

Shared Relay Assignment (SRA) for Many-to-One Traffic in Cooperative Networks

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Abstract—Relay assignment significantly affects the performance of the cooperative communication, which is an emerging technology for the future mobile system. Previous studies in this area have mostly focused on assigning a dedicated relay to each source-destination pair for one-to-one (121) traffic. However, many-to-one (M21) traffic, which is also common in many situations (for example, several users associate with one access point in a wireless access network such as a WLAN), hasn't been well studied. This paper addresses the shared relay assignment (SRA) problem for M21 traffic. We formulate two new optimization problems: one is to *maximize the minimum throughput* among all the sources (hereafter called M21-SRA-MMT), and the other is to *maximize the total throughput* over all the sources while maintaining some degree of fairness (hereafter called M21-SRA-MTT). As the optimal solutions to the two problems are hard to find, we propose two approximation algorithms whose performance factors are 5.828 and 3, respectively, based on the rounding mechanism. Extensive simulation results show that our algorithms for M21-SRA-MMT can significantly improve the minimum throughput compared with existing algorithms, while our algorithm for M21-SRA-MTT can achieve the close-to-optimal performance.

Index Terms—Cooperative Communication, Shared Relay Assignment, Max-Min Throughput, Max-Total Throughput, Fairness.

1 INTRODUCTION

RECENT studies on cooperative communication (CC) [1]–[7] show its potential to cope with lossy wireless channels using spatial diversity. Moreover, spatial diversity can be achieved by exploiting the antennas on other devices, called relay nodes, in the network under the cooperative communication scheme. Thus, the cooperative communication becomes one of the emerging technologies for the next-generation mobile systems [8]–[10]. In scenarios where a source (e.g., a mobile phone) and a destination (e.g., the base station) communicate with each other in two hops or less, there are two main cooperative modes, namely amplify-and-forward (AF) and decode-and-forward (DF), respectively [3].

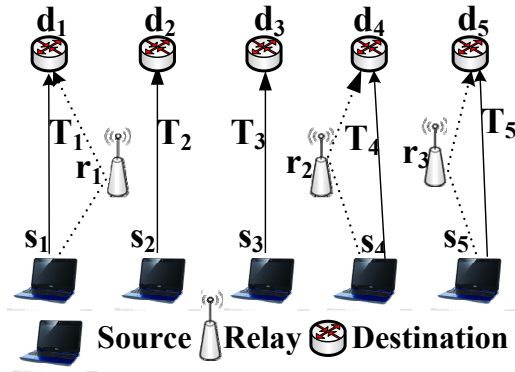
The previous studies in [11]–[13] have concluded that the choice of relay nodes played a significant role in achieving transmission performance (e.g., capacity and throughput) under both cooperative modes. Choosing an appropriate assignment of relay nodes will provide a higher capacity for the source-destination (or s - d for short) pair than using direct transmission (DT). In particular, Zhao et al. [11] showed that it was sufficient to select the best relay node for a given s - d

pair to achieve the full diversity, and thus there was no need to have multiple relay nodes for the cooperative transmission of a s - d pair (which in fact would also need more complex network management and precise time synchronization among several relay nodes [1]). Accordingly, the relay assignment problem has been widely studied in recent years, mostly under the de facto assumption that at most one relay node will be used for a given s - d pair.

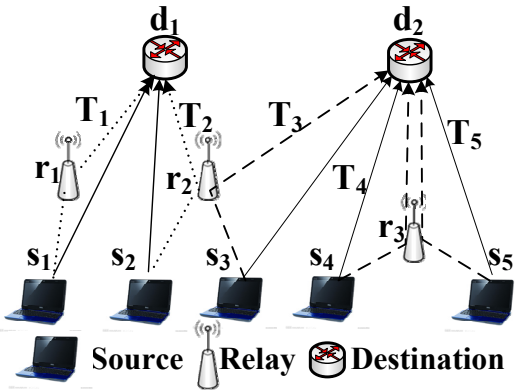
In the mobile access network such as a WLAN, each user expects to obtain a maximum bandwidth or throughput so as to improve the QoS of different applications. As the cooperative communication can improve the spatial diversity in the wireless network, this will help to increase the transmission throughput for each user in the WLAN. Now, we consider a common situation under the WLAN scene. For example, in a managed WLAN, there has a few access points (APs), and also puts in some relay nodes. Several terminal users (e.g., laptops or WIFI-compatible devices) will connect with one same AP using the previous association control method [14] for Internet access, which belongs to many-to-one (M21) traffic. In this application, the system will run a centralized management algorithm to select/assign relays to the users so as to reach the different QoS performances, such as max-min throughput or max-total throughput, etc. Therefore, it is of great importance to implement the relay assignment for M21 traffic in cooperative wireless networks.

Existing research in CC has focused only on one-to-one (121) traffic, but not on many-to-one traffic. As an example, the authors in [1] [15] studied relay assignment where multiple independent s - d pairs competed for a set of relay nodes. In particular, they assumed that a relay node could be used by only one s - d pair - a policy which we would refer to as *dedicated relay assignment* or *DRA*. As shown in Fig.1(a),

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(a) DRA in One-to-One (121)



(b) SRA in Many-to-One (M21)

Fig. 1: Different Relay Assignments and Traffic Patterns

the relay node r_1 is only used by the source node s_1 , and r_2 is by s_4 . Under such an assumption, they proposed an optimal algorithm, called ORA, based on linear marking to maximize the minimum throughput (MMT) among all the sources in a network. We will refer to this problem as 121-DRA-MMT. As another example, Yang et al. [16] studied the problem of relay assignment for multiple s - d pairs to maximize the total throughput (MTT) over all the sources in a network. Although their work considered the possibility of sharing a relay node by multiple s - d pairs, they proved that each relay node should be assigned to only one s - d pair so as to achieve the MTT objective. In other words, *the DRA policy should also be enforced for MTT*. Additionally, they used maximum weighted bipartite matching to solve the problem in polynomial time. We will refer to this problem as 121-DRA-MTT.

In this paper, we study several new relay assignment problems for M21 traffic as shown in Fig.1(b), under the same default assumption of at most one relay node per s - d transmission pair. These new problems also use different relay assignment policies including *shared relay assignment (SRA)* with which, the same relay can (but does not have to) be used by more than one source. For example, source nodes s_2 and s_3 will share the relay node r_2 to cooperatively communicate with the destination nodes d_1 and d_2 , respectively. More specifically, we focus on two new problems: M21-SRA-MMT and M21-SRA-MTT.

Note that, firstly, in several practical wireless applications,

multiple source nodes may associate with one common destination node (which serves as a sink or access point), so it is meaningful to study relay assignment for M21 traffic. Secondly, the case with M21 traffic and the SRA policy is more general than that with 121 traffic and DRA, since the latter can be considered as a special case of the former where there is (at most) one relay per source and only one source per destination. In fact, our solutions described in this work for the former cases will be applicable to the cases with strictly M21 traffic, strictly 121 traffic or a mixed M21 and 121 traffic. Thirdly, considering M21 traffic and the SRA policy leads to open problems and new challenges yet to be addressed in order to take the full advantage of SRA. For example, in 121-DRA-MTT [16], the relay assignment problem can be transformed into the bipartite matching problem where the bipartite graph consists of the set of sources on one side and the set of relay nodes on the other side. However, bipartite matching is no longer applicable when two or more sources actually share a relay node. In particular, when multiple sources share the same relay node, one has to consider the constraint that each of these sources will use the shared relay node for only a fraction of the time.

Moreover, when multiple sources send to the same destination as in M21 traffic, we need to consider the constraint that each of these sources can send to the common destination for only a fraction of the time. In fact, it is *due to the destination access time constraint* that makes our problems M21-SRA-MMT and M21-SRA-MTT different from the previous ones.

Due to the destination access time constraint in M21 traffic, when pursuing the MMT objective as in [1] [15], allowing SRA would provide more flexibility in choosing a better relay for each source. This is because no sources (sharing a destination with some other sources) can transmit 100% of the time anyway, and hence dedicating a relay node to such a source as in the early works [1] [15] could be wasteful. In other words, SRA is expected to be able to achieve a higher minimum throughput, which also implies better max-min fairness. Nevertheless, new and efficient relay assignment algorithms are needed to solve the M21-SRA-MMT problem.

More specifically, due to the *destination access time constraint* imposed on all the sources sending to the same destination, in order to pursue the MTT objective as in [16], one must consider the "fairness" issue. A reasonable fairness requirement is that the common destination will devote an equal amount of access time to each of its k sources. In other words, each source will be able to transmit $\frac{1}{k}$ of the time to the common destination (using the CC or DT). Without any fairness requirement such as this, only one of the k sources needs to be chosen per destination, such that the source can produce the maximum throughput at the common destination (with or without a relay), thus degenerating the solution to that of 121-DRA-MTT in [16], and resulting in starvation of all other sources sending to their common destination. However, with the fair (i.e., equal) destination access time requirement in place, it is now meaningful to study the SRA scheme, in conjunction with M21 traffic and the MTT objective. This clearly calls for new and efficient solutions to M21-SRA-MTT.

The main contributions of this work include:

- 1) We formulate two new optimization problems, namely M21-SRA-MMT and M21-SRA-MTT, respectively. To the best of our knowledge, this is the first time that SRA is considered in the context of M21 traffic.
- 2) For M21-SRA-MMT, we propose an approximation algorithm (RA-MM), which mainly uses the rounding mechanism to obtain the max-min throughput. This paper proves that the RA-MM algorithm can reach the approximation performance of $3 + 2\sqrt{2}$ or about 5.828.
- 3) We also present a variation of RA-MM to improve the average-case performance. The improved version, called IRA-MM, still guarantees the worst-case performance (i.e., the approximate factor of 5.828).
- 4) For M21-SRA-MTT under the equal destination access time constraint, a 3-approximation algorithm called RA-MT is proposed.
- 5) Our simulation results show a high efficiency of the proposed algorithms. For example, our IRA-MM increases the minimum throughputs by about 66% when averaged over many cases, and up to 116% in some cases, compared with ORA [1], while the RA-MT algorithm can achieve close-to-optimal result for M21-SRA-MTT.

The rest of the paper is organized as follows. Section 2 gives the cooperative communication model, and the two problem definitions. Section 3 proposes two approximation algorithms for the M21-SRA-MMT problem. Section 4 addresses the M21-SRA-MTT problem. Simulation results are presented in Section 5. Related works are discussed in Section 6. We conclude the paper in Section 7.

2 PRELIMINARIES

This section first reviews the mathematical expressions of transmission capacities under the CC and DT schemes. We then provide the problem definitions for M21-SRA-MMT and M21-SRA-MTT, respectively.

2.1 Cooperative Communication Model

For ease of expression, the variable SNR_{sd} is used to denote the signal-noise-ratio from node s to node d . There are two main forwarding modes for the cooperative communication, AF and DF . Under the AF mode, a cooperative relay node just amplifies the received signal from the source node and directly forwards it to the destination node without decoding the message. It has been shown in [3] that the capacity from node s to node d with a relay node r is:

$$C_{AF}(s, r, d) = W \cdot I_{AF}(SNR_{sd}, SNR_{sr}, SNR_{rd}) \quad (1)$$

where I_{AF} is the transmission gain under the AF mode, with $I_{AF} = \frac{1}{2} \log_2(1 + SNR_{sd} + \frac{SNR_{sr} \cdot SNR_{rd}}{SNR_{sr} + SNR_{rd} + 1})$, and W is the bandwidth. Under the DF mode, the relay node decodes the received signal, and re-encodes it before forwarding to the destination node. The capacity for the DF mode is given as follows [3]:

$$C_{DF}(s, r, d) = W \cdot I_{DF}(SNR_{sd}, SNR_{sr}, SNR_{rd}) \quad (2)$$

where I_{DF} is the transmission gain under the DF scheme, and $I_{DF} = \frac{1}{2} \min\{\log_2(1 + SNR_{sr}), \log_2(1 + SNR_{sd} + SNR_{rd})\}$.

When the cooperative communication is not used, sender node s transmits directly to receiver node d in both time slots.

This is just the traditional communication scheme. Thus, the maximum rate achievable from node s to node d is:

$$C_D(s, d) = W \cdot \log_2(1 + SNR_{sd}) \quad (3)$$

From the above theoretical results, although AF and DF are different cooperative modes, the expressions of their capacities are both the function of variables SNR_{sd} , SNR_{sr} and SNR_{rd} [1]. Then, the relay assignment algorithm designed for the AF mode can be easily extended to DF , and vice versa. Thus, the relay node assignment algorithms developed in this paper can be applied to both the AF and DF modes.

2.2 Problem Definition

We consider three disjoint node sets in a network. One is the source node set, $S = \{s_1, s_2, \dots, s_{n_s}\}$, with $n_s = |S|$; the second is the destination node set, $D = \{d_1, d_2, \dots, d_{n_d}\}$, with $n_d = |D|$; Another is the relay node set, $R = \{r_1, r_2, \dots, r_{n_r}\}$, with $n_r = |R|$. In many practical application scenarios, such as a large network with multiple cells or clusters, multiple source nodes s_i (e.g., clients) may associate with one common destination node $d_{i'}$ (e.g., the access point or sink node), resulting in what we call M21 traffic. We assume that each source node s_i has established a connection with a destination node $d_{i'}$ as in e.g., [14], etc, and will focus on SRA in such M21 traffic. For simplicity, the transmission from source s_i to destination $d_{i'}$ is denoted by $\Gamma_i = (s_i, d_{i'})$, with $1 \leq i \leq n_s$ and $1 \leq i' \leq n_d$. In our many-to-one scheme, since multiple sources will not communicate with the same destination at exactly the same time, these sources and the associated destination can be assigned only one channel for cooperative communications. Thus, the number of required orthogonal channels is mainly determined by the deployment of destination nodes in a wireless network. Under many practical scenarios, the number of destination nodes (e.g., sinks or APs) is usually less than that of source nodes (e.g., terminals). Moreover, the destination nodes will not densely deployed. Hence, there should be enough such orthogonal channels available given that the same assumption holds in the multiple 121 schemes (i.e., s - d pairs). In order to avoid the transmission interference, we assume that orthogonal channels are available in the network (e.g., using OFDMA), which is also used for the cooperative communication [1] [15].

Zhao et al. [11] had shown that for a single-hop transmission, the diversity gain obtained by exploiting multiple relay nodes was not higher than that by selecting the best relay. Accordingly, it is reasonable to assume that at most one relay node will participate into cooperative communication for a certain transmission pair Γ_i . For uniform description, we add a virtual relay r_0 , and denote $R^+ = R \cup \{r_0\}$. When we say that source node s_i uses the direct transmission, it is equivalent to say that this source node selects the virtual relay r_0 .

As multiple transmission pairs may share a relay node and destination node, each source node s_i will be allocated a transmission time t_i , such that the time constraint on each relay node as well as each destination node will be satisfied. Once the relay assignment and transmission time are determined, each source node s_i can achieve a certain throughput B_i . Our objectives are to maximize the minimum throughput and

the total throughput, respectively. We give the formal problem definition as follows.

Problem Definition: Consider a network where each source node $s_i \in S$ has associated with a destination node $d_{i'} \in D$, and multiple source nodes may associate with one common destination node. We assume that each source node will select at most one relay node for cooperative transmission, and such a relay node may be shared by multiple source nodes, which may or may not have the same destination (see Fig.1(b) for illustration). Moreover, each source node s_i will be allocated a transmission time t_i , so that the total transmission times of each relay node and each destination node do not exceed one unit. Then, each source node s_i will obtain the achievable throughput B_i . Two problems are defined with different optimization objectives. The first problem, called M21-SRA-MMT, aims to maximize the minimum throughput of all the source nodes, which is expressed by:

$$\text{Max}\{\min B_i, s_i \in S\} \quad (4)$$

The other problem, called M21-SRA-MTT, will optimize the max-total throughput in the network. That is,

$$\text{Max} \sum_{s_i \in S} B_i \quad (5)$$

Note that, if the transmission pair and relay node are regarded as the job and processor, M21-SRA-MMT is similar to the unrelated processor scheduling (UPS) problem [17]. However, the main difference is that there is time constraint on the transmission pairs (i.e., destination nodes) in the M21-SRA-MMT problem while no exit constraint is considered on the job in the UPS problem. Though time allocation [18] has been studied in cooperative networks, time allocation among all the sources sharing a relay and/or destination node also imposes new challenges that have not been addressed by any existing solution.

3 ALGORITHM FOR M21-SRA-MMT

This section mainly presents two relay assignment algorithms to achieve the max-min throughput. We also analyze the approximation performance of the proposed algorithm.

3.1 Problem Formulation

This section first formulates the M21-SRA-MMT problem as a mixed integer program. We define a binary variable x_{ij} , which is equal to 1 if relay node $r_j \in R$ is assigned to transmission pair Γ_i ; and 0 otherwise. That is,

$$x_{ij} = 1 \text{ or } 0, \forall s_i \in S, \forall r_j \in R \quad (6)$$

Since each transmission pair (or source node) will use one relay node at most for cooperative communication, we have,

$$\sum_{r_j \in R} x_{ij} \leq 1, \forall s_i \in S \quad (7)$$

We also use $I_{ik} \in \{0, 1\}$ to denote the s - d association. That is, if the source s_i is associated with the destination d_k , I_{ik} is 1. Otherwise, I_{ik} is 0. Assume that each source s_i will be allocated a fractional transmission time $t_i \leq 1$. For each destination node d_k , it may receive from (or be accessed by) several source nodes, and its total access time should not exceed one unit. That is,

$$\sum_{s_i \in S} I_{ik} t_i \leq 1, \forall d_k \in D \quad (8)$$

After relay assignment, the total transmission time of each relay node should not exceed one unit time either. So,

$$\sum_{s_i \in S} t_i x_{ij} \leq 1, \forall r_j \in R \quad (9)$$

Next, we use C_{ij} to denote the capacity when source node s_i communicates with destination node $d_{i'}$ using relay node r_j . That is, $C_{ij} = C_{XF}(s_i, r_j, d_{i'})$ according to equations (1) or (2), where XF denotes AF or DF . Note that $C_{i,0}$ denotes the capacity of transmission pair Γ_i under the direct transmission scheme. That is, $C_{i,0} = C_D(s_i, d_{i'})$ by equation (3). Now, we give the throughput expression of source node s_i followed with two cases. On the one hand, source node s_i selects one relay node r_j for the cooperative communication. That is, $x_{ij} = 1$. On the other hand, source node s_i uses the direct transmission scheme. So, $\sum_{r_j \in R} x_{ij} = 0$. As a result, the throughput achieved by each transmission pair Γ_i is:

$$B_i = \sum_{r_j \in R} C_{ij} t_i x_{ij} + C_{i,0} t_i (1 - \sum_{r_j \in R} x_{ij}) \quad (10)$$

For the M21-SRA-MMT problem, we aim to maximize the minimum throughput of all source nodes. That is,

$$\text{Max}\{\min B_i, s_i \in S\} \quad (11)$$

In this way, the optimization formulation of the M21-SRA-MMT problem is in the form of a mixed integer program. The optimal solution to this problem is hard to find according to the following lemma.

Lemma 1: The M21-SRA-MMT problem is NP-hard.

The proof of lemma 1 has been relegated to the appendix A.

3.2 Algorithm Description

Due to NP-hardness of the M21-SRA-MMT problem, we describe a rounding-based shared relay assignment algorithm, called RA-MM, to improve the minimum throughput of all the transmission pairs in the network. This algorithm consists of three steps, initialization, relay assignment and time allocation, respectively.

In the first step, the algorithm will construct a linear program $LP_1(t_{ij})$ as a relaxation of M21-SRA-MMT. More specifically, the M21-SRA-MMT problem assumes that each source node only selects one relay node at most for cooperative communication. By relaxing this assumption, we can formulate the following linear program $LP_1(t_{ij})$, which is solvable in polynomial time.

$$\text{Max } B_m$$

$$\text{s.t. } B_i = \sum_{r_j \in R^+} C_{ij} t_{ij} \geq B_m, \forall s_i \in S$$

$$\sum_{s_i \in S} t_{ij} \leq 1, \forall r_j \in R \quad (12)$$

$$\sum_{s_i \in S} \sum_{r_j \in R^+} I_{ik} t_{ij} \leq 1, \forall d_k \in D$$

$$t_{ij} \in [0, 1], \forall s_i \in S, \forall r_j \in R^+$$

Note that, t_{ij} is the transmission time of source node s_i using relay node r_j for cooperative communication. The second constraint says that the total transmission time fraction of each relay node r_j can not be more than one unit. The third constraint means that the total access time fraction of each destination node d_k should not exceed one unit. We obtain the optimal solution of $LP_1(t_{ij})$, denoted by $\{t_{ij}^*\}$, in which t_{ij}^* denotes the transmission time of source node s_i using the relay node r_j for CC or DT (note that in this

relaxed version, we allow a source to use more than one relay node). Under this solution, for each source node s_i , its total transmission time is denoted by $T_i = \sum_{r_j \in R^+} \widetilde{t}_{ij} \leq 1$ according to the time constraint on each destination node, and the throughput is $B_i = \sum_{r_j \in R^+} C_{ij} \widetilde{t}_{ij}$. Moreover, the minimum throughput of all source nodes is denoted by B_o . Since $LP_1(t_{ij})$ is the formulation of the relaxed M21-SRA-MMT problem, in which each source node may use several relay nodes for cooperative transmission, B_o is an upper-bound on the minimum throughput performance of M21-SRA-MMT.

In the second step, the algorithm will assign at most one relay for each source node using the rounding mechanism. We select a parameter $\alpha = \sqrt{2} + 1$, which will lead to the smallest approximation ratio, and be explained later. This step first defines a variable t'_{ij} for each source node s_i and relay node r_j . Given the variables B_i and T_i for each source s_i , if $B_i > \alpha C_{ij} T_i$, $t'_{ij} = 0$. Otherwise, $t'_{ij} = \widetilde{t}_{ij}$. Based on the solution $\{t'_{ij}\}$, the throughput of each source s_i becomes $B'_i = \sum_{r_j \in R^+} C_{ij} t'_{ij}$. Next, we define another variable $\widetilde{x}_{ij} = \frac{C_{ij} t'_{ij}}{B'_i}$, which denotes the percentage of throughput B'_i contributed by a relay r_j for a given source s_i . Accordingly, $\sum_{r_j \in R^+} \widetilde{x}_{ij} = \sum_{r_j \in R^+} \frac{C_{ij} t'_{ij}}{B'_i} = 1$. For each relay r_j , $\sum_{s_i \in S} t'_{ij} \leq \sum_{s_i \in S} \widetilde{t}_{ij} \leq 1$. It follows that $\sum_{s_i \in S} \frac{B'_i \widetilde{x}_{ij}}{C_{ij}} \leq 1$ after substituting t'_{ij} by $\frac{B'_i \widetilde{x}_{ij}}{C_{ij}}$. Thus, we know that $\{\widetilde{x}_{ij}\}$ is a solution for the linear program $LP_2(x_{ij})$ as follows:

$$\begin{aligned} S.t. \quad & \sum_{r_j \in R^+} x_{ij} = 1, \forall s_i \in S \\ & \sum_{s_i \in S} \frac{B'_i}{C_{ij}} x_{ij} \leq 1, \forall r_j \in R \\ & x_{ij} \in [0, 1], \forall s_i \in S, \forall r_j \in R^+ \end{aligned} \quad (13)$$

Then, an integer solution $\{\widehat{x}_{ij}\}$ can be obtained from $\{\widetilde{x}_{ij}\}$ by the rounding procedure [19]. Under the solution $\{\widehat{x}_{ij}\}$, if \widehat{x}_{ij} is 1, this means that the relay node r_j is assigned to source node s_i for cooperative communication. Otherwise, source s_i will use the direct transmission.

In the third step, we will determine the transmission time for each source node s_i . Under the solution $\{\widehat{x}_{ij}\}$, the algorithm will check all the relay nodes as follows. For each relay $r_j \in R$, the source nodes that share this relay for cooperative transmission are considered to be in set S_{r_j} . We compute its total time as $\delta_j = \sum_{s_i \in S_{r_j}} T_i$. If $\delta_j \leq 1$, $t_i = T_i$. Otherwise, let $t'_i = \frac{B'_i}{(1+\alpha)C_{ij}}$ and $\delta_j^0 = \sum_{s_i \in S_{r_j}} t'_i$. We set the transmission time of each source node $s_i \in S_{r_j}$ as $t_i = \min\{T_i, \frac{t'_i}{\delta_j^0}\}$. A more detailed description of RA-MM is given in Algorithm 1, where $R(s_i)$ denotes the assigned relay for the source node s_i .

3.3 Approximation Performance Analysis

Before analyzing the worst-case approximation performance of the RA-MM algorithm, we first show that:

Lemma 2: for each source node s_i , $B'_i \geq (1 - \frac{1}{\alpha})B_o$.

Algorithm 1 RA-MM:Relay Assignment Algorithm for Max-Min Throughput

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1: Step 1: Initialization (Allow multiple relays per source)
2: Construct a linear program  $LP_1(t_{ij})$ 
3: Obtain the optimal solution  $\{t_{ij}\}$ , and the result  $B_o$ 
4: for each source node  $s_i$  do
5:    $T_i = \sum_{r_j \in R^+} \widetilde{t}_{ij}$ 
6:    $B_i = \sum_{r_j \in R^+} C_{ij} \widetilde{t}_{ij}$ 
7: end for
8: Step 2: Relay Assignment (Choose one relay per source)
9: for each  $s_i \in S$  and each  $r_j \in R^+$  do
10:   Define the variables  $t'_{ij}$ ,  $B'_i$  and  $\widetilde{x}_{ij}$ 
11: end for
12:  $\{\widehat{x}_{ij}\}$  is obtained by rounding on the solution  $\{\widetilde{x}_{ij}\}$ 
13: for each  $\widehat{x}_{ij} = 1$  do
14:    $R(s_i) = r_j$  //Assign relay  $r_j$  to source node  $s_i$ 
15: end for
16: Step 3: Time Allocation (Finalize transmission time)
17: for each relay node  $r_j \in R$ ,
18:    $\delta_j = \sum_{s_i \in S_{r_j}} T_i$  and  $\delta_j^0 = \sum_{s_i \in S_{r_j}} \frac{B'_i}{(1+\alpha)C_{ij}}$  do
19:   for each source node  $s_i \in S_{r_j}$  do
20:     if  $\delta_j \leq 1$  then
21:        $t_i = T_i$ 
22:     else
23:        $t'_i = \frac{B'_i}{(1+\alpha)C_{ij}}$ 
24:        $t_i = \min\{T_i, \frac{t'_i}{\delta_j^0}\}$ 
25:     end if
26:   end for
27: end for

```

Proof: By the definition of variable B'_i in the second step of the RA-MM algorithm, for each source s_i , it follows that:

$$\begin{aligned} B_i &= \sum_{r_j \in R^+} C_{ij} \widetilde{t}_{ij} = \sum_{t'_{ij} > 0} C_{ij} \widetilde{t}_{ij} + \sum_{t'_{ij} = 0} C_{ij} \widetilde{t}_{ij} \\ &= B'_i + \sum_{t'_{ij} = 0} C_{ij} \widetilde{t}_{ij} \leq B'_i + \frac{B_i}{\alpha T_i} \sum_{r_j \in R^+} \widetilde{t}_{ij} \\ &= B'_i + \frac{B_i}{\alpha T_i} T_i \leq B'_i + \frac{B_i}{\alpha} \end{aligned} \quad (14)$$

This indicates that $B'_i \geq (1 - \frac{1}{\alpha})B_i \geq (1 - \frac{1}{\alpha})B_o$. \square

Now, we analyze the approximation performance for the RA-MM algorithm.

Theorem 3: the RA-MM algorithm can reach the approximate factor of $3 + 2\sqrt{2}$ for the M21-SRA-MMT problem.

Proof: By the definition of variables B'_i and \widehat{x}_{ij} , $\{\widehat{x}_{ij}\}$ is a solution of the linear program $LP_2(x_{ij})$ as in equation (13). In the second constraint of $LP_2(x_{ij})$,

$$\frac{B'_i}{C_{ij}} \leq \frac{B_i}{C_{ij}} \leq \alpha T_i \leq \alpha \quad (15)$$

Then, a fractional solution $\{\widehat{x}_{ij}\}$ can be rounded to a 0-1 solution $\{\widehat{x}_{ij}\}$ for the integer linear program $IP_3(x_{ij})$ as:

$$\begin{aligned} S.t. \quad & \sum_{r_j \in R^+} x_{ij} = 1, \forall s_i \in S \\ & \sum_{s_i \in S} \frac{B'_i}{C_{ij}} x_{ij} \leq 1 + \alpha, \forall r_j \in R \\ & x_{ij} \in \{0, 1\}, \forall s_i \in S, \forall r_j \in R^+ \end{aligned} \quad (16)$$

where \widehat{x}_{ij} is 1, if source node s_i will select relay node r_j for cooperative transmission. Otherwise, \widehat{x}_{ij} is 0. In the third step, each source node s_i will be allocated a transmission time t_i . Let $t'_i = \frac{B'_i}{(1+\alpha)C_{ij}}$. We consider the following two cases:

- 1) $\delta_j \leq 1.t_i = T_i$, and $t'_i = \frac{B'_i}{(1+\alpha)C_{ij}} \leq \frac{\alpha T_i}{1+\alpha} < T_i$. So, $t'_i < t_i$.
- 2) $\delta_j > 1$. Then, $t_i = \min\{T_i, \frac{t'_i}{\delta_j^0}\}$. Since $\delta_j^0 = \sum_{s_i \in S_{r_j}} t'_i$
 $= \sum_{s_i \in S_{r_j}} \frac{B'_i}{(1+\alpha)C_{ij}} \leq \frac{1+\alpha}{1+\alpha} = 1$, $t'_i \leq \min\{T_i, \frac{t'_i}{\delta_j^0}\} = t_i$.

Combining the above two cases, we know that $t'_i \leq t_i$. The final throughput of each source s_i , denoted by \overline{B}_i , is:

$$\begin{aligned} \overline{B}_i &= \sum_{r_j \in R^+} C_{ij} \widehat{x}_{ij} t_i \geq \sum_{r_j \in R^+} C_{ij} \widehat{x}_{ij} t'_i \\ &= \sum_{r_j \in R^+} C_{ij} \widehat{x}_{ij} \frac{B'_i}{(1+\alpha)C_{ij}} \\ &= \frac{B'_i}{1+\alpha} \\ &\geq \frac{1}{1+\alpha} \left(1 - \frac{1}{\alpha}\right) B_o \end{aligned} \quad (17)$$

We find the best parameter α to achieve a throughput as close to the optimum as possible, that is, to make $\frac{1}{1+\alpha} \left(1 - \frac{1}{\alpha}\right)$ as large as possible. This results in $\alpha = \sqrt{2} + 1$. So

$$\overline{B}_i \geq \frac{1}{1 + \sqrt{2} + 1} \left(1 - \frac{1}{\sqrt{2} + 1}\right) B_o = \frac{1}{3 + 2\sqrt{2}} B_o \quad (18)$$

As a result, we can conclude that the RA-MM algorithm can reach the approximation performance of $3 + 2\sqrt{2}$ for the M21-SRA-MMT problem. The theorem is proved. \square

3.4 An Improved RA-MM Algorithm (IRA-MM)

In the RA-MM algorithm, the third (i.e., time allocation) step determines the transmission time for all the source nodes in a proportional manner. Though this method can provide the approximate performance guarantee (in the worst case), it does not care for the different capacities among these transmission pairs. Thus, this section designs an improved algorithm, called IRA-MM, so as to enhance its minimum throughput of all the sources compared with that by the RA-MM algorithm.

After the second step of the RA-MM algorithm, each source node s_i has determined the relay assignment. For simplicity, a set of source nodes that share the relay $r_j \in R$ is denoted by $S_{r_j} = \{s_1, \dots, s_k\}$, with $|S_{r_j}| = k$. The basic idea of IRA-MM is to let selected sources use the relay without committing the relay to all the k sources so as to reach the almost same throughput among these sources. More specifically, we compute its total transmission time as $\delta_j = \sum_{s_i \in S_{r_j}} T_i$. If $\delta_j \leq 1$, we also set $t_i = T_i$ for each source $s_i \in S_{r_j}$. In this case, the minimum throughput of all sources in S_{r_j} will not be improved. Otherwise (i.e., if $\delta_j > 1$), the algorithm ranks all source nodes in a decreasing order of the throughput under the direct transmission (denoted by $C_{i,0}T_i$ for each source s_i). Without loss of generality, assume that $C_{1,0}T_1 \geq C_{2,0}T_2 \geq \dots \geq C_{k,0}T_k$. We compute the minimum throughput mt_q when the first $q \geq 0$ nodes use direct transmission, and the rest of the $k - q$ sources, denoted by $S_{r_j}^q = \{s_{q+1}, \dots, s_k\}$, will use the relay to boost their throughputs (note that the sum of the transmission time from these $k - q$ sources should be

less than 1). Among the first q sources, due to the fact that the sources are already sorted in the order of a decreasing throughput, the minimum throughput is $C_{q,0}T_q$ from source s_q . Among the rest of $k - q$ sources, let $t'_i = \frac{B'_i}{(1+\alpha)C_{ij}}$, and $\delta_j^q = \sum_{s_i \in S_{r_j}^q} t'_i (< 1)$. We set $t''_i = \min\{T_i, \frac{t'_i}{\delta_j^q}\}$ for each source s_i . The minimum throughput of the sources in $S_{r_j}^q$ is $b_q = \min\{C_{q,0}T_q, b_q\}$. So, mt_q can be expressed by:

$$mt_q = \min\{C_{q,0}T_q, b_q\}, \quad 1 \leq q < k \quad (19)$$

Finally, the algorithm determines the optimal q value, denoted by q_0 , so that $mt_{q_0} = \max\{mt_q, 1 \leq q < k\}$. The outcome of the algorithm is thus as follows: the first q_0 sources use the DT, and the rest $k - q_0$ source nodes use the cooperative communication with the help of relay node r_j . The IRA-MM algorithm is formally described in Algorithm 2, where $R(s_i)$ denotes the assigned relay for the source node s_i .

Algorithm 2 IRA-MM Algorithm

- 1: **Step 1: Initialization (Allow multiple relays per source)**
 - 2: Same as that of the RA-MM algorithm.
 - 3: **Step 2: Relay Assignment (Choose one relay per source)**
 - 4: Same as that of the RA-MM algorithm.
 - 5: **Step 3: Time Allocation (Finalize transmission time)**
 - 6: **for** each relay node r_j **do**
 - 7: Let $S_{r_j} = \{s_1, \dots, s_k\}$, with $C_{1,0}T_1 \geq \dots \geq C_{k,0}T_k$;
 - 8: $\delta_j = \sum_{s_i \in S_{r_j}} T_i$
 - 9: **if** $\delta_j \leq 1$ **then**
 - 10: $t_i = T_i$ //this is same as that in RA-MM
 - 11: **else**
 - 12: **for** $q = 1$ to $k - 1$ **do**
 - 13: $\delta_j^q = \sum_{s_i \in S_{r_j}^q} t'_i = \sum_{s_i \in S_{r_j}^q} \frac{B'_i}{(1+\alpha)C_{ij}}$
 - 14: $mt_q = \min\{C_{q,0}T_q, b_q\}$
 - 15: **end for**
 - 16: **end if**
 - 17: Select a value q_0 , such that $mt_{q_0} = \max\{mt_q, 1 \leq q < k\}$
 - 18: **for** $i = 1$ to q_0 **do**
 - 19: $R(s_i) = r_0$ //source s_i will use the DT
 - 20: $t_i = T_i$
 - 21: **end for**
 - 22: **for** $i = q_0 + 1$ to k **do**
 - 23: $R(s_i) = r_j$ //source s_i selects the relay r_j for CC
 - 24: $t_i = \min\{T_i, \frac{t'_i}{\delta_j^q}\}$
 - 25: **end for**
 - 26: **end for**
-

According to the above description, the minimum throughput should be no less than that obtained by RA-MM after the second step. Thus, the IRA-MM algorithm improves the MMT performance upon RA-MM. Therefore,

Theorem 4: The IRA-MM algorithm can reach the approximate factor of $3 + 2\sqrt{2}$ for the M21-SRA-MMT problem.

4 ALGORITHM FOR M21-SRA-MTT

The previous section tries to maximize the minimum throughput of all the source nodes. However, in some situations,

the total network throughput is much critical for wireless systems. Thus, this section mainly studies the shared relay assignment problem for M21 traffic that can maximize the total throughput, termed M21-SRA-MTT.

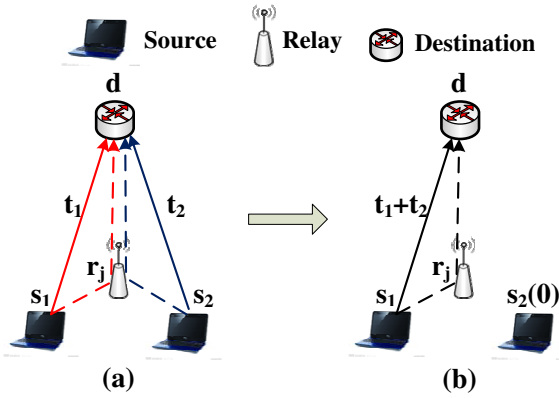


Fig. 2: Illustration of Anycast with Software Defined Networks

4.1 Motivation and Problem Definition

Let us now consider the following case, where two sources s_1 and s_2 communicate with the same destination node, and are allocated with transmission time t_1 and t_2 , respectively. Assume that they share the same relay node r_j , as shown in Fig.2(a). The total throughput of two sources is $C_{1,j}t_1 + C_{2,j}t_2$. Without loss of generality, assume that $C_{1,j} > C_{2,j}$. If we change the transmission time allocation to be $t'_1 = t_1 + t_2$ and $t'_2 = 0$, respectively, then, the total throughput will be $C_{1,j}t'_1 = C_{1,j}(t_1 + t_2) > C_{1,j}t_1 + C_{2,j}t_2$, illustrated in Fig.2. Though the total throughput will be improved, source node s_2 is not able to obtain any opportunity for transmission at all. This example shows that in general, some source nodes may become starved in the network when one blindly pursues the maximum total throughput, which is not only undesirable but also may degenerate the problem into dedicated relay assignment and 121 traffic. Thus, this section mainly studies the max-total throughput problem under a certain fairness constraint among all the source nodes. In particular, we require that for a given destination d , all its sources will have an *equal access* time, so that the starvation will be avoided. That is, the common destination will devote an equal amount of access time to each of its k associated sources. In other words, each source s_i will be allocated a transmission time $t_i = \frac{1}{k}$ to communicate with the common destination d (using the DT or CC schemes). We also take the same assumption that each source node will select one relay node at most for cooperative communication as in the definition of M21-SRA-MMT. After relay assignment, each source node s_i will obtain the achievable throughput B_i . The objective of the M21-SRA-MTT problem is to maximize the total throughput of all the sources in the network. That is, $Max \sum_{s_i \in S} B_i$.

Now, we give the formulation for the M21-SRA-MTT problem below. In the formulation, the Boolean variable x_{ij} denotes whether the source node s_i dominates the relay node r_j or not, and t_i is the pre-allocated transmission time for

source node s_i . In addition, in the M21-SRA-MTT formalization, t_i is a constant, and $t_i = \frac{1}{k}$ if source node s_i shares the same destination with $k - 1$ other source nodes.

$$\begin{aligned}
 Max \quad & B_m = \sum_{s_i \in S} \sum_{r_j \in R^+} C_{ij} t_i x_{ij} \\
 St. \quad & \sum_{r_j \in R^+} x_{ij} = 1, \forall s_i \in S \\
 & \sum_{s_i \in S} t_i x_{ij} \leq 1, \forall r_j \in R \\
 & x_{ij} \in \{0, 1\}, \forall s_i \in S, \forall r_j \in R^+
 \end{aligned} \tag{20}$$

The first constraint says that the total time fraction of each source node is 100%. The second constraint says that the total time fraction of each relay node r_j is not more than 1. In this way, the M21-SRA-MTT problem can be formulated into a mixed integer program. Although we do not prove the NP-Harness of M21-SRA-MTT in this paper, it is suffice to say that it is difficult to obtain the optimal solution to this problem. Accordingly, we will proceed with an approximate algorithm next.

4.2 Algorithm Description

Here we describe a relay assignment algorithm, called RA-MT, to maximize the total throughput of all the source nodes with time-wise fairness. This algorithm consists of two main steps, relay pre-assignment and relay adjustment, respectively.

The first step of relay pre-assignment will start by allowing multiple relays per source node and then narrow down to one relay at most per source using the rounding method. To do so, the algorithm constructs a linear program $LP_4(x_{ij})$, which is similar to $LP_1(t_{ij})$, as follows:

$$\begin{aligned}
 Max \quad & B_m = \sum_{s_i \in S} \sum_{r_j \in R^+} C_{ij} t_i x_{ij} \\
 St. \quad & \sum_{r_j \in R^+} x_{ij} = 1, \forall s_i \in S \\
 & \sum_{s_i \in S} t_i x_{ij} \leq 1, \forall r_j \in R \\
 & x_{ij} \in [0, 1], \forall s_i \in S, \forall r_j \in R^+
 \end{aligned} \tag{21}$$

where x_{ij} denotes the fraction of time in which the source node s_i dominates the relay node r_j , and t_i is the pre-allocated transmission time for source node s_i . The first constraint says that the total time fraction of each source node is 100%. The second constraint says that the total time fraction of each relay node r_j is not more than 1.

We can solve $LP_4(x_{ij})$ in polynomial time, and obtain its solution $\{\widetilde{x}_{ij}\}$. The optimal result of $LP_4(x_{ij})$ can be expressed by $B_t = \sum_{s_i \in S} \sum_{r_j \in R^+} C_{ij} t_i \widetilde{x}_{ij}$. Since $LP_4(x_{ij})$ is the formalization of the relaxed M21-SRA-MTT problem, in which each source node may use several relay nodes for cooperative transmission, B_t is an upper-bound on the total throughput performance of M21-SRA-MTT. Then, an integer solution $\{\overline{x}_{ij}\}$ is obtained from $\{\widetilde{x}_{ij}\}$ by rounding [20]. Under the solution $\{\overline{x}_{ij}\}$, if \overline{x}_{ij} is 1, the source s_i will select the relay r_j , and otherwise, it will use the direct transmission scheme. Let the total throughput achieved in this way be denoted by B'_t , which can be expressed by $B'_t = \sum_{s_i \in S} \sum_{r_j \in R^+} C_{ij} t_i \overline{x}_{ij}$. According to [20], this rounding procedure will not result in a lower total throughput than B_t . Therefore, B'_t is also an upper-bound for the M21-SRA-MTT problem. For simplicity, we use S_{r_j} to denote a set of sources that share relay r_j .

Note that, B'_i consists of two parts: the sum of the throughput from the source nodes who use the direct transmission scheme, denoted by $B(S_{r_0}) = \sum_{s_i \in S_{r_0}} C_{i,0} t_i$, and the sum of the throughput from the source nodes who use the cooperative communication with the help of a relay $r_j (\neq r_0)$, denoted by $\sum_{r_j \in R} B(S_{r_j}) = \sum_{s_i \in S_{r_j}} C_{ij} t_i$. That is,

$$B'_i = \sum_{s_i \in S_{r_0}} C_{i,0} t_i + \sum_{r_j \in R} \sum_{s_i \in S_{r_j}} C_{ij} t_i \quad (22)$$

Note that although solution $\{\bar{x}_{ij}\}$ will specify (at most) one relay per source node, multiple source nodes may share one relay. In particular, the total transmission time of each relay node $r_j \in R$ is $\delta_j = \sum_{s_i \in S_{r_j}} t_i \bar{x}_{ij} \leq 2$ (by the rounding method [20]), but the time constraint on some relay nodes may not be satisfied (as δ_j may be larger than 1). Accordingly, the second step should adjust the relay assignment as follows so as to satisfy the time constraint on each relay node.

For ease of expression, the set of sources that share the relay r_j is denoted by $S_{r_j} = \{s_1, \dots, s_k\}$, with $k = |S_{r_j}|$. We will order the sources in S_{r_j} in a descending order of t_i , and use C_{ij} as a tiebreaker. In other words, each source s_i will be assigned a weight, which is based on t_i with C_{ij} used for tiebreaker. For simplicity, we loosely define $w(s_i) = (t_i, C_{ij})$, and assume that $w(s_1) \geq \dots \geq w(s_k)$. The basic idea is to first partition this set S_{r_j} into as few subsets as possible such that the sum of transmission time by the sources in each subset does not exceed one. As to be shown later, the number of such subsets would be at least 2 but at most 3. The partitioned subsets can be denoted by V_1, V_2 and V_3 (if applicable). For each source set V_q with $1 \leq q \leq 3$, we compute its total throughput as $B(V_q) = \sum_{s_i \in V_q} C_{ij} t_i$. The algorithm then selects the one with the maximum total throughput, denoted by $V_{q'}$, where q' is either 1, 2 or 3, and assign the relay r_j to the source nodes in the set $V_{q'}$. Other source nodes in the set $S_{r_j} - V_{q'}$ will use the direct transmission scheme. A formal description of the RA-MT algorithm is shown in Algorithm 3.

Note that, for each relay node r_j (where $r_j \neq r_0$), assume without loss of generality that the second step of the algorithm picks $q' = 1$ (because, $B(V_1) \geq B(V_2)$ and $B(V_1) \geq B(V_3)$). Then, after the second step of the RA-MT algorithm, the total throughput of all the sources in the set S_{r_j} is expressed by $B^*(S_{r_j}) = B(V_1) + \sum_{s_i \in V_2} C_{i,0} t_i + \sum_{s_i \in V_3} C_{i,0} t_i$. Since the source nodes in V_2 and V_3 can no longer use the relay r_j , $B^*(S_{r_j})$ may be less than $B(S_{r_j})$. Nevertheless, the reduction will be no greater than $\frac{2}{3}$. That is,

$$B^*(S_{r_j}) \geq B(V_1) \geq \frac{1}{3} \sum_{s_i \in S_{r_j}} C_{ij} t_i = \frac{1}{3} B(S_{r_j}) \quad (23)$$

Finally, if we consider all the relays in set R , we have:

$$\begin{aligned} \sum_{r_j \in R} B^*(S_{r_j}) &\geq \frac{1}{3} \sum_{r_j \in R} \sum_{s_i \in S_{r_j}} C_{ij} t_i \\ &= \frac{1}{3} \sum_{r_j \in R} B(S_{r_j}) \end{aligned} \quad (24)$$

4.3 Approximation Performance Analysis

As mentioned earlier, at the end of the first step, each source node will be pre-assigned a relay node. The set of source nodes that select the relay node r_j is denoted by S_{r_j} . By the rounding method [20], we know the transmission time of each

Algorithm 3 Algorithm RA-MT:

- 1: **Step 1: Relay Pre-Assignment (One relay per source but multiple sources may share a relay)**
- 2: Construct $LP_4(x_{ij})$, and obtain its solution $\{\bar{x}_{ij}\}$
- 3: $\{\bar{x}_{ij}\}$ is obtained by rounding [20] on the solution $\{\widetilde{x}_{ij}\}$
- 4: **Step 2: Relay Adjustment (To satisfy total transmission time constraint at each relay)**
- 5: **for** each relay node r_j **do**
- 6: $\delta_j = \sum_{s_i \in S_{r_j}} t_i // S_{r_j}$ is the set of sources sharing relay r_j
- 7: **if** $\delta_j \leq 1$ **then**
- 8: Assign relay r_j to source node $s_i \in S_{r_j}$
- 9: **else**
- 10: Define $w(s_i) = (t_i, C_{ij})$ for each source $s_i \in S_{r_j}$
- 11: Let $S_{r_j} = \{s_1, \dots, s_k\}$, with $w(s_1) \geq \dots \geq w(s_k)$
- 12: Partition S_{r_j} to at most three disjoint subsets, V_1, V_2, V_3 , such that for each value q , $\sum_{s_i \in V_q} t_i \leq 1$;
- 13: **for** $q = 1$ (up) to 3 **do**
- 14: $B(V_q) = \sum_{s_i \in V_q} C_{ij} t_i$
- 15: **end for**
- 16: Determine the one with the max-total throughput, $V_{q'}$
- 17: Assign relay r_j to source $s_i \in V_{q'}$ (where $1 \leq q' \leq 3$)
- 18: **end if**
- 19: **end for**

relay r_j is $\delta_j = \sum_{s_i \in S_{r_j}} t_i \bar{x}_{ij} \leq 2$. If $\delta_j \leq 1$, there is no need for relay adjustment. We just consider the case of $\delta_j > 1$, and prove that:

Lemma 5: The second step of the RA-MT algorithm will partition the node set S_{r_j} into at most three subsets.

Proof: Assume by contradiction that three source subsets, denoted by V_1, V_2 and V_3 , cannot cover the set S_{r_j} . The sum of transmission time by the sources in each subset V_i is described as $\beta_i = \sum_{s_i \in V_i} t_i$, where $i = 1, 2, 3$. We consider two cases:

- 1) $\beta_1 = 1$. Then, we set $V_2 = S_{r_j} - V_1$, with $\beta_2 = \delta_j - \beta_1 \leq 1$. So, two subsets V_1 and V_2 can cover the node set S_{r_j} .
- 2) $\beta_1 < 1$. Let $q_i = |V_i|$, $i = 1, 2, 3$. For ease of expression, $t_{1'} = t_{q_1+1}$, $t_{2'} = t_{q_1+q_2+1}$ and $t_{3'} = t_{q_1+q_2+q_3+1}$. According to the algorithm, although the total transmission time by each subset does not exceed one, it would not after including the subsequent source node in the sorted list. So, $\beta_i + t_{i'} > 1$, for $i = 1, 2, 3$

Thus,

$$\beta_1 + t_{1'} + \beta_2 + t_{2'} + \beta_3 + t_{3'} > 3 \quad (25)$$

Since each of the sources sharing a common destination will be allocated an equal amount of access time in the form of $\frac{1}{k}$ for some k values, the possible transmission time of each source s_i is $t_i \in \{1, \frac{1}{2}, \frac{1}{3}, \dots\}$. Let us consider the value of $t_{1'}$.

- a) $t_{1'} = 1$. By assumption, $t_{1'} = 1 \leq t_1$. We have $t_1 = 1$ too (i.e., q_1 must be 1, and there are only two source nodes s_1 and s_2 in S_{r_j}). This thus becomes the same as case 1.
- b) $t_{1'} = \frac{1}{2}$. Given the sorted list of the sources, it follows that we have either $t_1 = 1$ or $t_1 = t_2 = \frac{1}{2}$. In either case, this also falls into case 1.

c) $t_{1'} \leq \frac{1}{3}$, which also indicates that $t_{3'} \leq t_{2'} \leq t_{1'} \leq \frac{1}{3}$. According to the assumption in the contradiction proof, and equation (24), we have:

$$\begin{aligned} \delta_j &= \sum_{s_i \in S_{r_j}} t_i \\ &> \sum_{s_i \in V_1 \cup V_2 \cup V_3} t_i \\ &= \beta_1 + \beta_2 + \beta_3 > 3 - t_{1'} - t_{2'} - t_{3'} > 3 - 3t_{1'} \\ &\geq 3 - 3 \cdot \frac{1}{3} = 2 \end{aligned} \quad (26)$$

This contradicts with the previously mentioned fact that by rounding, $\delta_j \leq 2$. Hence, there can be at most 3 subsets. \square

Based on this lemma, we analyze the approximation performance of the RA-MT algorithm.

Theorem 6: the RA-MT algorithm can reach the approximation performance of 3 for the M21-SRA-MTT problem.

Proof: Recall that at the end of the first step of relay pre-assignment in RA-MT, the total throughput B'_t is given in equation (21), which is no less than B_t according to [20].

Additionally, at the end of the RA-MT algorithm, the total throughput achieved, denoted by B_{MT} , is the sum of the first term in the left-hand side of equation (21), and $\sum_{r_j \in R} B^*(S_{r_j})$ in equation (23). That is,

$$\begin{aligned} B_{MT} &= \sum_{s_i \in S_{r_0}} C_{i,0} t_i + \sum_{r_j \in R} B^*(S_{r_j}) \\ &\geq \frac{1}{3} \sum_{s_i \in S_{r_0}} C_{i,0} t_i + \frac{1}{3} \sum_{r_j \in R} \sum_{s_i \in S_{r_j}} C_{ij} t_i \\ &= \frac{1}{3} B'_t \end{aligned} \quad (27)$$

In other words, the RA-MT algorithm can reach the approximate factor of 3 for the M21-SRA-MTT problem. \square

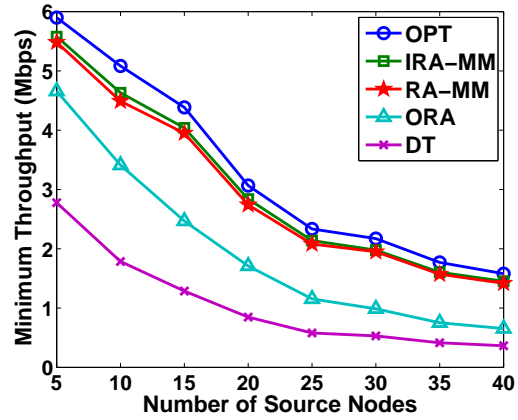
5 AVERAGE-CASE PERFORMANCE RESULTS

This section mainly presents the numerical results from simulations to demonstrate the average-case throughput efficiency of the proposed algorithms. The simulations are run using the network simulator OMNet++ (Objective Modular Network Test-bed in C++). We assume the reliable transmission in the wireless networks using the built-in MAC of OMNet++ (which uses CSMA) by setting packet loss ratio to zero.

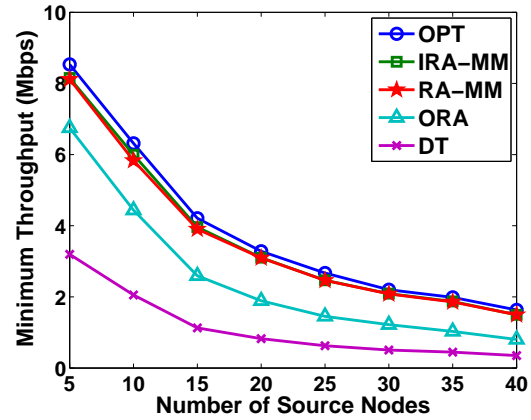
5.1 Simulation Setting and Measurements

In the simulations, we consider a wireless network whose nodes are randomly deployed in an area of $800m \times 600m$. That is, given a rectangle area, we randomly generate a position coordinate (according to a uniform distribution of both x and y coordinates), and place a node at this location. By default, the number of destination nodes and relays are 5 for each, while the number of sources (which should be more than that of destination nodes in M21 traffic) is set to 40. We will observe the impact of varying the numbers of source nodes, the numbers of relay nodes, and area sizes, etc., on the performances of minimum throughput and total throughput, respectively.

For most of the other parameters, we adopt the same settings as those in the ORA simulations [1]. For example, we assume that the bandwidth of each wireless channel is $W = 22MHz$.



(a) $n_r = 5$

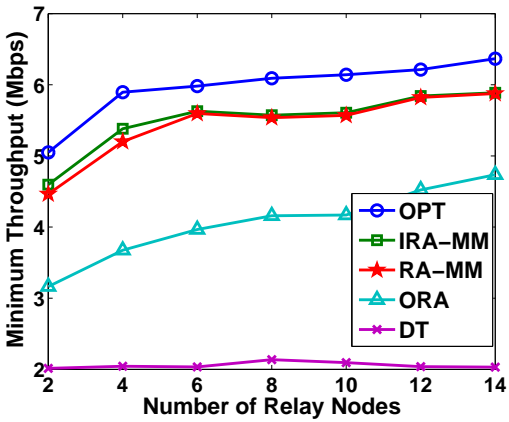


(b) $n_r = 10$

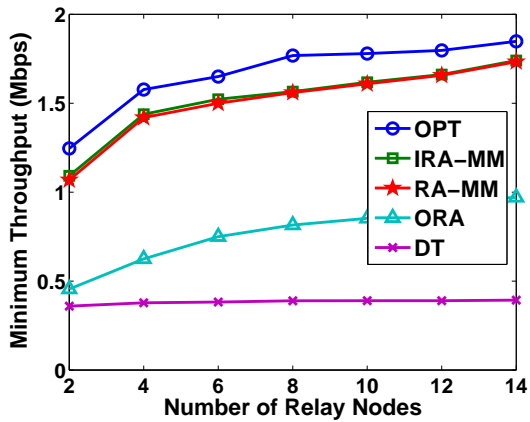
Fig. 3: Minimum Throughput vs. Number of Source Nodes

The signal-noise-ratio from node s to node d is derived by $SNR_{sd} = \frac{P_s * h_{sd}^2}{\sigma_d^2}$, where P_s is the transmission power of node s , h_{sd} is the effect of path-loss, shadowing and fading between nodes s and d , and σ_d^2 is the variance of the background noise at node d . For simplicity, we assume that h_{sd} only includes the path loss component between nodes s and d , and is expressed as $h_{sd}^2 = |sd|^{-4}$, where $|sd|$ is the distance (in meters) between two nodes. The maximal transmission power is set to $1W$ on both sources and relay nodes. For the AWGN channel, it is assumed that the variance of noise is $10^{-10}W$ at all nodes [1]. Also, each relay node works in the AF mode.

We evaluate our algorithms by comparing their max-min or max-total throughput performance with the following benchmark approaches. The first one is the direct transmission scheme. When applying direct transmission to M21 traffic, we allocate each source sharing the same destination an equal amount of time (whether the objective is max-min throughput or max-total throughput). The other is the ORA algorithm [1] [15], which was designed for max-min throughput, and hence will be compared with our RA-MM and IRA-MM only. As ORA does not at all consider time allocation among the source nodes for M21 traffic, we extend it by also allocating an equal amount of time to each of the source nodes sharing the same destination (while using a dedicated relay if any).



(a) $n_s = 10$



(b) $n_s = 40$

Fig. 4: Minimum Throughput vs. Number of Relay Nodes

Such a comparison would demonstrate the advantage of the SRA policy in M21 traffic, and our time allocation method. The third one is the OPRA algorithm [16] designed for max-total throughput and hence will be compared with our RA-MT only. For fair comparison, we also extend it by allocating an equal amount of time to each of the sources sharing the same destination. Such a comparison will also demonstrate the advantage of the SRA policy in M21 traffic. The last benchmark is the upper-bound result for M21-SRA-MMT and M21-SRA-MTT, respectively, denoted by OPT, which can be obtained by solving the linear programs LP_1 and LP_4 in equations (12) and (21), respectively. For performance comparison, we generate 100 random topologies for each simulation, and average the experimental results.

5.2 Simulation Results for M21-SRA-MMT

This section mainly observes the minimum throughput in the network for the different algorithms. Fig. 3 mainly illustrates that the minimum throughput decreases when the number of the source nodes increases from 5 to 40 for all algorithms (when the number of relay nodes is fixed). When the number of relay is less, shown in Fig. 3(a), our algorithms can perform much better than the ORA algorithm as there are much more source nodes in the network. For example, the

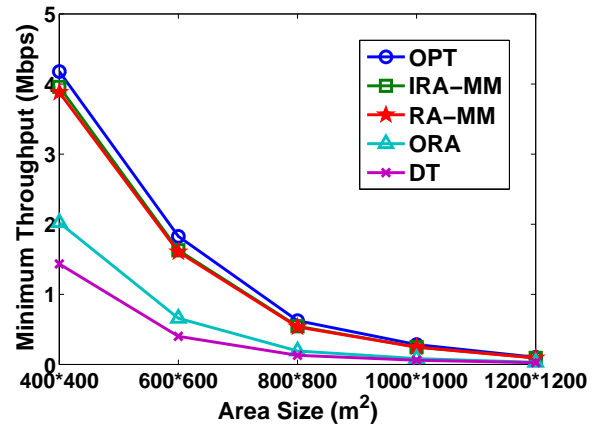
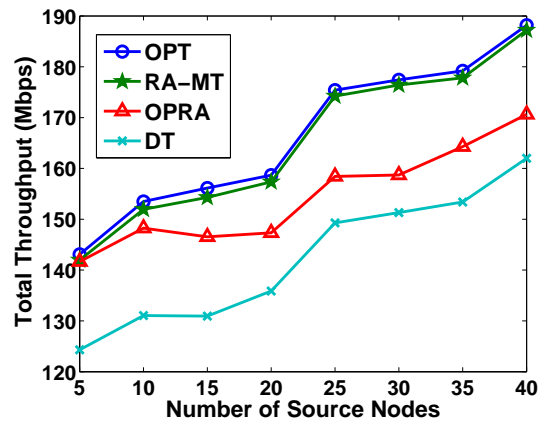
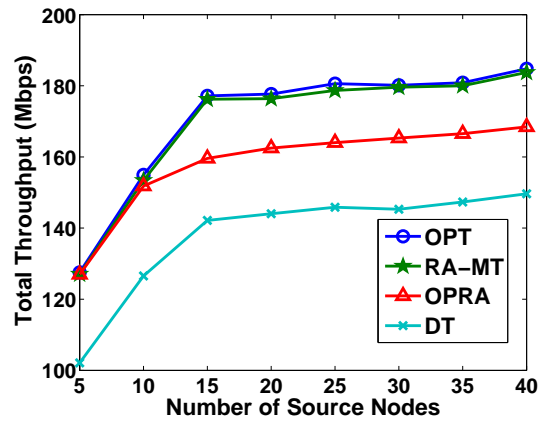


Fig. 5: Minimum Throughput vs. Area Size



(a) $n_r = 5$



(b) $n_r = 10$

Fig. 6: Total Throughput vs. Number of Source Nodes

RA-MM and IRA-MM algorithms can improve the minimum throughputs about 34.5% and 39.1% compared with ORA when there deploy 5 relay nodes. When there is more relay nodes (e.g., $n_r=10$), shown in Fig. 3(b), the RA-MM and IRA-MM algorithms improve the minimum throughputs about 23.0% and 29.1% compared with the ORA algorithm.

Fig. 4 shows that the minimum throughput increases with the number of the relay nodes (with a fixed number of source

nodes). From the figures, the minimum throughput is increased when the number of relays is increasing for all algorithms. When the number of source nodes is 10, Fig. 4(a) shows that the IRA-MM algorithm can improve the minimum throughput about 16.6% compared with ORA. When the number of source nodes is 40, both algorithms will perform better than the ORA algorithm. Especially, the proposed algorithms can improve the minimum throughput about 54.7% and 59.6% compared with ORA on average.

From Fig. 5, the minimum throughput decreases with the area size as expected. This is reasonable since according to Eqs. (1)-(3), the transmission capacity is a decreasing function of the communication distance. Note that, Fig. 5 shows that both our algorithms will perform much better than the ORA algorithm with improvement over 111% and 117%, respectively.

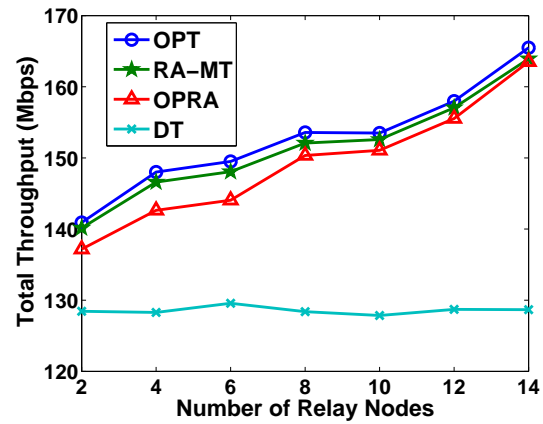
Also, from three figures, our algorithms can perform much better than the ORA algorithm. For example, when both the numbers of relays and source nodes are small (e.g., both 5), the RA-MM and IRA-MM algorithms can improve the minimum throughput by about 18% and 20%, respectively compared with ORA, which is the optimal algorithm for the 121-DRA-MMT problem. When the number of source nodes is large (e.g., 40) and the number of relays is small (e.g., 5), both algorithms will perform much better than the ORA algorithm with improvement over 110% and 116%, respectively. When averaged over all the values of the number of sources, and number of relays considered, the RA-MM and IRA-MM algorithms can improve the minimum throughput around 61% and 66% compared with ORA.

We observe the standard deviation for different algorithms, and make two conclusions. First, the standard derivation becomes smaller under a denser network (e.g., 30 source nodes) than that under a sparser network (e.g., 10 source nodes) for each algorithm. Second, the standard derivation would increase as the average-case performance is improved.

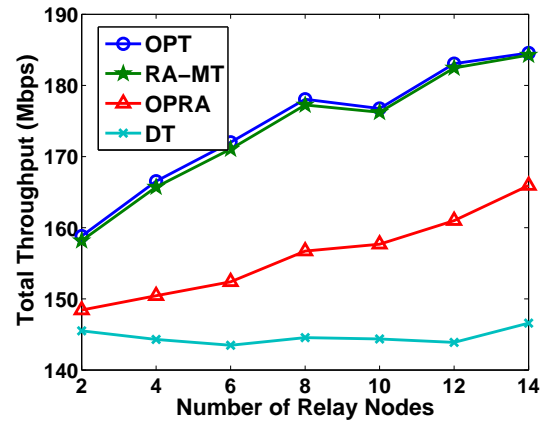
These results show the significant benefit of adopting the SRA policy (and allocating an appropriate transmission time). In particular, our algorithms can achieve better performance than ORA when there are much more sources than the number of relays. This because, under the DRA policy as in ORA, there are not enough relays available to all the sources using any relays and hence some sources only achieve a low throughput, whereas under the SRA policy as in M21-SRA-MMT, many sources can benefit from sharing a small number of relays to increase the minimum throughput in the network.

5.3 Simulation Results for M21-SRA-MTT

This section mainly observes the total throughput in the network for the different algorithms. Fig. 6 illustrates the impact of the number of source nodes on the total throughput in the network. From the figure, the total throughput is increased when the number of the source nodes is increasing for all algorithms. When the number of relay is less, shown in Fig. 6(a), our algorithms can perform much better than the OPRA algorithm as there are much more source nodes in the network. In addition, our proposed RA-MT algorithm improves the total



(a) $n_s = 10$



(b) $n_s = 40$

Fig. 7: Total Throughput vs. Number of Relay Nodes

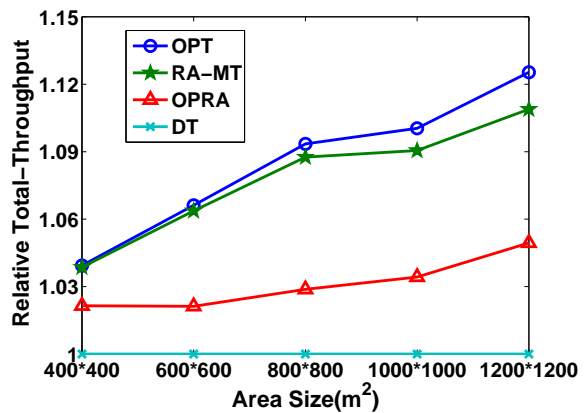


Fig. 8: Total Throughput vs. Area Size

throughput up to 22% (with 10% on average) compared with the OPRA algorithm, thanks to the SRA policy.

Fig. 7 illustrates the impact of the number of relay nodes on the total throughput in the network. When the number of source nodes is 10, Fig. 7(a) shows that the RA-MT algorithm can improve the total throughput about 17.9% compared with OPRA, which is optimal under the DRA policy. When the number of source nodes is 40, both algorithms will perform

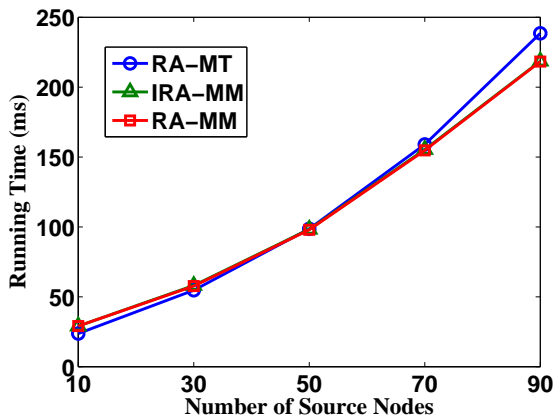


Fig. 9: Running Time vs. Number of Source Nodes

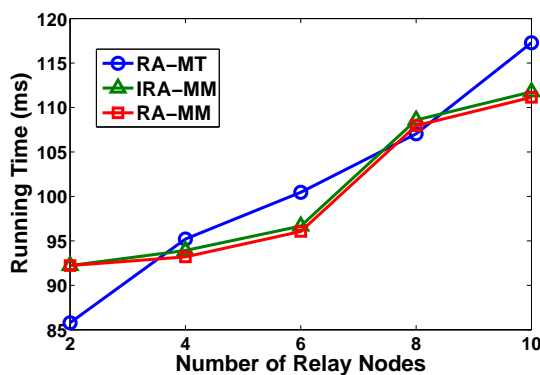


Fig. 10: Running Time vs. Number of Relay Nodes

better than the OPRA algorithm. Especially, the proposed algorithms will increase the total throughput about 20.0% compared with OPRA on average. Moreover, our proposed algorithm can achieve almost the similar performance compared with OPT, which is an upper-bound for the M21-SRA-MTT problem from the linear program LP_4 in equation (21).

We observe the impact of the area size on the total throughput in the network. For ease illustration, Fig. 8 plots the relative total-throughput when the area size varies. In the figure, we assume that the total throughput of the DT scheme is 1, and compute the total throughput of each other algorithm by compared with that by DT. We can find that our RA-MT algorithm can improve the total throughput much more in a larger area than that in a smaller area.

5.4 Time Complexity of Our Algorithms

Under the same simulation setting as described elsewhere in the paper, Figs. 9 and 10 illustrate that the average running times of the three algorithms increase super-linearly (but not exponentially) with the number of source nodes and the number of relay nodes, respectively. Hence, the running times of the three algorithms are quite acceptable in the practical scenarios as expected. For example, when there are 90 source nodes, 5 relay nodes and 5 destination nodes, the running times of the three algorithms are about 220ms as shown in Fig. 9. When when there are 50 source nodes, 10 relay nodes and 5

destination nodes, the running times of the three algorithms are about 115ms as shown in Fig. 10.

6 OTHER RELATED WORKS

The concept of cooperative communication had been around for many years [21]. This section briefly reviews the related works about relay assignment according to two categories. One is relay assignment for a single transmission pair, the other is focusing on relay assignment among multiple pairs.

For the first category, Nazaroglu et al. [22] studied the N-relay Gaussian network in which each node was equipped with multiple antennas. They showed that there existed a sub-network with two relays that could achieve approximately full capacity of the network in some situations. As mentioned earlier, Zhao et al. [11] proved that it was enough to choose the best relay node for a transmission pair to achieve the spatial diversity. Therefore, the previous works mostly assumed that each transmission pair would use at most one relay node for cooperative communication. For example, Bletsas et al. [12] designed the approach to select an optimal relay node for a single source-destination pair. In [23], the source node decided whether to employ the relay in forwarding the information or not, depending on the instantaneous channel gains. In [24], the source node decided when to cooperate by taking the ratio between the s - d channel gain and the optimal relay's metric, and selected the optimal relay for cooperative transmission. The studies in [5] [11] [23] [24] are limited to one s - d pair, and cannot be easily extended to a network scene where multiple s - d transmission pairs compete for a relay set, which is the focus of this paper.

With respect to the second category, there are some studies on relay assignment among multiple transmission pairs with different destination nodes to satisfy the different requirements such as the works in [1], [15] and [16] mentioned earlier. Following the work [1], Zhang et al. [25] proposed a relay assignment solution to minimize the network interference by the bipartite matching. Xu et al. [26] designed the efficient relay assignment algorithms to optimize the proportional fairness and lexicographical max-min fairness for wireless networks. In [27], Ng and Yu considered the relay selection, cooperative communication and resource allocation for utility maximization in a cellular network. However, the algorithm could not be finished in the polynomial time [1]. Cai et al. [15] studied the joint relay selection and power allocation problem for the AF mode. They considered the different network cases with only one-source and multiple-source. However, the proposed algorithm could guarantee the optimal or approximate performance. Xu et al. [28] studied the relay assignment problem to minimize the total power consumption while the required bandwidth of each transmission pair was satisfied. Then, they proposed a matching-based algorithm to solve this problem. The work in [29] formulated the problem of cooperative relay selection in a cognitive radio network as a stopping problem, and derived the optimal rule for relay selection. Cao et al. [30] proposed two auction schemes for relay assignment in wireless cooperative networks. The work in [31] studied the shared relay assignment for multiple independent transmission pairs

so as to increase the minimum throughput. Sharma et al. [32] studied the joint grouping and relay node selection problem for network-coded cooperative communications. These studies all assume the multiple transmission pairs with different destinations in networks. However, multiple sources may associate with one destination, such as in the WLAN, which is more general than the model in the above researches. Moreover, the SRA policy is also forbidden in almost all these works. Finally, the work in [33]–[35] studied "relay" placement for the M21 traffic in wireless sensor networks while such relays do not participate in cooperative communications and hence, differ from ours.

7 CONCLUSION

In this paper, we have studied two new shared relay (node) assignment (SRA) problems for many-to-one (M21) traffic in the context of cooperative wireless communications, namely M21-SRA-MMT and M21-SRA-MTT, in order to maximize the minimum and total throughputs. We have designed two rounding-based algorithms (RA-MM and RA-MT), whose worst-case performance is guaranteed by their approximate factors of 5.828 and 3, to maximize the minimum and total throughputs respectively. We have also proposed the variation of RA-MM to improve the average-case performance while guaranteeing the worst-case performance. Our simulations show that the proposed algorithm for M21-SRA-MMT can achieve about 66% improvement in the minimum throughput compared with ORA, while the proposed algorithm for M21-SRA-MTT can achieve close-to-optimal performance.

Note that, our solutions apply to the cases where there are both one-to-one and many-to-one traffics. In addition, we expect our work to inspire a lot of follow-up researches since the notion of SRA can be generalized. More specifically, let us call a set of source nodes that communicate with the same destination node a group. There can be two main variations for each of the M21-SRA-MMT and M21-SRA-MTT problems studied in this paper. One variation is that the DRA policy is applied to intra-group communications, while SRA is applied to inter-group communications. That is, only the source nodes from the different groups can possibly share the same relay node. The other variation is that the DRA policy is applied to inter-group, while SRA is applied to intra-group. As the above two variations are special cases of the M21-SRA-MMT and M21-SRA-MTT problems, we can modify the proposed RA-MM and RA-MT algorithms a little so as to satisfy the constraints of relay assignment. However, these algorithms cannot guarantee the (worst-case) approximation performance. As a future work, we will design other algorithms with guaranteed (worst-case) performance for these and other relay assignment problems. Moreover, another future work is, by starting from the proposed three algorithms, to design the efficient shared relay assignment mechanisms that can adapt to a dynamic and mobile wireless environment.

APPENDIX A PROOF OF LEMMA 1

Proof: Clearly, the problem is in NP, since we can verify in polynomial time if a candidate solution can accomplish the

shared relay assignment and achieve the minimum throughput constraint.

We prove the NP-hardness by showing that the association control problem [14] is a special case of the M21-SRA-MMT problem. In the WLAN network, the association control problem is to associate each terminal with one AP so as to maximize the minimum throughput of all the terminals. We consider a special case of M21-SRA-MMT, in which each destination is only connected with one source. This is just the 121-SRA-MMT problem. Next, we will show that the association control problem and the 121-SRA-MMT problem are equivalent. For the association control problem, there are n terminals, denoted by $\{v_1, \dots, v_n\}$, and m APs, denoted by $\{u_1, \dots, u_m\}$. Moreover, the transmission capacity between terminal v_i and AP u_i is denoted by C_{ij} . Then, we will transform this instant into one instant of the 121-SRA-MMT problem as follows: the network consists of m relays, denoted by $\{r_1, \dots, r_m\}$ and n transmission pairs, denoted by $\{\Gamma_1, \dots, \Gamma_n\}$. The cooperative transmission capacity that the transmission pair Γ_i uses a relay r_j is denoted by C_{ij} . It should be noted that APs and terminals in the association control problem correspond to relays and transmission pairs in the 121-SRA-MMT problem, respectively. Then, the association control problem is equivalent to the 121-SRA-MMT problem. In other words, a solution to the 121-SRA-MMT problem can be transformed into another solution to the association control problem, and vice versa. As a result, the association control problem is a special case of the M21-SRA-MMT problem. Thus, M21-SRA-MMT is an NP-Hard problem too. \square

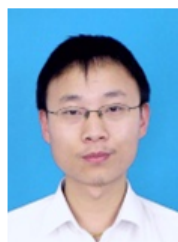
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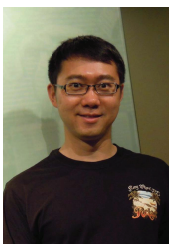


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cellular and ad hoc relaying systems (iCAR) in 1999, which is recognized as the harbinger for today's push towards the convergence between heterogeneous wireless technologies, and has been featured in BusinessWeek and Wireless Europe, as well as at the websites of New Scientists and CBC. These works have inspired a lot of follow-up works around the world and attracted funding from a dozen of major IT and telecommunications companies including Alcatel, Cisco, Google, NEC labs, Nokia, and Telcordia. Dr. Qiao has given a dozen of keynotes, and numerous invited talks on the above research topics. He has chaired and co-chaired a dozen of international conferences and workshops. He was an editor of several leading IEEE journals, and chaired a number of technical committees. He was elected to IEEE Fellow for his contributions to optical and wireless network architectures and protocols.



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