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Exact Optimum RAN Selection Algorithm for Heterogeneous-Type Cognitive Radio Networks

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Abstract–By the heterogeneous type cognitive radio network technology, communication qualities can be improved by appropriate selection of a radio access network (RAN) in heterogeneous wireless network environment. In such a wireless network system, the optimum RAN selection problem becomes combinatorial optimization problems in which the number of combinations increases exponentially. For such problems, usually we give up to find exact optimum solution and apply heuristic algorithms to find good near-optimum solutions. In this paper, we propose a novel approach that can exactly solve the RAN selection problem even when the number of combinations of the terminals and the base stations explosively increases. The proposed methods formulate such combinatorial optimization problems as a minimum cost flow problem, which can be solved rigorously even for large problems. We apply the proposed method to throughput fairness optimization by the load balancing as an example and confirm its effectiveness. Our results show the CPU time to obtain the rigorous solutions of base station selection problem can be very short time, even for very large-scale networks.

1. Introduction

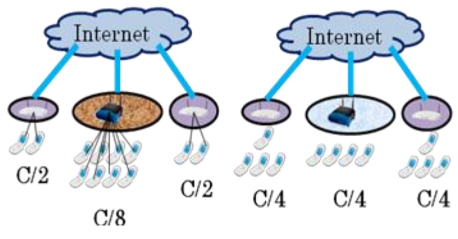
Various kinds of radio access networks (RANs), such as Wi-Fi, WiMAX, cellular phone systems, and so on, have been widely deployed. For such heterogeneous wireless network environment, a new approach to further improve efficiency of the usage of limited radio resources, the heterogeneous type cognitive radio technology, has been developed [1][2] and its management framework has already been standardized in IEEE1900.4 [3]. There are several types of cognitive radio use cases defined in the standard, dynamic spectrum allocation, dynamic spectrum sharing and distributed radio resource usage optimization (DRRUO). The DRRUO enables to optimize utilization and efficiency of the radio resources by appropriate RAN selection based on the context information of the terminals and the RANs.

The RAN selection problem in such a heterogeneous wireless networks becomes a combinatorial optimization problem. In this problem, the number of the combinations increases exponentially when the number of terminals and the number of base stations (BSs) increased, it's hard to solve the RAN selection problem in a reasonable time. For such a reason, we usually give up to find the exact solution and try to obtain good approximate solutions by applying heuristic algorithms. However, those algorithms do not have the guarantee that provides the optimum solution.

In this paper, we propose a novel approach to obtain the exactly optimum solution of RAN selection whose combination number increase exponentially. In order to solve it exactly, we formulate the problem as an minimum cost flow problem, which can be rigorously solved by an exact algorithm. We show our algorithm solves exact solution in short time with simulation results.

2. Load-balancing RAN selection problem

There are a lot of factors, which should be optimized, in heterogeneous type cognitive radio networks. As one of such RAN selection problems, we introduce the load-balancing problem in this paper. The load balancing can optimize fairness of the throughput among the users and the entire network's quality of service (QoS) in a limited amount of radio resource.



(a) When the traffic load is unbalanced, the throughputs for users become unfair.
(b) By balancing the traffic load, the throughputs for users become fair.

Figure 1. Load-balancing RAN selection problem modeled as a Minimum cost flow problem.

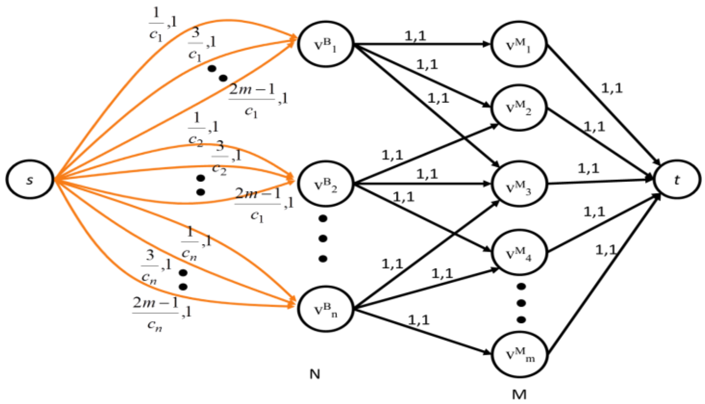


Figure 2. Load-balancing RAN selection problem modeled as a Minimum cost flow problem.

We assume that each BS shares radio resources equally to all of the connecting terminals in a packet based wireless network. Under this assumption, the throughput of the terminal *i* can be defined as follow,

$$T_i(t) = \frac{c_{L(i)}}{N_{L(i)}}, \quad (1)$$

where, c_j is the total throughput which the BS *j* can provide, N_j is the number of mobile terminals which are connecting to the BS *j* at time *t*, and $L(i)$ is the BS which the terminal *i* is connecting, respectively.

The summation of each terminal throughput and the total of provided throughput by all BSs does not change, $\sum_{j=1}^{n} c_j = \sum_{i=1}^{m} T_i = \text{const.}$, where the *n* is number of the BSs and *m* is number of the terminals, respectively. Therefore, the objective function for throughput fairness optimization can be defined as follows,

$$F = \sum_{i=1}^{m} \frac{1}{T_i}, \quad (2)$$

By minimizing *F*, differences between T_i is reduced with kept maximizing the sum of throughput T_i. By using Eq. (1), the objective function can be transformed as the following equation,

$$F_{OBJ}(\mathbf{L}) = \sum_{i=1}^{m} \frac{N_{L(i)}}{c_{L(i)}}. \quad (3)$$

This is the function of **L**, which is the list of connecting BS of each terminal $L_{(i)}$.

This is a problem to find optimum combinations of BSs and terminals selection. This combinatorial optimization problem becomes very hard when the number of BSs and terminals increase, because the number of combination increase exponentially. In this paper, we propose a new method to obtain rigorous solution by small computational complexity even for large scale network.

3. Exact optimization algorithm of RAN selection

Our proposed approach exactly solves the combinatorial optimization problem of RAN selection defined in the previous section, by transforming it to a network flow problem. We modify it to the minimum cost flow problem, which can be solved rigorously.

The minimum cost flow problem is to minimize the following objective function by assigning flow x_e for each edge *e*,

$$F_{\text{MCF}}(\text{x}) = \sum_{e \in E(G)} w_e x_e, \quad (4)$$

under the condition that $x_e < p_e$ and satisfying a given amount of the flow reaching from the source vertex *s* to the sink vertex *t*, where w_e is the cost of the edge *e* and p_e is the capacity of each edge *e*, respectively. This problem can be exactly solvable by the algorithms, such as the one in Ref. [4].

In order to exactly solve the RAN selection problem, we formulate it as the minimum cost flow problem, which is exactly solvable problem. For this purpose, at first, we transform Eq. (3) to the following form,

$$F_{OBJ}(\mathbf{N}) = \sum_{j=1}^{n} \frac{N_j}{c_j} \bullet N_j = \sum_{j=1}^{n} \frac{(N_j)^2}{c_j}, \quad (5)$$

which is the function of the numbers of connecting terminal to the BS *j*.

Because there are N_j terminals connecting to each BS *j* and their throughput are same, $\frac{c_j}{N_j}$ for all terminals connecting to the same BS, we can transform this function to the following form,

$$F_{OBJ}(\mathbf{N}) = \sum_{j=1}^{n} \frac{\sum_{k=1}^{N_j} 2k-1}{c_{L(i)}} = \sum_{j=1}^{n} \sum_{k=1}^{N_j} \frac{2k-1}{c_j}. \quad (6)$$

We formulate this form of the RAN selection optimization problem as the minimum cost flow problem as shown in Fig.2. The cost w_e and the capacity p_e of each edge *e* are shown as w_e, p_e, on each edge in the graph of the figure. The vertices v^{M}_i corresponds to the mobile terminals, and the vertices v^{B}_j to the BSs, respectively. The total flow from the source *s* to the sink *t* is the number of mobile terminals *m*.

The edges with (1,1) connecting destination *t* and the mobile terminals, means that each mobile can establish a wireless link with only one of available BSs. Between the vertices v^M_i and vertices v^B_j, we set (1,1) edges for the pairs of the mobile terminal i and the BS j that i is located in the coverage area of j and i has the capability to establish a wireless link to j. Since the exit from v^M_i is 1 for each, only one edge to v^M_i will have flow 1, and the corresponding edge having this flow will be the solution of the optimum RAN selection. For the edges between source s and v^B_j, we use multiple connections to give $\frac{N_j^{\,2}}{c_j}$ flow for each v^B_j.

By solving this minimum cost flow problem, the lowest cost edges will be chosen and the amount of traffic flow to the BSs will be balanced with the total throughput of each BS c_j as the weight. In this paper, we use the exact algorithm for the minimum cost flow problem proposed in Ref. [4] to obtain the exact solution of the RAN selection problem

4. Evaluation of the Proposed Scheme

4.1. Computational Complexity Analysis

The computational complexity of the algorithm [6] is $O(N_v N_e \log(N_v C))$, where N_v and N_e are the numbers of the vertices and edges in the graph, C is value of maximum cost. Therefore, for the problem for RAN selection shown in Fig. 2 becomes

$$O((n+m+2)^2(2nm+n)\log(n+m+2)) .$$

The number of combinations of the RAN selection problem is n^m, which increases exponentially with increase of the number of mobile terminals. For such problems with combinatorial explosion it is usually considered that it is impossible to obtain rigorous solution. Our proposed algorithm show that the RAN selection problem is not always NP-hard and we can obtain the exact solution in small computational amount. In Fig. 3, we show increase of the computational complexity of the proposed approach. For the comparison, increase of the computational amount for the full search to obtain the exact solution is also plotted. While the computational amount increases exponentially for the full search, the proposed scheme does not increase even for very large problems.

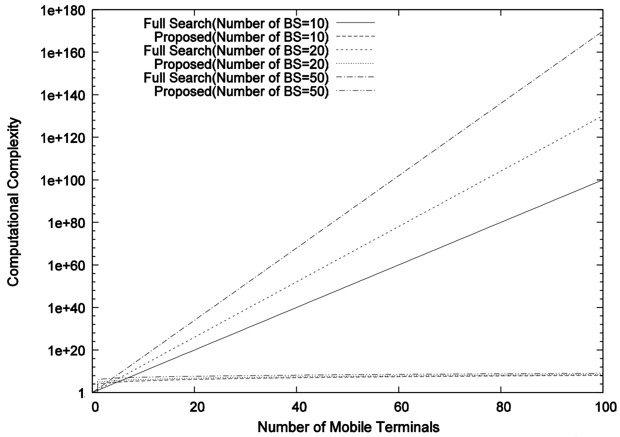


Figure 3. Computational complexity of the proposed scheme and full search.

4.2. Simulation Result

We run the proposed scheme on the computational simulation. In Fig. 4, we show the example layout of terminals and BSs. The black solid circles indicates the base stations and white circles indicates the terminals, respectively. We use two types of the base stations which provides 11Mbps with 80m coverage and 54Mbps 40m coverage, respectively.

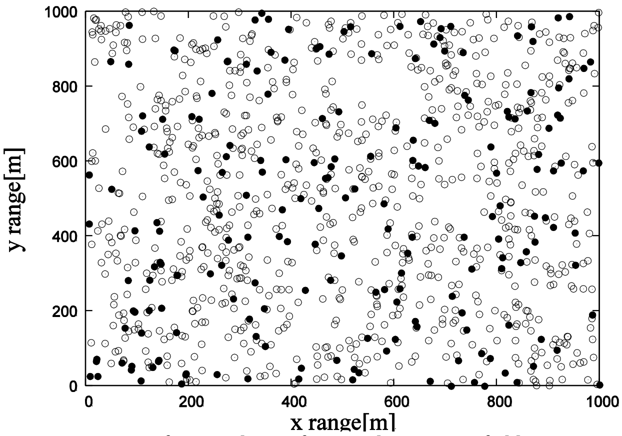


Figure 4. 200 of BSs and 900 of terminals in 1000m field range.

In Fig. 5 and Fig. 6, we show the CPU time to obtain the rigorous solutions. Fig. 5 is the result on the 1000m times 1000m field and Fig. 6 is the result of the 2000m times 2000m field, respectively. In the case shown in Fig. 5 with higher density, the optimization problem becomes more complex, since the number of available combinations of the terminals and the base stations increase. We run our simulation on Solaris 10 operating system installed on a server with floating point processor at 2926 MHz.

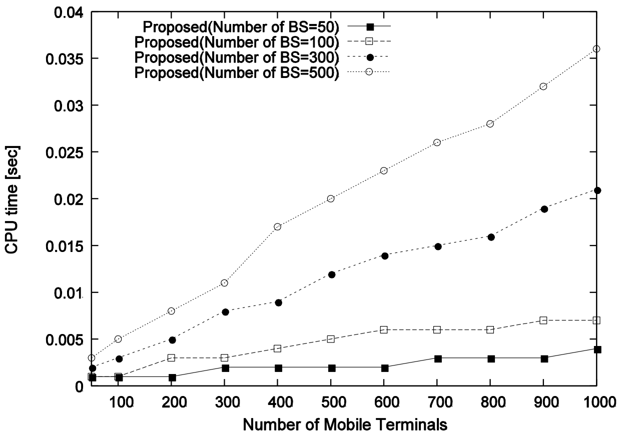


Figure 5. CPU time to obtain the rigorous solution of the RAN selection problem in 1000m time 1000m field.

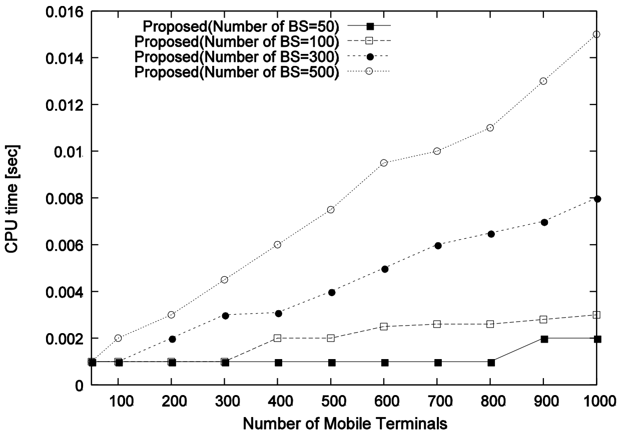


Figure 6. CPU time to obtain the rigorous solution of the RAN selection problem in 2000m times 2000m field.

In these result, proposed scheme can obtain rigorous solution in very short time. Even for the most complex case with 500 BSs and 1000 terminals in Fig. 5, the rigorous solution can be obtained in 0.036 seconds in average.

6. Conclusion

In this paper, we propose a new optimization approach for the network selection problem in heterogeneous type cognitive radio networks. Although the problem is a combinatorial problem whose number of combinations increase exponentially, our proposed algorithm can obtain rigorous solution, by formulating the network selection problem as a minimum cost flow problem. By computer simulation, we confirm that our algorithm can obtain rigorous solution in short time even for large scale problem.

As future works, we would like to implement the proposed scheme based on a standardized cognitive radio network architecture as we have already did for the heuristic algorithm as in Ref. [5]. We would also like to apply the proposal approach to optimize other factors which should be optimized in cognitive radio networks.

Acknowledgments

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