Supplementary File: Cooperative Coverage Extension in Relay-Union Networks

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Abstract—This supplementary file is for the manuscript "Cooperative Coverage Extension in Relay-Union Networks" submitted to TPDS, which mainly contains the literature review, proofs of the theorems, additional experimental data and some lengthy details of the paper's main idea. It improves the solidity and completeness of the TPDS manuscript.

1 BACKGROUND

RELAY-UNION Networks in our paper refer to public area WLANs deployed in public areas such as classroom and office buildings, in which clients often move in and out of AP's coverage area, and can provide data forwarding service for others. The objective of our work is to address coverage extension and connectivity enhancing issue.

There has been an increasing interest in enhancing the coverage and connectivity of wireless networks [1]–[6]. Wang *et al.* [1] investigate a connectivity-enhancing mechanism for large-scale wireless sensor and ad hoc networks by introducing k-hop clustering, and prove that random walk mobility with non-trivial velocity increases connectivity in k-hop clustered networks. Femtocell technology, which refers to the data access points installed by home users to get a better indoor voice and data coverage, has been utilized as a cost-efficient means of improving cellular coverage and capacity [2]. There are several recent literatures focusing on femtocell technologies [3]–[6]. A distributed and self-organizing femtocell management architecture called CTRL is proposed to successfully preserve users' service quality from femtocells' interference and limit the effects of the estimation errors of channel gains and feedback delay [3].

Note that both k-hop clustering and femtocell are single hop access technologies. Multi-hop access is investigated to extend the coverage of public area WLAN networks in our paper. Note that there are actually two-hops from client to AP in our current solution, three-hops or more might be involved in the future to better utilize the potential cooperative resources inspired by multiple users in public area WLANs.

This paper is an extended version of a full paper published in INFOCOM 2011 [7]. The extension mainly includes a RUN framework, a distributed dynamic deploy mechanism of MRMC, extensive evaluations for new algorithms, and more detailed analysis for the approach and the experimental results.

2 RELATED WORK

To better utilize the forwarding capability of each node in multi-hop public area WLAN, cooperation needs to be involved. The nodes in WLAN network may be cooperative or selfish. The former one indicates that all clients choose to cooperate with other nodes to maximize social welfare, any selfish or malicious behavior (e.g. free-riding) may not be involved in this scenario. Selfish nodes, on the other hand, usually choose to refuse offering any forwarding services to others if without any benefit.

In the context of cooperative scenario, several works have been proposed to maximize the revenue of ISP and address congestion control issue in infrastructure network. Non-competitive pricing has been extensively employed as a tool to handle resource (e.g. bandwidth, wireless channel) allocation in the literature ([8]–[14]). Hande et al. [9], as a representative contribution, present an ISP revenue maximization and congestion management scheme for the appropriate choice of flat-rate and usage-based components in the access price for broadband services offered by a monopoly ISP. However, the existing pricing-based solutions mainly focus on maximizing service providers' revenue in infrastructure network without considering end users' profit and are somehow failed to capture the full characteristics of RUN (e.g. the role (client or relay) exchange feature). In this paper, We try to explore an applicable solution to guarantee the aggregate revenue of all nodes in RUN.

In the meantime, a considerable amount of works focus on dealing with the selfishness of clients in multi-hop networks. Incentive mechanisms ([15]–[20]) or game theory analysis ([21]–[28] are usually employed to address the problem. The former one usually offers credits or reputations to the nodes who provide services to encourage cooperation. It can either employs a mechanism of charging for requesting service and rewarding for providing service by introducing virtual money, or build a credit system to maintain a degree of reputation for each node. The objective of these incentive mechanisms is to guarantee the revenue of service providers to achieve fairness. The latter one (game theory analysis) is also used to evaluate the optimal pricing strategy for competing users or service providers. Srinivasan *et al.* [21] first apply it to their scheme. Felegyhazi *et al.* [22] investigate the equilibrium conditions of packet forwarding strategies and point out that forwarding cooperation can exist without incentive mechanisms under certain strict conditions. An abstract model of content production and sharing over P2P networks has been constructed in [23]. Game theoretic analysis is used to decompose the inefficiency of non-cooperative equilibria into two parts, and then two classes of pricing schemes are proposed. E.C. Efstathiou *et al.* [29] leverage receipt exchange to achieve a reciprocity protocol under competitive scenario. They propose Peer-to-Peer Wireless Network Confederation (P2PWNC) protocol under the environment of Wireless Community Networks (WCN). They divide clients in WCN into several teams, each team requires a team leader to manage team identifier generation and receipt exchange. The centralized management node in this scheme may cause robustness and security issues.

Resource allocation for cooperative multi-hop access in RUN have not been widely investigated yet, which is the main focus of our paper. Note that the reason of employing credit-exchange in our approach is neither to encourage relays to help forwarding, nor to maximize the revenue of service providers. In other words, we do not intend to design a kind of incentive mechanism, we just deal with bandwidth allocation and client-relay association issues in RUN with the assist of credit-exchange mechanism. The only objective of credit-exchange is to maximize the social welfare of the entire RUN.

3 Assumption Clarification and Theorem Proofs

In this section, we first explain two assumptions in our main paper, then we list several supplementary definitions which can help readers better understand our work, finally, the proofs of the theorems depicted in our main file are included.

Assumption 1: The utility function of a client is concave.

Assumption 1 can be justified as follows. The derivative ${f_i}'(B)$ of the function $f_i(B)$ is equivalent to the marginal utility (MU) of the access bandwidth, which refers to the increase rate of the credit that the client is willing to pay relative to the access bandwidth. According to the Law of Diminishing Marginal Utility [30], MU decreases with the increase of the access bandwidth because a client's desire of getting more access bandwidth does not increase with each additional unit of bandwidth acquired. Therefore ${f_i}'(B)$ is a decreasing function. Thus $f_i(B)$ should be concave.

Assumption 2: The cost function of a relay is convex.

Assumption 2 can be justified as follows. The derivative ${g_j}'(B)$ of the function $g_j(B)$ is equivalent to the marginal cost (MC) of the serving bandwidth, which refers to the increase rate of the cost over the serving bandwidth. MC is increasing with the increase of the relay's serving bandwidth. The reason is that when the occupancy rates of CPU and bandwidth become higher, the harm to the performance of the relay caused by forwarding for others become heavier. Thus the more the relay's serving bandwidth, the more severe the negative impact it has on the performance of the relay. Therefore ${g_j}'(B)$ is an increasing function. Thus $g_j(B)$ is assumed to be convex.

Definition 1 (Revenue of a relay-client pair): The revenue $\mathcal{R}_{rc}$ of a relay-client pair $r-c$ is defined to be the revenue of a client plus the revenue of the corresponding relay.

Definition 2 (Revenue of a cluster): The revenue $\mathcal{R}_r$ of a cluster r is defined to be the revenue of a relay plus the total revenue of the corresponding clients that the relay serves for.

Theorem 1: Under single-relay single-client scenario, the revenue of pair c_i-r_j is maximized when the critical MU of its client c_i equals the critical MC of itself, which means that ${f_i}'(B_c^i) = {g_j}'(B_{cr}^j)$ holds.

Proof 1: The pair's revenue $\mathcal{R}_{ij} = f_i(B) - g_j(B)$ should be maximized when $B = B_c^i$. Therefore B_c^i is the zero-point of the derivative of function $\mathcal{R}_{ij}$, which means ${f_i}'(B_c^i) = {g_j}'(B_c^i)$. Since there is only one client, we have $B_c^i = B_{cr}^j$. Thus ${f_i}'(B_c^i) = {g_j}'(B_{cr}^j)$. ■

Theorem 2: Under SRMC scenario with the free bandwidth demand model and the optimal client cutoff bandwidth allocation, the critical MU of each client equals the critical MC of the relay.

Proof 2: To solve the problem defined by Eq. (2) in the main file, we need to evaluate the maximum value of the multivariate function $\mathcal{R}(\{B_c^i\}) = \sum_{j=1}^{N} f_j(B_c^j) - g(B_{cr})$. Therefore, we calculate the partial derivative of function $\mathcal{R}$ for each B_c^i and set it to 0. From $\frac{\partial \sum_{j=1}^{N} f_j(B_c^j)}{\partial B_c^j} = \frac{df_i(B_c^i)}{dB_c^i}, 1 \le i \le N$ and $\frac{\partial g(B_{cr})}{\partial B_c^i} = \frac{dg(B_{cr})}{dB_{cr}} \times \frac{dB_{cr}}{dB_c^i} = \frac{dg(B_{cr})}{dB_{cr}}, 1 \le i \le N$, we get the following set of equations.

$$\frac{df_i(B_c^i)}{dB_c^i} = \frac{dg(B_{cr})}{dB_{cr}}, 1 \le i \le N \qquad s.t. \quad B_c^i \ge 0 \qquad (1)$$

Since $\frac{df_i(B_c^i)}{dB_c^i}$ is the critical MU of the client c_i and $\frac{dg(B_{cr})}{dB_{cr}}$ is the critical MC of the relay, theorem holds. ■

Theorem 3: Under SRMC scenario with the dynamic bandwidth demand model and the optimal client cutoff bandwidth allocation, the critical MU of every client equals the critical MC of the relay.

Proof 3: We set the partial derivative function of $E_{\mathcal{R}}$ for each B_c^i to be zero, i.e. $\frac{\partial E_{\mathcal{R}}}{\partial B_c^i} = \frac{\partial E_{utility}}{\partial B_c^i} - \frac{\partial E_{cost}}{\partial B_c^i} = 0$, $1 \le i \le N$. From $\frac{\partial E_{utility}}{\partial B_c^i} = \frac{df_i(B_c^i)}{dB_c^i} \int_{B_c^i}^{+\infty} q_i(B)dB$ and $\frac{\partial E_{cost}}{\partial B_c^i} = \frac{dg(E_{bs})}{dE_{bs}} \int_{B_c^i}^{+\infty} q_i(B)dB$, we get Eq. (2).

$$\frac{df_i(B_c^i)}{dB_c^i} = \frac{dg(E_{bs})}{dE_{bs}}, 1 \le i \le N \qquad s.t. \quad B_c^i \ge 0 \qquad (2)$$

The solution $B_c^i = \{B_c^0, B_c^1, ..., B_c^N\}$ of Eq. (2) is just the optimal bandwidth allocation. It is clear that the critical MU $\frac{df_i(B_c^i)}{dB_c^i}$ of each client c_i equals the critical MC of the relay $\frac{dg(E_{bs})}{dE_{bs}}$. ∎

Theorem 4: The client-relay association and the client cutoff bandwidth allocation issue under MRMC scenario is a NP-hard problem.

Proof 4: Consider a special case of the issue in which the client cutoff bandwidth matrix B is a constant one and all utility and cost functions are linear. Then it becomes a linear integer programming problem, which has proved to be NP complete. Therefore the problem defined by Eq. 13 (in the main file) is at least as hard as integer programming.

To better compare the performance between MRMC and D^{2}MRMC, we consider a more specific scenario. In RUN, a group of clients are defined to be homogeneous if they employ the same revenue functions, same minimum bandwidth demands, and same bandwidth demand distributions. We get the following theorem:

Theorem 5: If all clients are homogeneous, D^{2}MRMC achieves the same result as MRMC.

Proof 5: In MRMC, we select the relay-client pair with the highest contribution during each iteration. If all the clients are homogeneous, the contribution of each client does not depend on its identity according to Eq. (11) (main file) any more. It is determined by the amount of clients that have already been served by the relay. Therefore, the contribution has nothing to do with the sequence of the client arrivals. Thus D^{2}MRMC can achieve the same result as that of MRMC. ∎

Theorem 6: Under SRMC and MRMC scenario, the charge function of each client is independent of the revenue of the entire network.

Proof 6: In SRMC scenario with one relay and N clients, assume the charge and utility function of client i to be $h_i(B)$ and $f_i(B)$, respectively; and the cost function of the relay is $g(B)$. Thus the summation of the revenue of N clients can be formulated by $\sum_{i=1}^{N}(f_i(B_i) - h_i(B_i))$, while the revenue of the relay being $\sum_{i=1}^{N} h_i(B_i) - g(\sum_{i=1}^{N} B_i)$. Hence the total revenue of the cluster should be $\sum_{i=1}^{N}(f_i(B_i) - g(\sum_{i=1}^{N} B_i)$, which is still independent of the charge functions.

Similar situation happens under MRMC scenario, it can be treated as K (number of relays) clusters, and each cluster follows the theorem we have proved before.

4 Additional Analysis

4.1 An Example of SRMC Optimal Bandwidth Allocation

Let's take a look at a simple example of three clients with utility functions $f_i(B) = a_i B^{\frac{1}{2}}, 1 \le i \le 3$, and a relay cost function $g(B) = bB^2$, where a_i and b are constants. Then

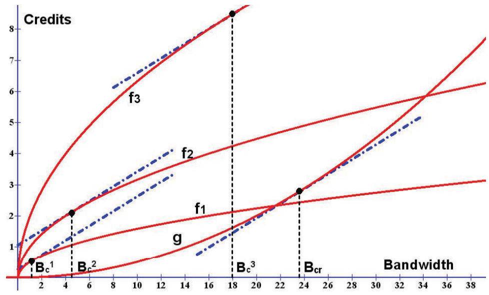


Fig. 1. An illustration of Theorem 2

Eq. (1) can be written as

$$\begin{cases} \frac{1}{2}a_1(B_c^1)^{-\frac{1}{2}} = 2b(B_c^1 + B_c^2 + B_c^3) \\ \frac{1}{2}a_2(B_c^2)^{-\frac{1}{2}} = 2b(B_c^1 + B_c^2 + B_c^3) \\ \frac{1}{2}a_3(B_c^3)^{-\frac{1}{2}} = 2b(B_c^1 + B_c^2 + B_c^3) \end{cases} \quad (3)$$

By solving Eq. (3) we obtain the expressions shown in the middle column of Table 1. The numerical results are reported in the third column when $a_1 = 0.5$, $a_2 = 1$, $a_3 = 2$, and $b = 0.005$.

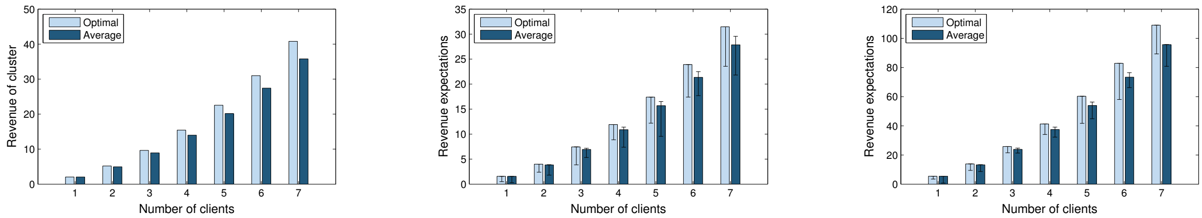
Fig. 1 illustrates the intuitive meaning of Theorem 2. We obtain four tangent lines with the tangency points located at $(B_c^1, f_1(B_c^1))$, $(B_c^2, f_2(B_c^2))$, $(B_c^3, f_3(B_c^3))$ and $(B_{cr}, g(B_{cr}))$. These four tangent lines are parallel to each other, which means that $f_1{}'(B_c^1) = f_2{}'(B_c^2) = f_3{}'(B_c^3) = g'(B_{cr})$, demonstrating the equivalence of critical MUs and the critical MC. Meanwhile, $B_c^1 + B_c^2 + B_c^3 = B_{cr}$ because B_{cr} is the aggregate cutoff bandwidth of the relay. Note that B_c^1, B_c^2, and B_c^3 are the optimal client cutoff bandwidths that maximize the total revenue of N pairs.

4.2 Revenue Contribution of Each Client Under Dynamic Bandwidth Demand Model

Under SRMC scenario, to find out the client with the least contribution to the network revenue, we calculate δ_i for each client. Under dynamic bandwidth demand

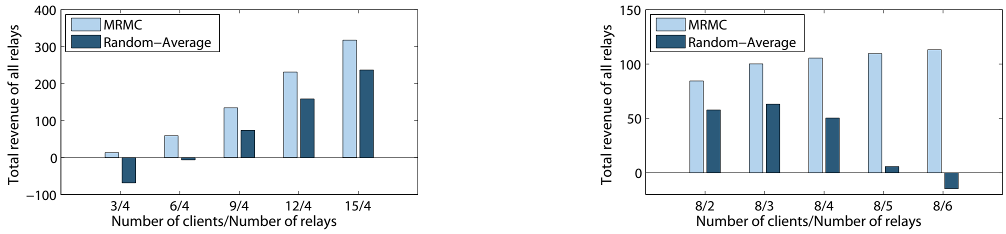
TABLE 1
Evaluation result of the example in subsection A

Parameters	Expressions	Values
B_c^1	$\frac{a_1^2}{\sqrt[3]{16b^2(a_1^2+a_2^2+a_3^2)^2}}$	1.1233
B_c^2	$\frac{a_2^2}{\sqrt[3]{16b^2(a_1^2+a_2^2+a_3^2)^2}}$	4.4930
B_c^3	$\frac{a_3^2}{\sqrt[3]{16b^2(a_1^2+a_2^2+a_3^2)^2}}$	17.972
B_{cr}	$\sqrt[3]{\frac{a_1^2+a_2^2+a_3^2}{16b^2}}$	23.588
Critical MU	$\frac{\sqrt[3]{4b(a_1^2+a_2^2+a_3^2)}}{2}$	0.2359
Critical MC	$\frac{\sqrt[3]{4b(a_1^2+a_2^2+a_3^2)}}{2}$	0.2359
$\mathcal{R}$	$\frac{(a_1^2+a_2^2+a_3^2)}{\sqrt[3]{4b(a_1^2+a_2^2+a_3^2)}} - b(B_c^1 + B_c^2 + B_c^3)^2$	8.346



(a) Free model with polynomial utility/cost function (b) Dynamic model with uniform distribution (c) Dynamic model with normal distribution

Fig. 2. Cluster's revenue with single relay multiple clients



(a) Number of clients varies (b) Number of relays varies

Fig. 3. Performance of MRMC

model, the calculation of δ_i can also be depicted as follows:

$$\delta_i = E^i_{utility} - (g(E_{bs}) - g(E_{bs} - E^i_b)) \quad (4)$$

where $E^i_{utility} = \int_0^{B^i_c} f_i(B)q_i(B)dB + \int_{B^i_c}^{+\infty} f_i(B^i_c)q_i(B)dB$, $E_{bs} = \sum_{j=1}^{N}(\int_0^{B^j_c} Bq_j(B)dB + \int_{B^j_c}^{+\infty} B^j_c q_j(B)dB)$, and $E^i_b = \int_0^{B^i_c} Bq_i(B)dB + \int_{B^i_c}^{+\infty} B^i_c q_i(B)dB$.

4.3 Comparisons Between Centralized MRMC and D²MRMC

In this section, we give a simple comparison between the centralized MRMC and the distributed one. We compare them from the perspective of average response time, load balancing and fault tolerance performance.

Consider this scenario: a user leaves the coverage area of AP and needs forwarding service from relay. Define response time to be the time interval from the moment it generates bandwidth demand to the moment it obtains forwarding service. In centralized solution, the client should sends its utility function to the centralized control node, the control node re-invokes MRMC algorithm to compute the latest association decision and cutoff bandwidth for each client (which is not necessary), and sends the results back to the client. Assume the average round-trip time (RTT) between the client and the centralized node is T_c. From the analysis in the main file we know the time complexity of MRMC is:

$$T(MRMC) = O(N^2(N + K)T_B(N)) \quad (5)$$

where N refers to the number of clients and K refers the number of relays, and $T_B(N)$ refers to the time complexity of $BandAlloc()$; then the average response time T_{center} of the client can be derived as follows:

$$T_{center} = T_c + p_1 N^2(N + K)T_B(N) \quad (6)$$

where p_1 is a constant.

Under D²MRMC, the client listens to the beacon frames of all the relays that it can connects to, and gets the pricing parameter set from them. It then invokes SRMC algorithm for K times to find the best relay to associate with. After the chosen relay receives the association request, it invokes Alg. 4 (main file) to update its cutoff bandwidth vector. Note that if the serving bandwidth of the relay exceeds its capacity, the client may be kicked out and it has to find another relay to associate with. This case happens at most K times. Hence, the average response time of the distributed scheme $T_{distributed}$ can be derived as follows:

$$\begin{aligned} T_{distributed} &= K^2 T(SRMC) \\ &= K^2 O(N \cdot T_B(N)) \\ &= p_2 N K^2 T_B(N) \end{aligned} \quad (7)$$

Where p_2 is a constant. As a result, our distributed scheme reduces the average response time by:

$$T_{center} - T_{distributed} = T_c + (p_1 N^3 + p_1 N^2 K - p_2 N K^2)T_B(N) \quad (8)$$

It can be seen from Eq. 8 that unless K is large enough, N is small enough and T_c is small enough compared with computation time, our distributed scheme achieves positive average response time reduction compared with the centralized one. In real-world network environment, T_c is always far more larger than the computation time, thus the response time is significantly reduced after employing our distributed scheme.

Besides response time reduction, D^2MRMC also performs better than the centralized one in load-balancing. The latter one processes all the computation tasks on one node. If the center node is a battery-powered device, its battery will be quickly used up. D^2MRMC distributes computation tasks to different clients to avoid single-node bottleneck. With the role exchange of the nodes in RUN, the entire network can achieve load balancing in the long run.

The above analysis on the centralized one both bases on one assumption: clients can always connect to center node. It is impractical in real network. If the client cannot connect to the center node (e.g. too far or center node departs from RUN), it will be impossible to obtain forwarding service from any relay even it's in the coverage area of the relays. The problem will not happen if the distributed scheme is employed. Each client relies on itself to find and associate with one relay.

4.4 Limitations of RUN mechanism

Although our credit-exchange based RUN mechanism is able to adapt for various scenarios, it has its inherent limitations. First of all, since we choose social welfare maximization as the only optimization objective, relays will always serve the clients who can bring more network revenue. From client perspective, the clients with low utility contributions will always be kicked out from obtaining relays' service, they cannot be fairly treated during the running of RUN. The phenomenon can be observed in Fig. 4(b) of our main file. With the increase of the number of clients, the clients which have less contributions (e.g. $2\sqrt{B}$ for Client $\#1$) will be kicked out in priority. When the number of clients equals 7, client $\#1$ will always be kicked out, it can never get service from this relay. In a word, our current mechanism cannot achieve fairness from client perspective.

From relay perspective, load-balancing of the entire network would also be a significant problem. With the mobility of the nodes, it is hard for the clients to be uniformly distributed according to the distribution of the coverage areas of the relays. A portion of the relays may suffer from heavy load caused by providing forwarding service, while other relays cannot provide any service because there is no clients in the coverage area of them. Besides, consider two relays in a certain area, all the clients in this area would choose the same relay as the serving relay because its cost function is smaller. This will also lead to imbalance traffic distribution in RUN. To address the problem, a sort of coordination mechanism between relays and clients can be introduced in the future.

However, since the objective of our system is to maximize social welfare and the revenue is independent of the charge, we believe our mechanism can work well under most of the scenarios. For instance, even if the nodes in RUN do not move at all, the profit of the relays can still be guaranteed since clients should pay real money for relays periodically based on the credits recorded. We will take fairness and load-balancing into considerations in our future work.

5 Additional Experimental Results

In this section, we list some of our experimental results about the performance of our SRMC and MRMC algorithm under different bandwidth model. Note that we mainly calculate the total revenue gained after one unit time, the mobility of the nodes and long-term revenue of the network are not involved. The results demonstrate that our optimal and approximate algorithms both achieve similar revenue increment under different parameter settings.

5.1 Performance evaluation under SRMC scenario

We consider the case of single-relay multi-client first. To study the impact of different cutoff bandwidth allocation strategies on the relay's revenue, we vary the utility/cost functions and the bandwidth demand distributions. The results for 1 to 7 clients are reported in Fig. 2, in which each data point is evaluated by only one run because the results are deterministic under the same simulation parameters. Note that no constraint on the relay bandwidth capacity and the client minimum bandwidth demand is placed in this part. The legend "Optimal" in the figures stands for the optimal cutoff bandwidth allocation obtained from Eq. (1) or Eq.(2) while "Average" is listed for comparison, with "Average" meaning that relay's cutoff bandwidth are equally allocated to all clients.

The free bandwidth demand model is employed in Fig. 2(a). The utility and cost functions are selected according to Assumptions 1 and 2. In Fig. 2(a), the utility functions for the seven clients are defined by $2\sqrt{B}, 3.5\sqrt{B}, 5\sqrt{B}, ..., 11\sqrt{B}$ (step 1.5) while the cost function is $0.2B^2$. It is clear that our allocation scheme leads to a higher relay revenue than the other two schemes.

The results of the dynamic bandwidth demand model are shown in Fig. 2(b) and Fig. 2(c). The utility functions are the same as in Fig. 2(a), and the cost functions are $0.4B^2$ in Fig. 2(b) and $0.25B^2$ in Fig. 2(c). The bandwidth demand of a client follows a uniform distribution in $[0.5, 2.5]$ Mbps in Fig. 2(b), while it follows a normal distribution with $\sigma = 2$ and $\mu = 4$ in Fig. 2(c). It can be observed that our scheme still achieves the maximum revenue, while "Average" performs bad with a small number of clients.

5.2 Performance evaluation under MRMC scenario

Fig. 3 depicts the simulation results of MRMC in comparison with a "Random-Average" scheme, in which clients are randomly associated with relays and relays allocate its bandwidth capacity to all clients equally. The free bandwidth demand model is used under the constraints on the relay bandwidth capacity and the client minimum bandwidth demand. The utility functions of the clients are defined as $\sqrt{B}, 3\sqrt{B}, 5\sqrt{B}, ..., 23\sqrt{B}$ (step 2) while the cost functions of the relays are $0.1B^2, 0.15B^2, 0.2B^2, ..., 0.35B^2$ (step 0.05). The bandwidth capacities of the relays follow a uniform distribution on [6,14] Mbps, while the minimum bandwidth demands of the clients follow a uniform distribution on [0.5,2.5] Mbps. Fig. 3(a) reports the total revenue of all relays under a various number of clients while the number of relay is 4. Fig. 3(b) shows the result under a various number of relays while the number of client is fixed to 8. The result of MRMC is an average over 50 runs while that of "Random-Average" is over 1000 runs to reduce randomness. It is obvious that MRMC possesses an apparent advantage over "Random-Average". The latter has very poor performance when the number of client is small or the number of relay is large. When there are only 2 or 3 relays, the performance of these two schemes are close to each other. This is because the effect of MRMC on optimizing the relay-client association is not significant when the number of relay is small.

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