheless, the loss of the system rate affecting the residual capacity of relays is considerable because the subcarriers select the optimal relay depending on two conditions. The results show that the minimum survival time of the relay system is the shortest when w = [0.5 0.5] and is almost 2 h depending on the relay2 (Figures. 2—4). The minimum survival time is also the longest at nearly 4 h depending on relay1, when w= [0.75 0.25], [0.85 0.15]. However, the survival time of the two relays is the closest when w = [2/3 1/3], which is slightly lower than those in the two previous cases (w = [0.75 0.25], w = [0/85 0.15]), though the sum-rate losses are the smallest. We calculate the rate loss percentage at 0—3(dB) of w = [2/3 1/3], w = [0.75 0.25], w = [0.85 0.15] corresponding to 2.448%, 3.862%, 6.5%; 3.038%, 4.966%, 7.225%; 3.604%, 5.495%, 8.018%; 3.144%, 5.523%, 8.326% (Figure. 5).

5. Conclusion

In this paper, relay selection and resource allocation considering the residual capacity of the relay system was formulated. Weighted rate used in the relay selection was proposed. Subsequently, the optimization problem was transformed into optimizing weighted rate by satisfying the individual power constraint for every user and relay, as well as the individual user's QoS requirements. The joint optimization of the relay assignment, the subcarrier assignment, and the power allocation were discussed. The simulation results showed that the minimum survival time of the whole relay system can be improved depending on the residual capacity of the relays.

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