Distributed Channel Access, Relay Selection and Time Assignment for QoE-Aware Relay Networks

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Abstract—In this paper, we tackle the comprehensive problem jointing channel access, relay selection and available time assignment for distributed relay networks which includes multiple source nodes and relay nodes. Driven by various communication requirements, source nodes search for relay nodes to improve the quality of transmission. Due to the interaction relationship, source nodes have to compete for channels and time resource of relay nodes with other source devices. To promote the satisfaction performance among source nodes, we divide the optimization problems of channel access and relay selection into two sub-problems, respectively. Then the distributed hierarchical game models are constructed, in which the problem of channel access is modeled as a congestion game model, and relay selection jointing time assignment is modeled as a matching model with dynamic quotas. Combining two game models, a distributed hierarchical scheme is designed, which is shown to reach a stable result and the properties are studied. The simulation and experimental results show that the proposed distributed QoE-aware method has obvious performance improvement in terms of satisfaction, fairness and convergence.

Index Terms—Distributed multi-relay networks, channel access, relay selection, hierarchical game model.

I. INTRODUCTION

THE relay technology is seen as a promising technology to meet the increasing demands of wireless network capacity and has been adopted in such as Long-Term Evolution Advanced (LTE-A) systems [1] and Internet of Things (IoT) networks [2]. Relay nodes receive the transmitted data from source nodes and retransfer them to the destination nodes so as to achieve spatial diversity and increase data rates of communication. Due to the diverse deployments, only suitable selection strategies can optimize the transmission, or else the strategies may lead to negative influence [3]. Therefore, the

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relay selection problem becomes a key issue in multi-node relay networks.

To date, many approaches to cope with the problem including relay selection and routing protocol [4] have been proposed. Existing works mainly focused on the problem of one-to-one [5]–[7] or many-to-one [8]–[12] relay selection strategies in different situations. In these articles, the available channels in systems were considered as enough for wireless transmission devices. This assumption may be unreasonable, since the competitive relationship between devices is difficult to avoid in the large-scale network. Therefore, the relay selection as well as the channel access are both taken into account in this paper, where the number of channels is considered fewer than that of relay nodes.

Moreover, most of existing literatures [5]–[9] focused on the absolute transmission capacities, and ignored the actual requirements of the communication devices. It is unsuitable to overemphasize the absolute throughput performance when the demands of source nodes are various, because there will be more or fewer users unsatisfied with their obtained resource and some nodes may feel a surplus. In the future networks, the quality of experience (QoE) performance of each user can not to be neglected [13]. Therefore, this paper mainly develops more reasonable resource assignment for multiple source nodes.

Driven by various requirements of data rates, the problem jointing channel access, relay selection and resource assignment is studied in this paper. For multi-relay networks, centralized approaches always requires a powerful controller and some connection metrics, such as channel state information, to make the decisions of channel allocation, relay selection and time assignment accurately. When the number of wireless devices increases, the optimization problem becomes increasingly complicated. Since the distributed architecture can effectively reduce the load on the system controller, it has received extensive attention of research. There are already existing studies [14]–[16] on distributed methods for other practical networks such as small cell networks and cognitive networks, in which the game theory has been proven to be a very effective method for distributed models [16]. Therefore, this paper tackle the relay transmission problem from the perspective of game models.

Based on the game theory, the comprehensive problem is divided into two sub-problem and a distributed hierarchical game model is formulated. Without a powerful centralized controller, relay nodes have to compete and share channels equally with the other devices, so the channel access issue is

modeled as a congestion game [17]. After that, relay nodes can assign their time resources to source nodes according to the transmission demands. We model the relay selection combining with the time assignment problem as a matching game [18] with dynamic quotas. For the congestion game of the channel access problem, a best response (BR)-based channel access algorithm is proposed. On the other hand, a requirement-aware matching algorithm is proposed to achieve the stable matching for the problem of relay selection and time assignment. Finally, a joint algorithm is designed and we prove that the proposed scheme can achieve a stable solution. The main contribution of this article is:

- The multiple relay transmission problem including channel access, relay selection and time assignment of demand-driven relay model is divided into two sub-problem. To cope with this comprehensive problem, a hierarchical game architecture is modeled.
- Based on optimization features of different sub-problem, corresponding game models are constructed, where the problem of channel access and relay resource assignment are formulated as a congestion game model and a matching game model, respectively. We prove that the proposed game model is able to achieve the Nash equilibrium (NE) point.
- Based on the proposed hierarchical game, distributed algorithms for corresponding game models are designed respectively, and then a joint distributed algorithm is proposed to achieve the equilibrium solution for the relay networks.
- Extensive simulation results are shown and analyzed to investigate the performance of the proposed scheme. The performance results show that the proposed algorithm outperforms in terms of user experience and fairness within a reasonable convergence time.

The rest of this paper is organized as follows. In Section II, the related works are given. In Section III, the system model is provided, then the problems of channel access and relay selection are formulated. In Section IV, a game based distributed model is analyzed and the optimizing objective is decomposed to two subproblems. In Section V and Section VI, the congestion game model and matching game model are studied to solve subproblems, respectively. In Section VII, a joint algorithm is proposed and the convergence performance is proved. In Section VIII, the simulation result is shown and the performance of the distributed algorithm is analyzed. Finally, the conclusion is drawn in Section IX.

II. RELATED WORKS

Existing works [19] pointed out that it is effective to select the optimal relay node instead of multiple relay nodes for one source node. Therefore, many researches focused on the problems of one-to-one or many-to-one relay selection model. In [6], Yang et al. maximized the total throughput for the one-to-one relay networks. Similarly, Sharma et al. in [7] proposed an "optimal relay assignment" algorithm to maximize the minimal performance among source nodes. Moreover, many works extended the one-to-one relay selection works to many-to-one models based on different systems [8]–[12]. Different

from one-to-one relay communications, source nodes have to share the resource of relay nodes with the other source nodes in many-to-one relay networks, which are suitable for resource constrained scenarios. In this kind of models, centralized and distributed algorithms were both developed in existing works. For example, Xu et al. studied the many-to-one traffic using a centralized scheme [8]. While in [9]–[11] and [12], distributed schemes were proposed to address the relay transmission issues for classic relay networks and IoT networks, respectively.

Different from classic relay models with infinite available channels, the many-to-one relay selection problem is solved jointing the problem of channel access and time assignment in this paper. Some related works are given as follow. In [20], a solution combining relay assignment with channel access was proposed to maximize the global capacity, in which each relay node can assist only one source node. In [21], a learning algorithm was designed to optimize the fairness performance of relay selection and channel access. In [22], Li et al. studied the energy and spectrum efficient cooperative communications in the multi-channel wireless networks. Most of them utilized centralized methods to solve the relay selection problem, which can not be applied in the distributed networks. Moreover, the existing work ignored the problem of data requirement of source nodes. Distributed models driven by data requirement make the problem more difficult to solve, and it is the main work of this paper.

III. SYSTEM MODEL

A. System model

As shown in Fig. 1 (a), we consider a relay network involving N cell edged source nodes, M relay nodes and one destination D, where each source-destination pair $\{n, D\}$ has an opportunity to be assisted by relay nodes which locate near the destination. The set of source nodes and relay nodes are denoted by $\mathcal{N} = \{s_1, s_2, ..., s_n, ..., s_N\}$ and $\mathcal{M} = \{r_1, r_2, ..., r_m, ..., r_M\}$, respectively. For ease of presentation, we use n and m to represent the source node and relay node, respectively. We assume that nodes in the communication network share the set of channels denoted by $\mathcal{L} = \{1, 2, ..., L\}$ and there is $L < M < N$. Each device is equipped with one radio to connect with one channel. In the relay model, each source node can connect with one relay node, while one relay node can share its time resource to multiple source nodes [9].

According to the theory of the relay technology, the transmission capacity of source node n assisted by the relay model [3] is given by,

$$C^{DF}(n, m, D)$$
$$= \frac{B}{2} \log_2\left(\min\left\{1 + \gamma(n, m), 1 + \gamma(n, D) + \gamma(m, D)\right\}\right),$$
(1)

where the transmission bandwidth is denoted by B. For ease of expression, the signal-to-noise-ratio (SNR) at relay nodes coming from source nodes is denoted by $\gamma(n, m)$, $\gamma(n, m) = P_n|h(n, m)|^2/\sigma^2$. The transmission power of source node is
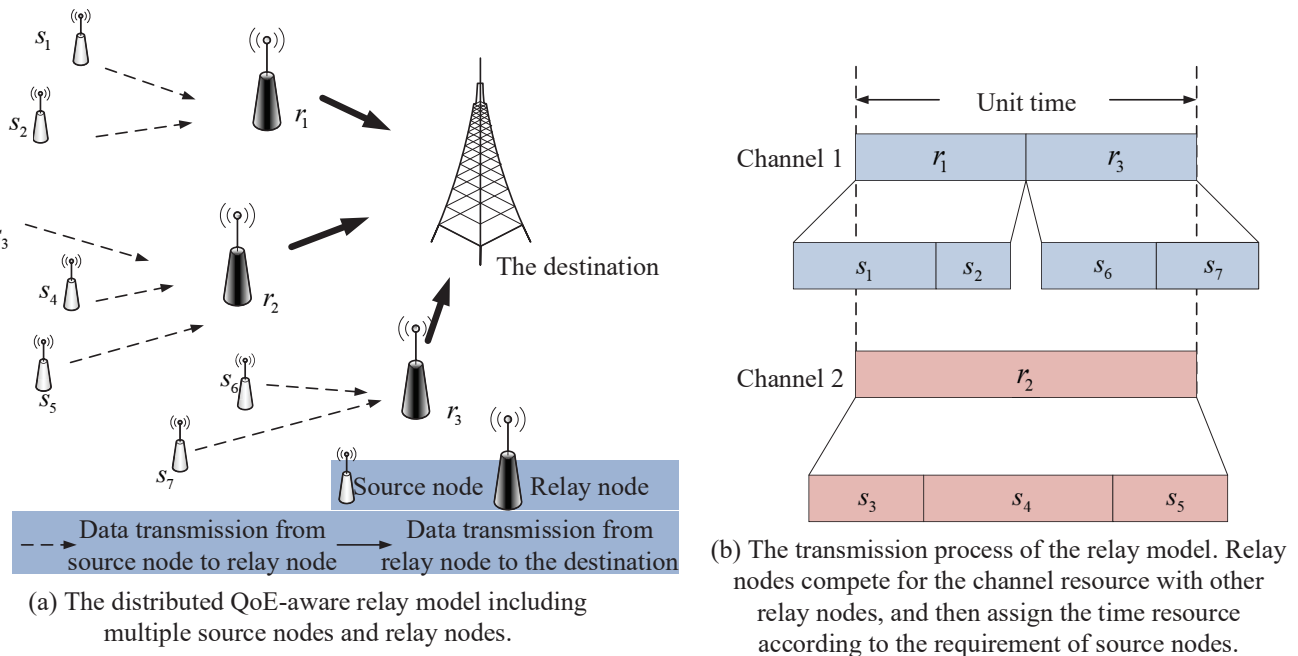
(a) The distributed QoE-aware relay model including multiple source nodes and relay nodes.

(b) The transmission process of the relay model. Relay nodes compete for the channel resource with other relay nodes, and then assign the time resource according to the requirement of source nodes.

Fig. 1.   A example of the relay model including channel access, relay selection and time assignment.

denoted by P_n. $h(n,m)$ captures the path gain between the source node and the relay node, and the parameter σ^2 is the variance of white Gaussian noise (AWGN). Similarly, the SNR from source node to destination and from relay node to destination are denoted by $\gamma(n,D)$ and $\gamma(m,D)$, respectively. Expressed by (1), the decode-and-forward (DF) transmission model is used, in which relay nodes demodulate and decode the received signals and then modulate and encode them again before retransmitting to the destination. The results of this paper can also extend to the other cooperative communication models such as amplify-and-forward (AF) model and hybrid model.

If one source node chooses the direct transmission (DT) model to communicate with the destination node, the capacity is given by [3],

$$C^{DT}(n,D) = B\log_2\left(1+\gamma(n,D)\right). \tag{2}$$

According to the cooperative communication [3], the transmission process of relay model is a frame-by-frame fashion.

Without a central controller, we assume when multiple relay nodes choose a same channel, they equally share it by by using the time division multiple access (TDMA) scheme. The channel serves each relay node in a round-robin fashion connection. Relay nodes compete for available channels and then assign the acquired resources to source nodes. One source node can connect with one relay node at most, that is,

$$\sum_{m\in\mathcal{M}} x_{nm} \leq 1, \forall n \in \mathcal{N} \tag{3}$$

$$\text{s.t. } x_{n,m} = \begin{cases} 1, & \text{if } n \text{ connect with } m \\ 0, & \text{else,} \end{cases} \tag{4}$$

where x_{nm} is an indicator function which is equal to 1 or 0. Without connecting with relay nodes, source nodes will choose

the DT model, where we assume that there is a specific channel for the DT transmission. Therefore, the obtained data rate of source node n can be given by,

$$C_n = \sum_{m\in\mathcal{M}} \frac{C^{DF}(n,m,D)}{A^l} x_{n,m} t_{n,m} + \frac{C^{DT}(n,D)}{A^{DT}}\left(1-\sum_{m\in\mathcal{M}} x_{n,m}\right), \tag{5}$$

where the number of relay nodes which connect to the channel l is denoted by A^l, and the number of source nodes choosing the DT mode is denoted by A^{DT}. $\sum_{m\in\mathcal{M}} x_{n,m}$ is equal to 1 or 0, which means that each source node can choose one mode (DF or DT) at most. Each relay node m assigns a period of time t_{nm} to the source node n which connects with it [8], and $0 \leq t_{nm} \leq 1$ means the percentage of time span does not exceed the available resources of relay nodes. The specify transmission process is shown in Fig. 1 (b), where relay nodes can assign different time resource to different source nodes based on their demands of data rates.

B. Problem formulation

Due to the various urgency of services, different source nodes have different requirements of data rates. We consider that the data rate requirement of source node n is C'_n, and n aims to find one of relay nodes which can meet its demands. We use u_n to denote the satisfaction index of n and the satisfaction equation is given as,

$$u_n = \frac{1}{1+\exp\left[-\alpha_n\left(C_n - C'_n + \beta\right)\right]}, \tag{6}$$

where $\beta = 7/\alpha_n$, so we can approximate the result to 1 that is $u_n = 1$ when $C_n \geq C'_n$. α_n denotes the requirement urgency

of source node n. It is noted that the satisfaction function performs as a universal sigmoid function, which shows a slightly S-shaped curve to unify different traffic needs of source nodes [23]. The data requirement will become more stringent as the value of α_n becomes larger, and lower α_n represents the non-urgent data requirement.

For the global network, the problem of channel access, relay selection and time assignment can be formulated as an optimization problem in which relay nodes dominate channel resources and assign time resource to source nodes such that the overall satisfaction is maximized. Therefore, the optimization problem of the global network can be given as,

$$\text{maximise} \sum_{n \in \mathcal{N}} u_n, \tag{7}$$

$$\text{s.t.} \sum_{m \in \mathcal{M}} x_{nm} \in \{0, 1\}, \tag{8}$$

$$0 \leq t_{nm} \leq 1, \tag{9}$$

$$\forall n \in \mathcal{N}, m \in \mathcal{M}, \tag{10}$$

where the first constraint means that source node n is able to connect no more than one relay node or destination. The second constraint represents the maximum time resource dominated by source nodes is not exceed the capability of relay nodes. The last constraint ensures the range of nodes involved in decision making.

IV. A GAME-BASED SCHEME FOR THE DISTRIBUTED RELAY MODEL

In the transmission process, source nodes have to choose relay nodes as well as the channel resources. The proposed formula in (7), subject to (8-10), is a non-convex problem, which involves the channel competition, relay selection and resource allocation of source nodes. There is a large decision space for source nodes and relay nodes.

For a large-scale network with multiple nodes, the problem of dynamic resource competition, heterogeneous throughput requirements and large number of nodes will become more severe, which makes the problem of the optimizing relay communication more difficult. Centralized approaches require a large amount of information exchanges, which causes the over load of the control center. It is desirable to solve the demand aware relay selection problem in (7) using a self-organizing scheme in which the source nodes and relay nodes can interact and make resource allocation decisions based on their limited information exchanges without relying on a centralized controller for coordination.

According to the architecture of relay networks, the problem is decomposed into two subproblems in this paper, where one subproblem is the channel access of relay nodes, and the other is the relay selection and time assignment of source nodes. For the first subproblem, relay nodes compete for channel resources to improve the satisfaction of source nodes which connect with them. The optimal utility of relay nodes can be given

$$u\left(a_m, a_{-m}\right) = \sum_{n \in \mathcal{N}} u_n x_{n,m}, \tag{11}$$

where a_m is the selection strategy of m and the elements of a_m are relay channels, that is $a_m \in \mathcal{L}$. $a_{-m} =$
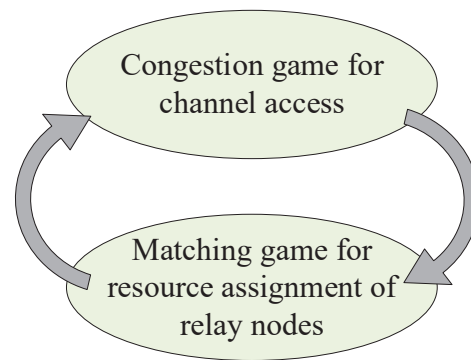

Fig. 2. The proposed hierarchical game model, where the iteration performs among two games of the sub-problems.

$\{a_1, a_2, ..., a_{m-1}, a_{m+1}, ..., a_M\}$ represents access strategies of the other relay nodes. To maximize the experiences of source nodes which connect with relay nodes, the optimization objective of the first subproblem is

$$P1 : \max \sum_{m \in \mathcal{M}} u\left(a_m, a_{-m}\right). \tag{12}$$

Similarly, for the second subproblem, each source node selects the appropriate relay node and obtains sufficient resources to maximize its own utility function. The optimization objective of the second layer is

$$P2 : \quad \max \sum_{n \in \mathcal{N}} u_n. \tag{13}$$

As denoted by the $P1$ and $P2$ in (12) and (13), both two subproblems aim at maximizing the global satisfaction, which is also the original objective presented in (7). However, because analysis of two subproblems are from the perspectives of relay nodes and source nodes respectively, it is possible to address the comprehensive issue by a layered approach.

Inspired by the game theory, which is a promising and powerful framework in distributed wireless networks [16], we model the relay transmission problem including channel access, relay selection and time assignment as a hierarchical game model. According to the specific situation of different layers in the model, the first subproblem of channel access is constructed as a congestion game with player-specific payoff functions. Then the issue of relay selection and time assignment is modeled as a matching game with dynamic quotas. We analyze the proposed game model hierarchically and present corresponding optimization algorithms, where the channel access problem of the relay nodes is studied firstly, then the relay resource assignment problem of the source nodes is developed. Finally, the discussion jointing two-layer models is carried out. Fig. 2 shows the architecture of the hierarchical game model, in which two game models mutual influence each other and global performance is optimized by the iterations.

V. CONGESTION GAMES WITH PLAYER-SPECIFIC PAYOFF FUNCTIONS FOR CHANNEL ACCESS

As mentioned above, due to the lack of effective centralized controllers, relay nodes share channel resources equally when

they select the same channels. The obtained time resource of one relay node is related to the number of relays which select the same channel. Inspired by the congestion model [17], we model the channel access problem of relay system as a congestion game with player-specific payoff functions.

Definition 1. *The congestion game of the channel access model is defined as* $\mathcal{G}1 : \left(\mathcal{M}, \mathcal{L}, (\mathcal{A}_l)_{l \in \mathcal{L}}, u(a_m, a_{-m})_{m \in \mathcal{M}} \right),$

where the set of relay nodes and available channels for relay nodes are denoted by $\mathcal{M}$ and $\mathcal{L}$, respectively. For $\forall l \in \mathcal{L}$, $\mathcal{A}_l$ represents the number of relay nodes which access the channel l, and $u(a_m, a_{-m})$ represent the utility of relay node m selecting the strategy a_m $(a_m \in \mathcal{L})$. It is noted that, even relay nodes access a same channel, they will obtain various utility values due to the gaps of relative distance. Moreover, as shown in (5) and (6), the utility function is a nonincreasing function of the number of the participants. Since the utility of a relay node is related to the number of relay nodes with same strategies, the game model can be modeled a congestion game with player-specific payoff functions [17].

Mathematical analysis of the congestion game with player-specific payoff functions were studied in [17]. We find that the theory is suitable to describe the subproblem of the channel access in this paper. Based on [17], the congestion game with player-specific payoff functions has at least one Nash equilibrium (NE).

Definition 2. *In the relay model, a channel selection profile* $a = \{a_1, ..., a_m, ..., a_M\}$ *is a pure Nash equilibrium (NE) point of* $\mathcal{G}1$ *if there is* $\nexists a' = \{a_1, ..., a'_m, ..., a_M\}$ *satisfying:*

$$u(a'_m, a_{-m}) > u(a_m, a_{-m}), \tag{14}$$

where the function means that no relay node can improve its utility function by deviating unilaterally. To achieve the NE point, we propose the best response (BR)-based distributed channel access algorithm which is shown in Algorithm 1.

We discuss the Algorithm 1 for finding the equilibrium of channel access among relay nodes as follow. The inputs are the distribution of the wireless devices and the number of channels. In the initialization, relay nodes initially access channels randomly. Next, we start the loop of channel selection among relay nodes, which is shown in (15), where the time iteration is denoted by t, we change the strategy of a_m as a'_m at time $t+1$, and let the $a_{-m}(t+1) = a_{-m}(t), j \in \mathcal{M} \backslash m$. Finally, with the iteration of the algorithm, the stable channel access can be determined.

Theorem 1. *The proposed BR-based distributed channel access algorithm can converge to an pure NE point in a finite iterations among relay nodes.*

Proof: The detailed derivation can be referred to [17]. ∎

According to [17], the optimal or sub-optimal result of channel access can be achieved by the BR-based distributed channel access algorithm.

VI. MATCHING GAME FOR RELAY SELECTION AND TIME ASSIGNMENT

After accessing channels, relay nodes assign the channel resources to source nodes according to source nodes' demands

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Algorithm 1: *The proposed BR-based distributed channel access algorithm*

Phase I: Initialization
 - Each relay node randomly accesses one channel.
Phase II: Algorithm evolution
Repeat
 - All relay nodes detect the information of channels and calculate the expected rewards.
   For $m = 1 : M$
 - The other relay nodes repeat their previous channel access strategies, that is $a_{-m}(t+1) = a_{-m}(t)$, where t means the iteration time. At the same time, by receiving the rewards from channels, relay node m selects the channel with maximal utility function as next strategy $a_m(t+1)$ which satisfies:
$$a_m(t+1) = \arg \max_{a_m \in \mathcal{L}} u_m(a_m, a_{-m}|t). \tag{15}$$

   end
Until the channel selection of relay nodes in $t+1$ has not changed compared with that in t.

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of data rate and the emergency degree, where the problem of time assignment is also considered in this paper. Here, we model the problem of relay selection combining with time assignment as a matching game model. Matching theory is a powerful distributed solution to tackle the problem of resource assignment without global information exchange or a central controller [24]–[26]. Different from the classic matching game with fixed quotas [27]–[29], a matching game with dynamic quotas [24] is constructed in this paper, and the detailed analysis of the proposed model are as follows.

A. Source nodes' preferences

Driven by various service transmission requirements, source nodes calculate the estimated data rates assisted by relay nodes, and then order the relay nodes according to the transmission quality and the available time resource.

According to the function (6), the transmission requirement of source node n is denoted by C'_n, and they try to select the optimal relay nodes so as to achieve

$$C_n > C'_n \Rightarrow u_n = 1. \tag{16}$$

Therefore, relay nodes with high transmission rate will get higher priorities, that is

$$(n, m) \succ_n (n, j) \text{ if } u_n(m) > u_n(j), \tag{17}$$

where the source node is denoted by $n \in \mathcal{N}$, and $m, j \in \mathcal{M}$ represent relay nodes. $u_n(m)$ and $u_n(j)$ mean the satisfaction utilities of n assisted by m and j, respectively. The preference profile $\succ_n$ means that for the source node n, the priority of matching (n, m) is superior to (n, j).

B. The preferences of relay nodes

Following the application of the source nodes, relay nodes will prioritize the source nodes according to the transmission rate to make the transmission more efficient. The objective of the relay node is

$$\max \ u(a_m, a_{-m}) = \max \ \sum_{n \in \mathcal{N}} u_n x_{n,m}. \tag{18}$$

In the transmission process, not only the transmission satisfaction but also the urgency of communication are important.

Considering both two factors, the priority selection order of the relay nodes is defined as follow,

$$(n,m) \succ_m (i,m) \text{ if } \alpha_n u_n(m) > \alpha_i u_i(m), \quad (19)$$

where source nodes are denoted by n, $i \in \mathcal{N}$, and $m \in \mathcal{M}$ represents the relay node. The meaning of the formula is similar to (17). Differently, the factors of the preference of relay nodes includes the satisfaction of source nodes and the urgency of communication demands.

C. The proposed matching algorithm and the stable matching

In classic matching models, the available resource is indivisible, and players can only be accepted with fixed resource or be rejected. However, the resource of relay nodes can be allocated to source nodes quantitatively according to their transmission demands, and the remaining resources can be shared by the other source nodes, which involves the issue of peer effects and dynamic quotas [24], [25]. Moreover, the channel resource competition among relay nodes leads to the fact that the resources of relay nodes are dynamic in different iterations. For the matching game with dynamic quotas, the stable matching [18] of relay model is given,

Definition 3. *For the relay model, a stable matching μ means that no pair of $\{(i,j)|i \in \mathcal{N}, j \in \mathcal{M}\}$ blocks the current matching result between source nodes and relay nodes:*

$$\nexists(i,j) \text{ s.t. } i \succ_j \mu(j) \text{ and } j \succ_i \mu(i), \quad (20)$$

where $\mu(i)$ and $\mu(j)$ represent the current matching results of i and j, respectively.

To achieve the stable matching result, a distributed matching algorithm is proposed. The matching algorithm allocates the resource of relay nodes according to the individual demands of source nodes (shown in Algorithm 2), which includes two stages, i.e., relay discovery and matching evolution. In the first stage, source nodes collect required parameters of relay nodes and construct the preference lists. In the second stage, source nodes and relay nodes iterate the matching process until the result converges to the stable matching. Finally, relay nodes assign the time resource to source nodes. The proof of the stable matching is given in Section VII, Theorem 2.

VII. A JOINT-ALGORITHM AND STABLE GLOBAL RESULTS OF ASSIGNMENT

After analyzing two subproblems, we propose a two-layer iterative distributed algorithm, as shown in Algorithm 3, to achieve the convergence of the whole relay transmission network.

The algorithm starts from that source nodes select relay nodes by estimating data rates. The results of two levels interact with each other, in which utilities of the relay nodes will be influenced by the selection strategies of source nodes. While the channel access of relay nodes also affects the relay selection of source nodes. In Algorithm 3, two algorithms do not iterate until the relay nodes maintain their channel selection as well as source nodes keep their relay selection in

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Algorithm 2: *The proposed matching algorithm with dynamic quotas*

Phase I: Relay discovery
- Each source node discovers its neighboring relay nodes and collects the required parameters of selection.
- Initialize the preference list of matching set.

Phase II: Matching evolution
Repeat
- Unsatisfied source node updates its preference list based on (16) and (17).
  If the preference list of source node is empty, **then**
  - It will choose the DT mode.
  else
  - It will choose most preferred relay node which has not rejected it, and propose its requirement.
  End if
- Relay nodes receive the requests from source nodes, and order the source nodes based on (19).
- Based on the requirement of data rate, relay nodes assigns corresponding time resource to the accepted source nodes.
  If the resource is not enough
  - Relay node will assign the remaining resource to the most preferred source node which has not assigned resource, and then rejected the other not preferred source node.
  End if
- Unsatisfied source nodes apply for the next relay node. If there are not better choices, they will keep the former strategies (relay node with insufficient resource).
Until no matching is changed at the previous iteration.

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the last iteration process. We prove that the proposed scheme can converge to a stable result of the whole relay model.

Theorem 2. *After a finite number of iteration steps, the proposed two algorithms of the two-level model respectively have an equilibrium solution, and thus the proposed joint congestion-matching model can converge to a stable result.*

Proof: This proof will be analyzed from the perspective of source nodes. If source node n is satisfied with the previous matching result, which is

$$C_n > C'_n \rightarrow u_n = 1, \quad (21)$$

it is not necessary to choose the other relay nodes. If the data rate of n is lower than its requirement, it will search for the next relay node which satisfy

$$t_{nm}x_{nm} + \sum_{i \in \mathcal{N}\backslash n} t_i x_{im} \leq 1, \quad (22)$$

$$\text{s.t.} \quad t_{nm} = C'_n/C_n, \quad (23)$$

$$x_{im} = 1, \quad (24)$$

$$i \in \{\mathcal{N} | (i,m) \succ_m (n,m)\}. \quad (25)$$

Once the inequality above is satisfied, n will stop looking for the next relay node. Otherwise, if all of relay nodes do not meet the requirement, n will select the relay node which can achieve its maximum satisfaction, i.e.,

$$\max \quad \left(1 - \sum_{i \in \mathcal{N}\backslash n} t_i x_{im}\right) C_n, \quad (26)$$

$$\text{s.t.} \quad i \in \{\mathcal{N} | (i,m) \succ_m (n,m)\}, \quad (27)$$

where i represents the set of source nodes which satisfy $(i,m) \succ_m (n,m)$. According to the matching game [25], source nodes which have been received by relay m will not be replaced by the source node with lower priority. That means

Algorithm 3: The proposed joint congestion-matching algorithm

Phase I: Initialization
 - Source nodes estimate the transmission rates of relay nodes and then select the relay nodes preliminarily.
Phase II: Joint congestion-matching algorithm
Repeat
 - Based on the relay selection of source nodes, relay nodes contend for the channel resource in Algorithm 1, and assign the resource to source node.
 - Based on the channel access of relay nodes and previous resource assignment, Algorithm 2 is performed.
Until no selection strategy is changed at the previous iteration.

the optimal relay node has been found for n. According to the preference lists, entire source nodes can achieve to the stable matching result.

When the stable result is obtained in the matching model, each relay node will compete for channels according to the utilities of source nodes which connect with it. Suppose that a relay m is satisfied with obtained resource, that is,

$$u_m = \sum_{i \in \mathcal{N}} x_{im}. \qquad (28)$$

It means that all of the source nodes in m are satisfied with current data rates, and the relay node will maintain the present channel access. Assuming that m can tolerate k neighbor nodes, i.e., it can tolerate k other relay nodes to choose the same channel, and when it have $k + 1$ neighbor, it will try to search channels with k neighbors. According to [17], the choices of relay nodes will also tend to be stable. Of course, this change will influence the strategies of source nodes.

Assuming the situation that one source node connecting with m is influenced by the other relay nodes, and the resource of m is reassigned. For the relay node m, the priorities of source nodes are not changed. The decrease of the number of source nodes which connect with m means that more source nodes try to search for other relay nodes. It leads that the other relay nodes can only tolerate neighbors less than or equal to $k - 1$. However, channel access has been determined in the last round, and each relay node must have at least k neighbors. Therefore, when the channel selection tends to be average or $k = 0$, the change of relay selection will not affect the result of channel access. This trend of the algorithm will lead to the convergence of the global network.

■

VIII. SIMULATION RESULTS

In a 2000×2000 square metre topology, as shown in Fig. 3, there are series of relay nodes close to destination, and

TABLE I
PARAMETER SETTINGS IN SIMULATIONS.

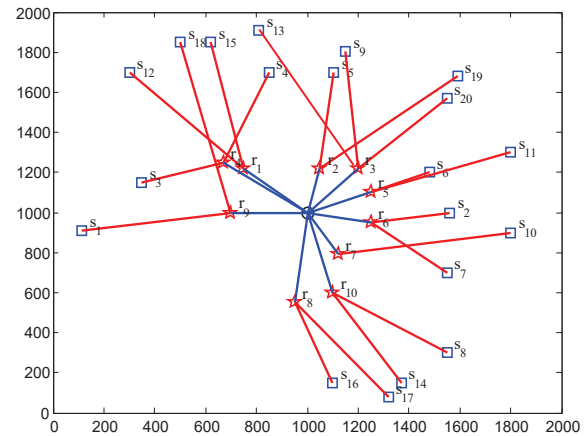| Parameter	Description	Value
f_c	Carrier frequency	2 GHz
P_n	The transmission power of source nodes	23dBm
P_m	The transmission power of relay nodes	30dBm
M	Number of relay nodes	10
L	Number of channels	8
N_0	Noise power spectral	-170 dBm/Hz
B	Bandwidth	10MHz
α	The Urgency of requirements	$1 \leq \alpha \leq 3$
C'_n	The transmission requirement of source node n	8-25 Mbps

Fig. 3. An example of the simulation model and the result of the corresponding relay selection for each source node.
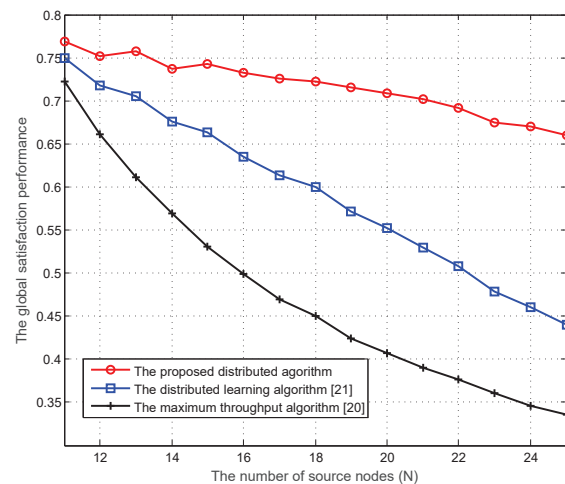

Fig. 4. The global satisfaction performance of the proposed scheme compared with the existing algorithm ($M = 20, L = 8$).

cell edged source nodes randomly distributed. The destination is located at centre of this topology. Each channel of relay nodes has an opportunity to be shared by source-destination pairs. The experimental parameters of the relay transmission follow the simulation methodologies of 3GPP specifications [30], and the performance of various algorithms is evaluated through extensive simulations using MATLAB. The details of the simulation parameters are shown in Table I.

Firstly, we fix the number of relay nodes and channels, and vary the number of source nodes to detect the influence caused by the variation of the network. We analyze the performance of satisfaction, fair performance and convergence to verify the proposed algorithm. After that, the value of α was adjusted to analyze the performance of the proposed algorithm in the different transmission requirement situation. In order to validate the performance of the proposed algorithm, the results of the proposed algorithm is compared with the existing relay selection algorithms.
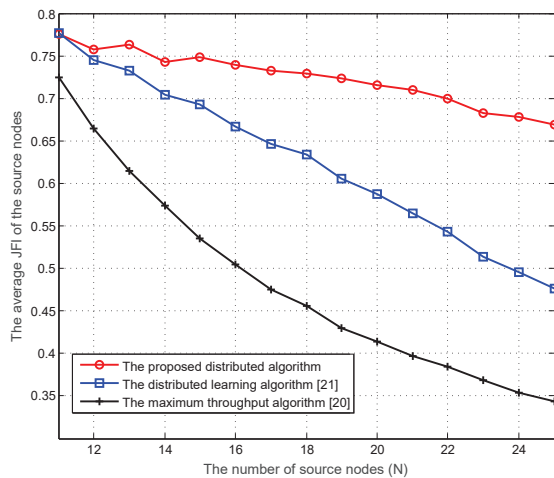
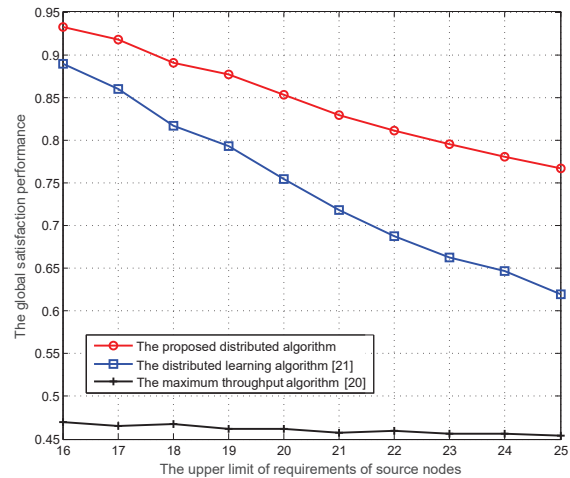Fig. 5. The fairness performance among source nodes of the proposed scheme compared with the other algorithms ($M = 10, L = 8$).

Fig. 6. The global satisfaction performance when the range of requirement varies ($N = 20, M = 10, L = 8$).

An example of the network topology of this paper is shown in Fig. 3, and the connection results of the proposed algorithm in this topology are also given. The blue line and the red line respectively represent the connection of the relay node to the destination node, and the source node to the relay node. After giving the intuitive connection diagram, we average 600 results of different topologies and give the results of data analysis as follow.

In Fig. 4, the global satisfaction of the proposed algorithm is shown by varying the number of source nodes. The number of relay nodes and channels are fixed as $M = 10$, $L = 8$, respectively. Results of the maximum throughput algorithm [20] and the learning algorithm in [21] are compared. It can be seen in Fig. 4 that the performance of the proposed algorithm in term of satisfaction is better than the existing algorithms at all network sizes. Increasing number of source nodes bring a sharp decline to the other algorithms, while the downward trend of the proposed algorithm is relatively flat and its advantage is more and more obvious compared with the other algorithms. The main reason is that existing algorithms focused on the performance of average throughput or maximum throughput, while the QoE-aware relay selection model need more accurate method to optimize. Different from the existing algorithm, the proposed algorithm can assign the resource of relay nodes according to the requirement of source nodes.

Fig. 5 shows the fairness performance of the proposed algorithm compared with the existing algorithms. The JFI is a widely used index to compute the global performance of fairness [31]. In order to detect the fairness performance of the global satisfaction, the satisfaction aware JFI [10] is used, that is

$$\text{JFI} = \frac{\left(\sum\limits_{n=1}^{N} u_n \right)^2}{N \sum\limits_{n=1}^{N} {u_n}^2}. \tag{29}$$

Shown in the Fig. 5, the simulation results and trends are similar to those shown in Fig. 4. The result means that the proposed algorithm not only outperforms in term of the global satisfaction compared with the existing algorithms, but also ensures the rationality of the resource assignment. The fairness of distribution is taken into account during the matching process in the premise of maximizing the global satisfaction.

Next, we vary the range of transmission requirement among source nodes and discuss its impact on the system performance. We set the numbers of source nodes, relay nodes and channels as 20, 10, and 8, respectively. The communication requirement of the source nodes randomly falls within the interval $[8, x]$ (Mbps), where we adjust the x value from 16 to 25. It can be noted that when x changes from 16 to 25, the difference of requirements between nodes is constantly increasing, and the effect is shown in Fig. 6. As can be seen from the figure, the global satisfaction will decrease with the increase of transmission demand. However, the performance of the proposed algorithm is superior to other existing algorithms in various requirements, indicating that it can cope with the difference of transmission requirements.

The convergence performance of the proposed distributed algorithm is shown in Fig 7, which is given in the form of cumulative distribution function (CDF). In the simulation, the number of the relay and channel number are constant, and the number of source nodes is varied from 15 to 25. We can see that larger number of source nodes needs more time to converge, where the network with 25 source nodes generally need 2 times than that of 15 source nodes. The reason is that the increasing density of network will lead to the conflicts among nodes intensified. Even so, the network with 25 source nodes spend about 80 iterations to be stable, which can effectively cope with the effects of fleet formation change. From the results, the rationality of the convergence performance is verified.
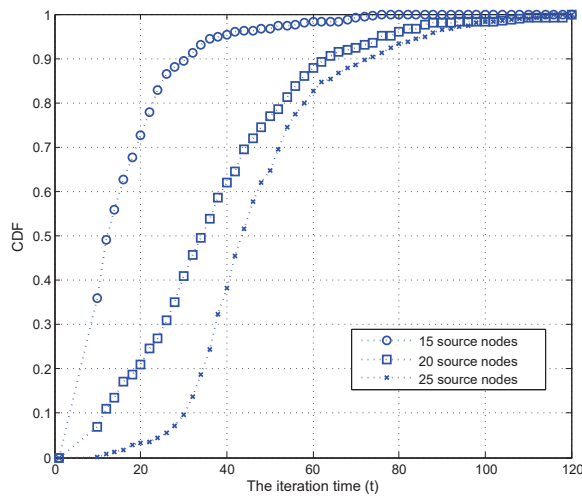
Fig. 7. The CDF of the proposed distributed algorithm with various numbers of source nodes, i.e., $N = 15, 20$ and 25.

IX. CONCLUSION

This paper studied the problem jointing the channel access, relay selection and resource allocation in QoE-aware relay network. Different from the traditional relay model, a self-organizing relay networks including multiple source nodes and relay nodes was considered, in which each source node had its own communication requirement. A distributed hierarchical game model was constructed to solve the problem, where the channel access problem was modeled as a congestion game model, and the problem of relay selection jointing time assignment was modeled as a matching model with dynamic quotas. A hierarchical algorithm combining two game models was designed for the QoE-aware relay network and the stable convergence was proved. The simulation results showed that the proposed distributed optimizing method outperformed in terms of satisfaction, fairness and convergence.

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