Efficient Bandwidth Allocation Scheme for Wireless Networks Using Relay Stations

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***Abstract*—With the advance of wireless communications technologies, it has been proved that the usage of relay stations can improve the transmission rate and enlarge the coverage. The present usage of relay stations (RS) focus on retransmitting signal to the destination to ensure the correctness of signal. In this paper, we propose a novel relay transmission scheme and consider in using the bandwidth between the BS and RS for relaying the required data of User Equipments (UEs). In order to use the bandwidth resource efficiently, our proposed scheme considers the transmission time of the UEs under different requirement of data and assigns the bandwidth resource to reduce the overall transmission time. The simulation results show that our proposed scheme can reduce the overall transmission time noticeably compared to the method that does not assign the bandwidth resource.**

Keywords—Wireless networks; resource allocation; relay station

I. Introduction

In recent years, relay technologies have been actively studied and considered in the next-generation mobile communication systems, such as 3GPP LTE-Advanced [1] and IEEE 802.16j [2]. Relay transmission can be considered as a kind of collaborative communications, in which a Relay Station (RS) helps to forward user information from neighboring User Equipment (UE) to a local Base Station (BS). RSs can effectively extend the signal and service coverage of a BS and enhance the overall throughput performance of a wireless communication system [1, 2]. By placing RSs properly in the network, the service coverage and system throughput can be effectively improved in 3GPP LTE-Advanced and IEEE 802.16j [3]. Moreover, the usage of RSs has also been proposed in novel cognitive radio networks to help for the data transmission [4].

A typical network structure of those kinds of networks with relay scheme consists of BSs, RSs and UEs. The radio links between BSs and RSs are called relay links, while both the links between BSs and UEs, and the links between RSs and UEs are called access links. There are bandwidth resources of the relay links between BS and RSs, thus, how to allocate these resources for UEs is a critical problem that will affect the overall performance of the networks. Researchers have presented numerous schemes to solve the bandwidth allocation problems with relay transmission scheme. Some of the schemes are designed for unicast and allocate the bandwidth resources in a dynamic manner with different performance purposes. On the other hand, several new bandwidth allocation schemes [5], [6], [7] have also been developed in the last few years for multicast.

To improve efficiency of transmission and reduce the duration time of a communication with relay scheme, we provide a novel way to use the RSs. We consider the relay links as extra data flows and allocates the bandwidth of relay links to those UEs as another data flow for transmitting the UEs' data. The UEs links to the RSs may be allocated with some bandwidth. Furthermore, with the constraint of available bandwidth resource, our proposed algorithm targets to use available bandwidths efficiently for data transmission and reduce the overall transmission time. Thus, based on the available bandwidth resource of relay links from BS to RSs, we propose a method to allocate the bandwidth resources of relay links to those UEs. Our proposed method considers the acquirement of every UE and allocates more bandwidth resource to the UEs with longer transmission time to reduce the overall delay of current transmission.

Rest of this paper is organized as follows. Section II describes the related work on bandwidth resources allocation schemes in wireless communication systems. Detailed approach of our bandwidth resource allocation algorithm based on RSs is introduced in Section III. The simulation results are given in Section IV, and Section V concludes this paper.

II. Related Work

Many relay transmission schemes have been proposed for multi-hop (relay-based) communication between BS and UEs through RSs [2]. In the Amplify and Forward (AF) scheme, RS receives the signal from the BS at the first phase. Then it amplifies this received signal and forwards it to the UE at the second phase. The advantage of AF scheme is that AF is relatively simple with very short delay, but the disadvantage is that AF can also amplify the noises. In the Selective Decode and Forward (DCF) scheme, a RS decodes the received signal which is encoded by and from the BS at the first phase. If the decoded data is checked correctly by using cyclic redundancy check (CRC) scheme, the RS will perform channel encoding and forward the encoded signal to the target UE at the second

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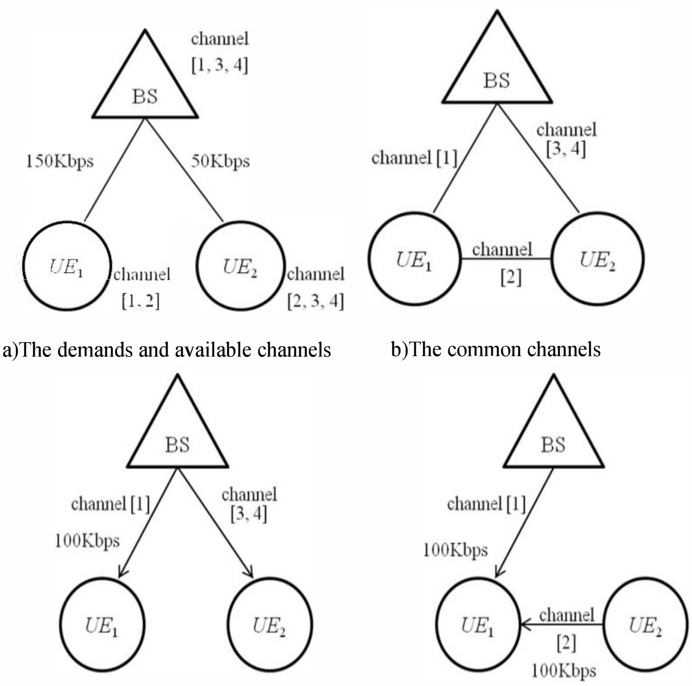
phase. The advantage of DCF scheme is that it can effectively avoid error propagation through the RS, but the processing delay is quite long.

In the Demodulation and Forward (DMF) scheme, a RS demodulates the received signal, which is modulated by and from the BS and makes a decision at the first phase. It modulates and forwards the new signal to the UE at the second phase. This DMF scheme has the advantages of simple operation and low processing delay, but DMF cannot avoid error propagation due to the hard decisions made at the symbol level in the first phase. Based on the relay transmission scheme mentioned above, standards of relay technologies in IEEE 802.16j and 3GPP LTE-Advanced have been proposed and processed. According to the 3GPP LTE-Advanced technical report and IEEE 802.16j technical specification, an RS can act as the BS units and should have its own physical cell identifier. It should be able to transmit its own synchronization channels, reference symbols and downlink control information. So a RS has the full functions of a BS including the capabilities of knowing the radio bearer of received data packets and performing traffic aggregation to reduce signaling overhead.

Under different kinds of relay transmission schemes as mentioned above, there have been kinds of researches about the usage of RSs in IEEE 802.16j and 3GPP LTE-Advanced. Some researchers focus on the cost efficiency and efficient deployments of RSs, and others focus on bandwidth allocation problems with relay scheme. In [8], the authors provide a new model of cost-efficient deployment of relays in LTE-A cellular networks and aim at analyzing the tradeoff between the deployment cost and the cell performance gain. In [9], the authors study the problem of sub-frame; sub-channel and power allocation in OFDMA (Orthogonal Frequency-Division Multiple Access) based multi-hop relay networks. In this work, authors consider two problems including minimizing power subject to rate constraints and maximizing fairness subject to power constraints.

In [10], authors formulate a weighted power minimization problem, optimizing over both power usage and bandwidth under the constraints on required rate, bandwidth and transmitting power for serving multiple users. Although there are many studies investigate the bandwidth allocation problems with relay schemes in IEEE 802.16j and 3GPP LTE-Advanced, they do not consider the situation that the bandwidth resources of relay links can be portioned into multiple parts and each part is a calculated suitable bandwidth that be allocated for a specific UE. We want to show that by distributing these parts properly to those needy UEs, we can have more efficient bandwidth usage. Since our proposed scheme aims to combine the access links to every UE as the total bandwidth, a technology D-OFDM (Discontiguous Orthogonal Frequency-Division Multiplexing) [11] will be used in our paper. D-OFDM allows a transmitter to transmit data to different users with different channels and allow receiver to receive data from different channels.



a)The demands and available channels b)The common channels

c) Cooperative relay transamission(left in time slot 1 and right in time slot 2)

Fig. 1. An example for the demand improvement by using cooperative transmission

The research in [12] has shown that it can be achieved better spectrum utilization and improve system capacity with D-OFDM in cognitive radio networks. On the basis of D-OFDM, they propose a new physical layer technology, relay-assisted D-OFDM, to enable the efficient transmission among BS and UEs. The authors use D-OFDM technology to exploit other UEs with redundant resources. The BS will have multiple paths to transmit data and the UEs can receive data from multiple paths simultaneously. For example, the available channels and the bandwidth demands of destinations are shown in Fig 1 (a). We assume that the bandwidth of each channel is 100 Kbps. It is shown in Fig 1 (b) that the bandwidth demand is not satisfied in UE_1 if UE_1 is only assigned with channel 1 as the common communication channel between BS and UE_1.

In order to satisfy the bandwidth demand of UE_1, authors try to exploit channel bandwidth on destination node UE_2. Actually, UE_2 is assigned with two channels (channels 3 and 4), where one channel is enough for communication request and the other channel is redundant, which can be used for helping transmission. At same time, UE_2 have a common channel (channel 2) with UE_1, UE_2 has the ability to relay UE_1's data request transmission in two time slots transmission scheme, as shown in Fig 1 (c). In the first time slot, UE_1 receives data from BS on their common channel 1, UE_2 receives both data based on the request of itself on channel 3 and data for UE_1 on channel 4. In the second time slot, UE_1 receives data from BS on channel 1 and data from UE_2 on channel 2. Therefore, the average data rates in the two time slots for UE_1 and UE_2 are 150 Kbps and 50 Kbps, respectively, which can satisfy the demands of both destinations. This work provides an efficient way to use the limited bandwidth resource, but it does not consider in the usage of RSs and how to handle the situation with multiple requests of UEs.

In order to exploit the bandwidth of relay links to utilize efficiently resources in data transmission, we also involve OFDMA in this paper. With the inspiration of the multiple sub-channels access nature of OFDMA, we can cut the channels of relay links into multiple sub-channels for more efficient bandwidth resources assignment. In this study, we use a novel relay transmission scheme that different from those in the related work and proposed an efficient algorithm to assign properly the RSs bandwidth resources to UEs to minimize the maximum transmission time of BS to the UEs.

III. THE SCHEME OF RELAY RESOURCES ASSIGNMENT

A. System Model

Our study considers the resources allocation problems in wireless networks with help of relay stations. There will be different required data to be transmitted from BS to several UEs with assigned bandwidths. As illustrated in Fig. 2, our network topology consists of one BS located in the middle of the networks with m RSs and n UEs. The RSs are denoted from RS_1 to RS_m, and the UEs are denoted from UE_1 to UE_n. We consider that the BS can connect to RSs and UEs directly if they are in the communication range of BS. Moreover, we assume that each UE can choose and connect to one RS, but each RS can serve several neighboring UEs. Serving as helping node, RSs have no data transmission requirement from BS, so that we exploit and allocate the bandwidth resources of RSs to UEs. The calculation of the downlink relay resources assignment will be executed by the BS.

It is also assumed that the channel bandwidths of relay links between BS and RSs can be cut into sub-channels for being utilized more efficiently by more UEs, as a result, those BS and RSs can serve multiple users with different sub-channels based on OFDMA technology without interferences. In the network structure, each UE may have at most one direct access link from the BS and one indirect link from a RS. The data flow of the two access links of a certain UE can be combined as a total bandwidth which is used by the UE actually. We can achieve this data flow combination by D-OFDM technology mentioned in Section II. For example, in Fig. 2, UE_1 has two access links, direct and indirect links, from BS and RS_1, respectively, and the UE_1 can use the combinational bandwidth of the two links. In Fig. 2, we use B_i that represents the bandwidth of the relay link between the *BS* and RS_i, $B_{i,j}$ represents the bandwidth between RS_i and UE_j, and D_j represents the amount of required data of UEj, for $1\leq i \leq$ m and $1 \leq j \leq$ n, and we also use $B_{0,j}$ to represent the bandwidth between *BS* and UE_j.

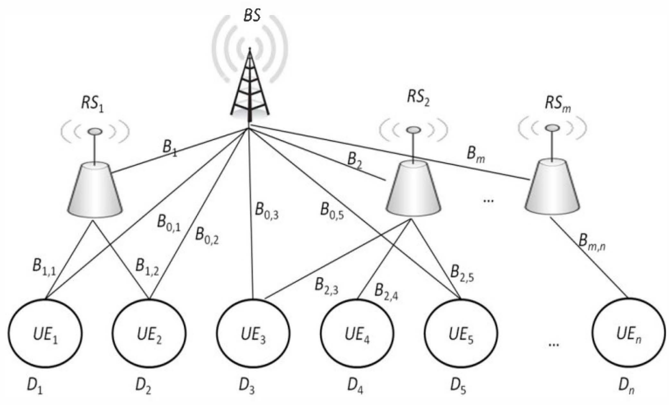


Fig. 2. A system model with BS, RSs, and UEs

Moreover, let $X_{i,j}$ denote the partial bandwidth of B_i used to transmit data from *BS* to RS_i for UE_j , which is the value we want to solve for the bandwidth allocation problem in this system model. Thus, the bandwidth assignment of B_i with k UEs connect to RS_i can be expressed as in equation 1.

$$B_i = \sum_{j=1}^{k} X_{ij} \ , \tag{1}$$

Considering the required data bandwidth and available bandwidth of the UEs, we want to find a bandwidth assignment of RSs to minimize the maximum transmission time of BS to the UEs. Suppose that we have one unit data transmission from *BS* to UE_j through RS_i, then the total transmission time of this path, $T_{i,j}$, can be expressed as in equation 2, and then we can find the Transmission Bandwidth of Indirect communications (TBI) through RS_i to UE_i, which is the inverse of transmission time and can be regarded as in equation 3.

$$T_{i,j} = \frac{1}{X_{i,j}} + \frac{1}{B_{i,j}} = \frac{X_{i,j} + B_{i,j}}{X_{i,j}B_{i,j}}, \tag{2}$$

$$TBI_{i,j} = \frac{1}{T_{i,j}} = \frac{X_{i,j}B_{i,j}}{X_{i,j} + B_{i,j}}, \tag{3}$$

The Total Available Bandwidth (TAB) of UE_j can be expressed as the combination of two data flows: one is the direct link from *BS*, $B_{0,j}$ and another one is the indirect link through RS_i, $TBI_{i,j}$, as given in equation 4.

$$TAB_j = B_{0,j} + TBI_{i,j} = B_{0,j} + \frac{X_{i,j}B_{i,j}}{X_{i,j} + B_{i,j}}, \tag{4}$$

With the TAB and required data of the UE_j, D_j, we can express the transmission time of UE_j, t_j as follows.

$$\mathrm{t_j} = \frac{\mathrm{D_j}}{\mathrm{TAB_j}} = \frac{\mathrm{D_j}}{B_{0,j} + \frac{X_{i,j}B_{i,j}}{X_{i,j} + B_{i,j}}}, \tag{5}$$

For example, in Fig 2, UE_1 connects to *BS* and relay stations RS_1. Suppose the required data of UE_1 is 150 Kbits, the assigned bandwidth of RS_1 to UE_1, $X_{1,1}$ is 100 Kbps, and the bandwidths of $B_{0,1}$, $B_{1,1}$ are 100 Kbps. Thus, by applying to equation 4, we have $TAB_1 = B_{0,1} + \frac{X_{1,1}B_{1,1}}{X_{1,1}+B_{1,1}} = 100 + \frac{100 \cdot 100}{100+100} =$ 150 Kbps, which is the total available bandwidth of UE_1, and the transmission time of UE_1 is $t_1 = \frac{D_1}{TAB_1} = \frac{150}{150} = 1$ second by equation 5.

B. Relay Resources Assignment Algorithm

In this section, we consider the relays with a limited bandwidth, and proposed an algorithm to improve the target network performance, that is, we want to reduce transmission time of the k UEs connect to a certain RS taken as an entirety and minimize the maximum number between t_1, t_2, … , t_k. Since each RS in our system model has bandwidth resources from BS and some connections to UEs, we try to find an algorithm to allocate the bandwidth of each RS to the connected UEs. We will assign properly the RSs bandwidth resources to UEs to minimize the maximum transmission time of BS to the UEs.

1) Bandwidth Assignment Scheme: We will describe our scheme step by step as follows. First of all, after having the information of bandwidths of each link, we will know that the number of requests contending for each RS's bandwidth resources. Then, we will use simultaneous linear equations to find all unknown assigned values and solve the problem of RS bandwidth assignment.

For each RS_i, assume there are k_i UEs contending for RS_i's resources. To minimize the maximum transmission time of the k_i UEs, we let the transmission time $t_1 = t_2 = \ldots = t_{ki}$, then we can have $k_{i\text{-}1}$ equivalences: $t_1 = t_2$, $t_2 = t_3$, …, and $t_{ki\text{-}1} = t_{ki}$. In addition, the bandwidth of RS_i is equal to the summation of the assigned bandwidths to the k_i UEs as shown in equation 1. Thus, with the k_i UEs connecting to the RS_i, we have k_i linear equations and k_i unknown variables $X_{i,1} \sim X_{i,ki}$ which can be solved by Gaussian elimination method. For example, as shown in Fig 2, there are two assigned bandwidths $X_{1,1}$ and $X_{1,2}$ for UE_1 and UE_2, respectively. Therefore, we have two equations $B_1 = X_{1,1} + X_{1,2}$ and $t_1 = t_2$. By the Gaussian elimination method, we can get the bandwidths of $X_{1,1}$ and $X_{1,2}$.

There are two cases after we get the k_i values of $X_{i,1} \sim X_{i,ki}$. In first case, k_i values are larger than or equal to zero. Then the solution is feasible. Now, take an example of this case and show the processes of our proposed scheme. As shown in Fig 2, suppose bandwidth B_1 = 300 Kbps to be assigned to UE_1 and UE_2 for relaying required data. We have $B_1 = 3000 = X_{1,1} + X_{1,2}$ by equation 1. Then applying equation 5, we have $t_1 = \frac{D_1}{TAB_1} = \frac{D_1}{B_{0,1} + \frac{X_{1,1}B_{1,1}}{X_{1,1}+B_{1,1}}} = \frac{200}{100 + \frac{X_{1,1} \cdot 200}{X_{1,1}+200}}$ and $t_2 = \frac{D_2}{TAB_2} = \frac{D_2}{B_{0,2} + \frac{X_{1,2}B_{1,2}}{X_{1,2}+B_{1,2}}} = \frac{150}{100 + \frac{X_{1,2} \cdot 100}{X_{1,2}+100}}$. With the equations $B_1 = 300 = X_{1,1} + X_{1,2}$ and $t_1 = t_2$, we will assign $X_{1,1}$ = 200 Kbps for UE_1 and $X_{1,2}$ = 100 Kbps for UE_2. Thus, we have TAB_1 = 200 Kbps and TAB_2 = 150 Kbps and both UE_1 and UE_2 can finish their data transmission in one second.

In the second case, there exist at least one $X_{i,j}$ value less than zero, for $1 \leqq j \leqq k_i$. It implies that some UEs do not need the help of RS such that the assigned bandwidths of these UEs are less than zero. Thus, we will remove the UEs with negative values of bandwidth allocation. After removing these UEs, we will recalculate the solutions for the remaining UEs. We do the check-and-remove process repeatedly until we can find the solution set with all of the bandwidth assignments to the UEs are not less than zero.

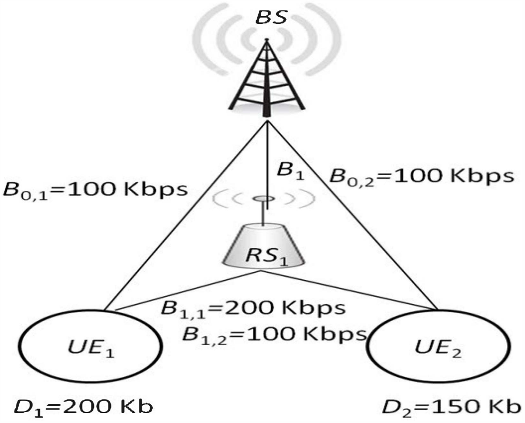


Fig. 3. An example of our system model

For example, as shown in Fig 3, if we add an extra UE_3 connecting to RS_1 with D_3 = 50 K bits, $B_{1,3}$ =100 Kbps and $B_{0,3}$ =100 Kbps. We can find the transmission time of UE_3 without help of RS_1 is 0.5 second. After applying the Gaussian elimination method, we have $X_{1,1}$=219, $X_{1,2}$=114, and $X_{1,3}$ = -33. So, we will remove UE_3 and reallocate the bandwidth of B_1 to UE_1 and UE_2 only. Finally, after the calculation of bandwidth assignment of the RS is done, we will take the results of $X_{i,j}$ values to a multiple number of the sub-channel size to satisfy the restriction of OFDMA.

For a certain RS with n UEs connecting to the RS, the time complexity of one Gaussian elimination method calculation will be $O(n^3)$. Moreover, the necessary calculation times of our proposed scheme is at most n-1, so the overall time complexity will be $O(n^4)$ for each RS. We can apply the same method to all RSs to find the bandwidth assignments of every RS.

IV. Simulation Results

In this section, we will present simulation results to demonstrate the performance of our proposed scheme. In our simulations, we supposed that there are several UEs trying to receive different data from the BS through the direct and indirect access links. Moreover, we will compare the performance of our relay bandwidth resource assignment scheme with the traditional sequentially using scheme named greedy method here. In greedy method, BS does not assign the bandwidth resources of relay link between BS and RSs. The BS will calculate the transmission time according to the required data and direct link bandwidth of every UE, and the UE with longest transmission time will use the whole bandwidth of its connecting RS to help data transmission first.

After this UE finishes its data transmission, BS will recalculate the transmission time of all unfinished UEs again. The UE with longest transmission time will use the whole bandwidth of its connecting RS to help data transmission and BS will repeat this procedure until all UEs complete their data transmission. According to the system model in Section III (A), we construct the scenario including one BS, several RSs and UEs. The basic simulation parameters are as follows: We set the bandwidth of each channel to be 100 Kbps, thus the bandwidth of every link is a multiple number of 100. The required data of every UE is in the range of 300 ~ 500 K bits except Fig. 4. The bandwidth of the relay links between BS and RSs are in the range of 100 ~ 500 Kbps. The bandwidth between BS (RS) and each UE is 100 ~ 200 Kbps. Finally, we set the sub-channel size to be l0 Kbps. There are one RS and 5 UEs in the following simulations.

First, we compare the transmission time and the improved rate of our relay resource assignment scheme over the greedy method with the required data size of all the UEs are the same. Fig. 4 shows the transmission time of the two schemes under different size of required data. We can see that with the increasing of the required data size, the transmission time of our relay resources assignment scheme is always shorter than greedy method and the increasing time is linear. Fig. 4 also shows that the required data sizes do not influence the improved rates of our proposed scheme over the greedy method. The improved rate is about 20% at various data sizes.

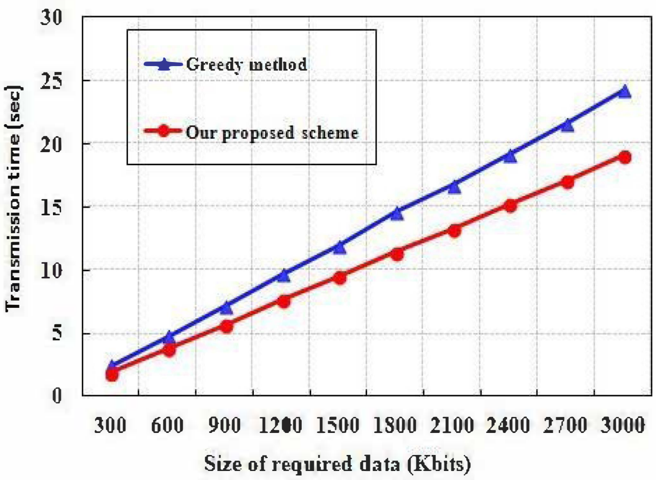


Fig. 4. Size of required data vs. transmission time

Then, we will consider the impact of the bandwidth of relay link between BS and RS. Fig. 5 shows that once the bandwidth of relay link between BS and RS increases, our proposed method will use resource more efficiently and the average transmission time will be much shorter than the greedy method. The improved rate of our relay resource assignment scheme over the greedy method is increasing with the increasing of the bandwidth of relay link, and reach about 23% when the size of relay resource is larger than 500 Kbps.

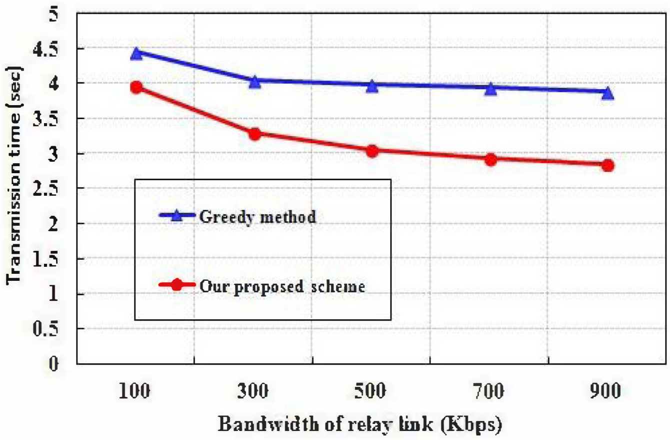


Fig. 5. Bandwidth of relay link vs. transmission time

Moreover, we compare our scheme with the greedy method on bandwidth of the direct access links from BS. We set the bandwidths of direct links between RS and UEs under three fixed bandwidths 100 Kbps, 200 Kbps and 300 Kbps. Fig. 6 shows that the transmission times of both schemes decrease severely with the increase of the bandwidth of direct links. The improved rates of our proposed scheme over the greedy method decrease as the bandwidth of the direct links increase. This is because once the bandwidths of the direct links increase, the impact of the help from RSs will decrease. As a result, it is an advantage nature of our proposed mechanism when there are UEs with low bandwidth of direct links.

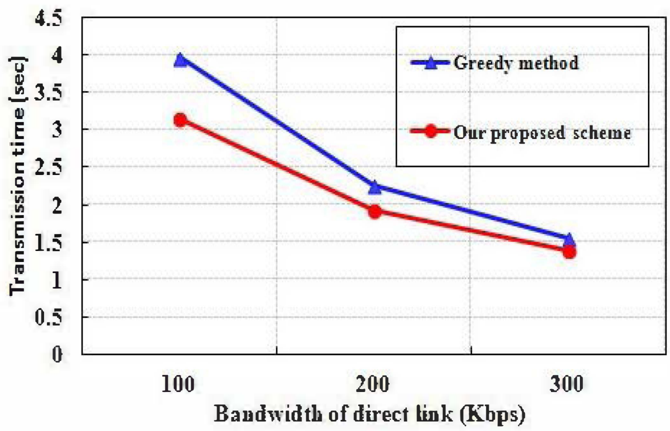


Fig. 6. Bandwidth of direct link vs. transmission time

Moreover, we consider the impact of different numbers of UEs. Fig. 7 shows that the transmission time of the both schemes. Our relay resource assignment scheme increase more slowly than the greedy method. Fig. 8 shows the improved rate of our proposed scheme over the greedy method. We can see that when the number of UEs is about 7, we have the highest improved rate 23%.

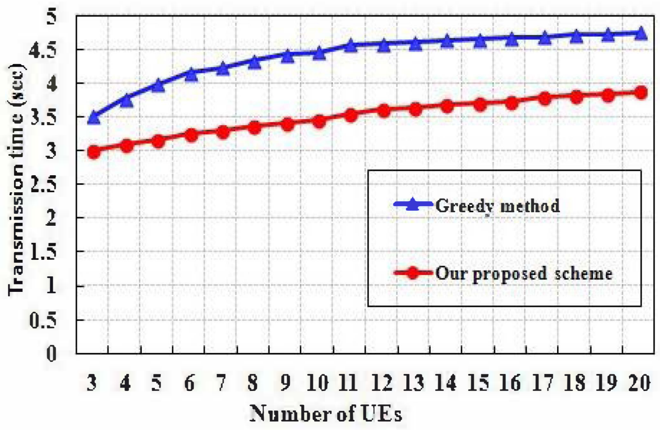


Fig. 7. Number of UEs vs. transmission time

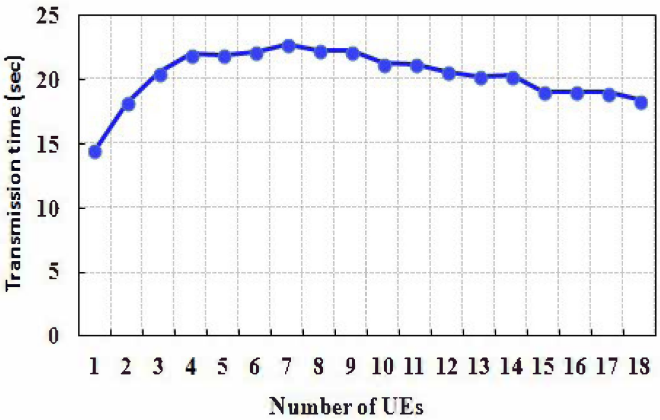


Fig. 8. Number of UEs vs. improve rate

Finally, we make a simulation on the impact of the relay link bandwidth to total network bandwidth. In Fig. 9, we can see that when the relay links bandwidth increases, the transmission time of both schemes decreases. The transmission time of our scheme is better than the greedy one and the improved rate can be up to 25% when the fraction of relay bandwidth is 50%.

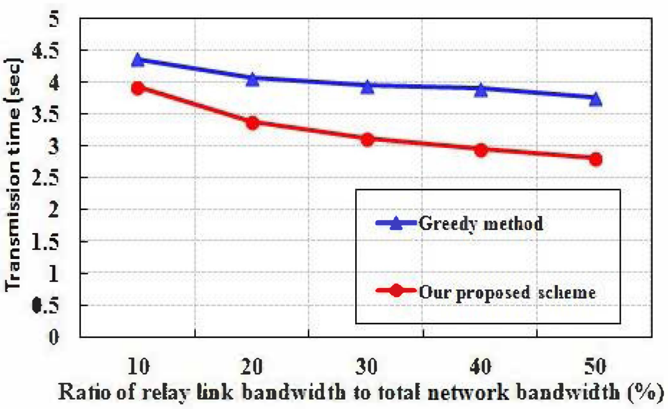


Fig. 9. The percentage of relay link bandwidth to total network bandwidth vs. transmission time.

V. CONCLUSION

In this paper, we use the limited resources of wireless communication more carefully and properly. We propose a novel relay transmission scheme and an efficient resource allocation scheme to assign the bandwidth resources of relay links between the BS and RSs for UEs to transmit required data. Our proposed scheme takes the transmission time of UEs into consideration to allocate the available relay link bandwidth resources. Assign more relay bandwidths to the UEs with longer transmission time will improve the overall transmission time of the network. The simulation results show that our proposed scheme will use the relay links bandwidth resources sufficiently and improve the network performance.

REFERENCES

[1] 3GPP TR 36.814 V1.2.1, "Further Advancements for EUTRA: Physical Layer Aspects," *Technical Specification Group Radio Access Network Release 9*, June 2009.

[2] IEEE P802.16j/D9, "Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems: Multihop Relay Specification," February 2009.

[3] Y. Yang, H.-L. Hu, J. Xu, and G.-Q. Mao, "Relay Technologies for WiMAX and LTE-Advanced Mobile Systems," *IEEE Communications Magazine*, vol. 47, pp. 100-105, October 2009.

[4] Y. Zou, Y.-D. Yao, and B. Zheng, "Cooperative Relay Techniques for Cognitive Radio Systems: Spectrum Sensing and Secondary User Transmissions," *IEEE Communications Magazine*, vol. 50, pp. 98-103, April 2012.

[5] W.-H. Kuo and J.-F. Lee, "Multicast Recipient Maximization in IEEE 802.16j WiMAX Relay Networks," *IEEE Transactions on Vehicular Technology*, vol.59, no.1, pp.335-343, January 2010.

[6] W.-H. Kuo, "Recipient Maximization Routing Scheme for Multicast over IEEE 802.16j Relay Networks," *IEEE International Conference on Communications* (ICC), pp.1-6, June 2009.

[7] I. Guvenc, U.C. Kozat, M.-R. Jeong, F. Watanabe and C.-C. Chong, "Reliable Multicast and Broadcast Services in Relay-Based Emergency Communications," *IEEE Wireless Communications*, vol.15, no.3, pp.40-47, June 2008.

[8] Y. Wang, G. Feng, and Y. Zhang, "Cost-efficient Deployment of Relays for LTE-Advanced Cellular Networks," in *Proceedings of IEEE International Conference on Communications* (ICC), pp. 1-5, Kyoto, Japan, June 2011.

[9] T. Girivi, "Joint Power, Subcarrier and Subframe Allocation in Multihop Relay Networks," *International Journal of Communication Systems*, vol.22, pp. 835-855, July 2009.

[10] N. Krishnan, R. D. Yates, N. B. Mandayam, and J. S. Panchal, "Bandwidth Sharing for Relaying in Cellular Systems," *IEEE Transactions on Wireless Communications*, vol.11, pp. 117-129, January 2012.

[11] J. Poston and W. Horne, "Discontiguous OFDM Considerations for Dynamic Spectrum Access in Idle TV Channels," in *Proceedings of IEEE Dynamic Spectrum Access Networks* (DYSPAN), pp. 607-610, Baltimore, MD, USA, November 2005.

[12] J.-C. Jia, J. Zhang and Q. Zhang, "Cooperative Relay for Cognitive Radio Networks," in *Proceedings of IEEE International Conference on Computer and Communications* (INFOCOM), pp. 2304-2312, Rio de Janeiro, Brazil, April 2009.