Joint Optimization for Congestion Avoidance in Cognitive Radio WMNs under SINR Model

Jie Jia, Qiusi Lin, Jian Chen, and Xingwei Wang

Due to limited spectrum resources and differences in link loads, network congestion is one of the key issues in cognitive radio wireless mesh networks. In this letter, a congestion avoidance model with power control, channel allocation, and routing under the signal-to-interference-and-noise ratio is presented. As a contribution, a nested optimization scheme combined with a genetic algorithm and linear programming solver is proposed. Extensive simulation results are presented to demonstrate the effectiveness of our algorithm.

Keywords: Congestion avoidance, channel assignment, power control, SINR, genetic algorithm.

I. Introduction

Wireless mesh networks (WMNs) are suitable for wireless backbone transmission environments and have proven valuable in next-generation Internet [1]. With the increasing number of users and a growing demand for better quality of service (QoS), limited spectrum resources create serious obstacles to obtaining high-performance data services in WMNs. Fortunately, the emergence and development of cognitive radio (CR) technology has provided a novel solution for WMNs [2]. However, optimal resource allocation should be considered, as it is affected by the openness of the wireless frequency spectrum [3].

We consider a CR-based WMN with multiple routing sessions, each session characterized by a specific capacity requirement. To guarantee QoS for each session, we study the congestion avoidance problem under the signal-to-interference-and-noise ratio (SINR) model, in which a transmission is deemed successful only if the SINR is larger than a specified threshold. Although the SINR model is more realistic than the "protocol model" [4] for interference characterization, the joint optimization under the SINR model is generally nondeterministic polynomial time (NP) hard and very difficult to solve. We propose a novel nested optimization technique based on a genetic algorithm (GA) as an efficient solution.

II. Network Model

Consider a cognitive WMN with $V=\{i|1\leq i\leq N\}$ nodes and C noninterfering channels $OC=[1, 2,\ldots, C]$, in which each node $i\in V$ is equipped with I intelligent interfaces to perceive available channels, $OC_i\subset OC$. Denote $OC_{ij}=OC_i\cap OC_j$ as the set of channels that is common between nodes i and j. The maximum transmission power is totally quantized into T levels, and each node can intelligently select its transmission power levels, $t\in [1, 2,\ldots, T]$, for all its interfaces.

Let $x_{ij}^{m,t}$ indicate the resource allocation between node i and j. If $x_{ij}^{m,t}=1$, it means that node i assigns channel m ($m\in OC_{ij}$) and power level t ($t\in T$) communicating with j; otherwise, $x_{ij}^{m,t}=0$. Since concurrent transmission may cause the disorder of arriving packets, only one channel and one power level are assigned between i and j at a time.

$$\sum\nolimits_{m\in OC_{ij}}\sum\nolimits_{t\in T}x_{ij}^{m,t}\leq 1\quad (i,j\in V,\ i\neq j). \tag{1}$$

The channel allocation of node i is indicated by y_i^m. If $y_i^m=1$, then $\exists j\in V$, $i\neq j$, $m\in OC_{ij}$, $t_1,t_2\in T$, x_{ij}^{m,t_1} or $x_{ji}^{m,t_2}=1$; otherwise, $y_i^m=0$. Since the number of channels simultaneously used by a node is limited by the number of

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interfaces,

$$\sum_{m\in OC_i} y_i^m \le I \quad (i\in V). \tag{2}$$

When transmitter i adopts channel m and power level t, the receiving power of node j, denoted as $p_{ij}^{r,m,t}$, is

$$p_{ij}^{r,m,t} = p^t \cdot d_{ij}^{-\gamma} \cdot x_{ij}^{m,t} \quad (i,j\in V,\ i\neq j,\ m\in OC_{ij},\ t\in T), \tag{3}$$

where $d_{ij}^{-\gamma}$ is the communication gain between node i and j, γ is the path loss factor, and d_{ij} is the distance between i and j. Define the interference of receiver j hearing from other connections on band m in all power levels as p_{ij}^m, that is,

$$p_{ij}^m = \sum_{k\in V,(k\neq i)} \sum_{h\in V,(k\neq h)} \sum_{t\in T} p^t \cdot d_{kj}^{-\gamma} \cdot x_{kh}^{m,t} \quad (j\in V). \tag{4}$$

Let P_N be the noise power and $s_{ij}^{m,t}$ be the SINR from node i to j on channel m and power level t, that is,

$$s_{ij}^{m,t} = \frac{p_{ij}^{r,m,t}}{P_N + p_{ij}^m} \quad (i,j\in V,\ i\neq j,\ m\in OC_{ij},\ t\in T). \tag{5}$$

Denote $U_{ij}(m, t)$ as the effective capacity of link $e(i, j)$ on channel m and power level t. According to Shannon's capacity formula, it can be calculated as

$$U_{ij}(m, t)= H_m\cdot\log_2(1+s_{ij}^{m,t}) \quad (i,j\in V,\ m\in OC_{ij},\ t\in T). \tag{6}$$

In practice, if the SINR is very small, the effective capacity is too small to carry traffic flow. Define the SINR threshold as α, and the minimum capacity is $H_m\cdot\log_2(1+\alpha)$. As only one channel and one power level is assigned on link $e(i, j)$, the effective capacity of link (i,j) is defined as the sum of $U_{ij}(m, t)$:

$$U_{ij} = \sum_{m\in OC_{ij}} \sum_{t\in T} U_{ij}(m,t) \quad (i,j\in V,\ i\neq j). \tag{7}$$

Define $<s_q, d_q, r_q>$ as denoting the routing sessions, where s_q, d_q, and r_q represent the source, destination, and traffic demand of session $q\in[1, 2,\ldots, Q]$, respectively. Define $f_{i,j}^q$ (and $f_{j,i}^q$) as the traffic flow traveling from i to j (and from j to i) for session q. We have

$$f_{i,j}^q \ge 0, f_{j,i}^q \ge 0 \quad (i,j\in V,\ i\neq j,\ q\in Q), \tag{8}$$

$$\sum_{(k,i)\in E}^{k\neq d(q)} f_{k,i}^q = \sum_{(i,j)\in E}^{j\neq s(q)} f_{i,j}^q \quad (i\neq s_q,\ i\neq d_q,\ i\in V,\ q\in Q), \tag{9}$$

$$\sum_{(i,j)\in E} f_{i,j}^q = r(q) \quad (i=s_q,\ q\in Q), \tag{10}$$

$$\sum_{(j,i)\in E} f_{j,i}^q = r(q) \quad (i=d_q,\ q\in Q), \tag{11}$$

$$\sum_{q\in Q} f_{i,j}^q \le U_{ij} \quad (i,j\in V,\ i\neq j,\ q\in Q), \tag{12}$$

where (8) restricts the amount of flow on each link to be nonnegative, (9) states that the amount of incoming flow is equal to the amount of outgoing flow at each node (except the source and destination), (10) represents that the outgoing flow from the source is equal to its traffic demand, (11) states that the incoming flow to the destination is equal to its traffic demand, and (12) indicates that the sum of the flows over all sessions traversing a link cannot exceed the effective capacity.

Let δ_{ij} be the difference between the efficient capacity U_{ij} and the actual carrying load $\sum_{q\in Q} f_{i,j}^q$,

$$\delta_{ij} = U_{ij} - \sum_{q\in Q} f_{i,j}^q. \tag{13}$$

Intuitively, if δ_{ij} on the most heavily congested link tends to be 0 (negative value), the corresponding logical link e_{ij} tends to become congested. On the contrary, if δ_{ij} on the most heavily congested link is maximized, the congestion rate in the network is minimized. With the above notion, let $\delta_{\min}$ be the congestion avoidance parameter of the network, which is defined as the smallest δ_{ij} across all the links:

$$\delta_{\min}=\min_{i,j\in V,\ i\neq j} \delta_{ij}. \tag{14}$$

Hence, the congestion avoidance problem combined with channel allocation, power control, and routing is defined as

$$\max : \delta_{\min} = \max : \min_{i,j\in V, i\neq j} \delta_{ij}$$

$$\text{s.t. (1)-(13).} \tag{15}$$

The objective function and all constraints are linear with linear and integer variables, which can be viewed as a mixed integer linear programming (MILP) problem. In general, this optimization problem is NP-hard.

III. Nested Optimization Approach

The effective capacity of each link is determined by channel assignment and power control. Furthermore, the traffic load distribution in the network can be changed by routing schemes. Thus, the congestion avoidance highly depends on both routing and resource management including both channel assignment and power control. To handle such a relationship between congestion avoidance, routing, and resource allocation, all these subproblems should be combined to obtain optimal network performance. However, the integration of them for joint optimization further increases the process complexity. Hence, an alternative is to use some evolutionary computation techniques to find the optimal solutions [5]. In this letter, we propose a crosser-layer optimization approach based on a GA. The entire solution contains a GA-based power control and channel allocation and a linear programming (LP) solver to evaluate the individual with the given resource allocation and routing sessions.

For the problem mapping of joint channel allocation and power control using a GA, we design a node-based chromosome coding mechanism, in which each individual node is represented as a two-vector string, $\{\vec{a}_v, \vec{t}_v\}$, where $\vec{a}_v$

$=\{a_{v,1},\ldots, a_{v,j},\ldots, a_{v,C}\}$ represents the set of channels assigned to node v and $\vec{t_v} = \{t_{v,1},\ldots, t_{v,j},\ldots, t_{v,C}\}$ represents the power level allocation of node v. If $a_{v,j}=1$, then channel j is selected by v; otherwise, $a_{v,j}=0$. Only when $a_{v,j}$ is set to 1 does $t_{v,j}=t$ ($0<t\leq T$); otherwise, $t_{v,j}=0$. For individual decoding, the channels and power levels are sequentially bounded to the wireless interfaces of each cognitive user. For example, if $a_{v,j}=1$ and j is the m-th selected channel ($1\leq m\leq I$), channel j and power level $t_{v,j}$ are used by the m-th interface of this cognitive user.

In population initialization, to ensure that none of the nodes use more than I channels, each node randomly sets I bits of its channel vector to 1, and the power level is set as $t_{v,j}=\text{rand}(1, T)$ if $a_{v,j}=1$. Based on this coding and initialization strategy, we can get an initial population with M randomly generated individuals. In subsequent generations, this population evolves via a series of selection, recombination, mutation, and replacement operations. The main procedure of GA-based channel allocation and power control is described as follows.

Algorithm 1. GA-based channel allocation and power control.

```
Generate initiation population $P$ with randomly generated $M$ individuals using coding and initialization strategy
Calculate $f$ value for each individual in $P$ using LP solver
while $Max\_gen$ generations are not completed do
    while $numP/2$ loops are not completed do
        Select $p_1$, $p_2$ from $P$ using selection strategy
        Create $o_1$, $o_2$ from $p_1$, $p_2$ using recombination and mutation strategy
        Calculate $f(o_1)$, $f(o_2)$ using LP solver
        Find two channel assignment schemes $b_1$, $b_2$ that have the largest $f$ values in $P$
        Replace $b_1$, $b_2$ with $o_1$, $o_2$
    end while
end while
Return the best resource allocation scheme in $P$
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Here, the selection strategy used is the roulette wheel selection method, where the chosen probability is proportional to the individual fitness. The fitness function is the maximum congestion avoidance and can be calculated by an LP solver. Due to the local optimization property in the channel assignment problem described in [5], the recombination operator used in this letter is simply single-point crossover and only executed by the substring chromosomes of each individual, which can ensure that the new individual generated still obeys the node-interface constraint. The mutation operator is applied to each substring, and the swap mutation is used to avoid illegal solutions.

After channel allocation and power control, each individual can be mapped to a network topology graph $G(V, E, U)$, where each vertex $i\in V$ corresponds to a cognitive user, there is a directed link $e(i, j; m, t)\in E$ in G if $x_{ij}^{m,t}=1$, and $s_{ij}^{m,t}\geq\alpha$, $u(i, j)\in U$ is the effective capacity of link $e(i, j)$. Additionally, the congestion avoidance problem can be rewritten as

$$\max : \delta_{\min} = \max : \min_{i,j\in V, i\neq j} \delta_{ij}$$

$$\text{s.t. (8)-(13).} \tag{16}$$

This problem only includes linear variables and can be viewed as an LP problem, which is much simpler than MILP. In our letter, the LP solver *linprog* in the Matlab toolbox is introduced, which can evaluate the problem quickly.

IV. Performance Evaluation

In the simulation, 30 mesh nodes are randomly located in a 500×500 area. Each node has the same number of interfaces, that is, four. The path loss index γ is 4, P_N is set to –85.9 dBm, and the SINR threshold α is 10 dB. The maximum transmission power P_t is 20 dB and is quantized into T=16 levels. Assume there are 10 available orthogonal channels and each channel has a bandwidth of H_m=55 Mbps. At each node, only a subset of channels is available. There are five communication sessions generated with random source, destination, and different traffic demands, which are listed in Table 1. The crossover probability and mutation probability are set to 0.95 and 0.05, respectively. Here, we should note that the brute force approach cannot solve the problem for the above-mentioned 30-node network. Because the number of $x_{ij}^{m,t}$

Table 1. Information of five routing sessions.

Session ID	1	2	3	4	5
Source ID	16	24	13	19	26
Destination ID	28	11	1	29	15
Demand (M)	40	70	10	80	10

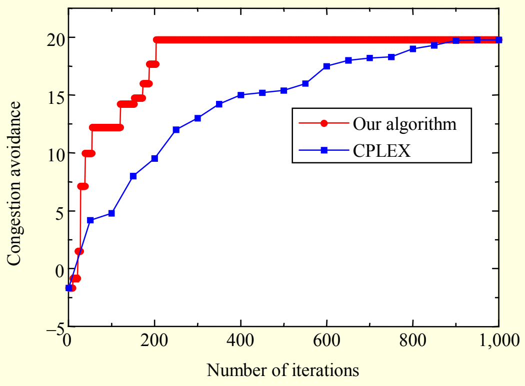

Fig. 1. Congestion avoidance in different generations.

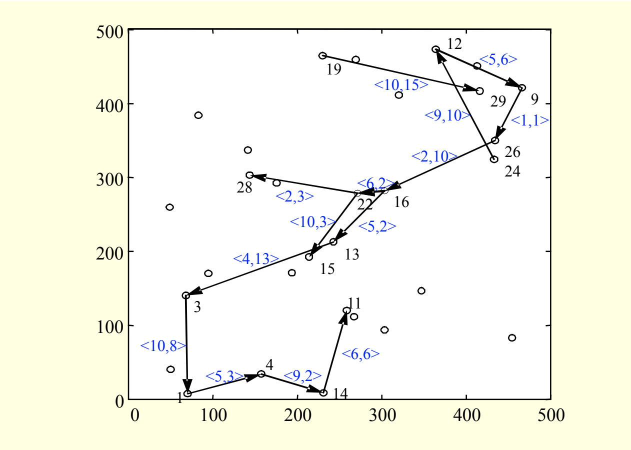

Fig. 2. Final routes.

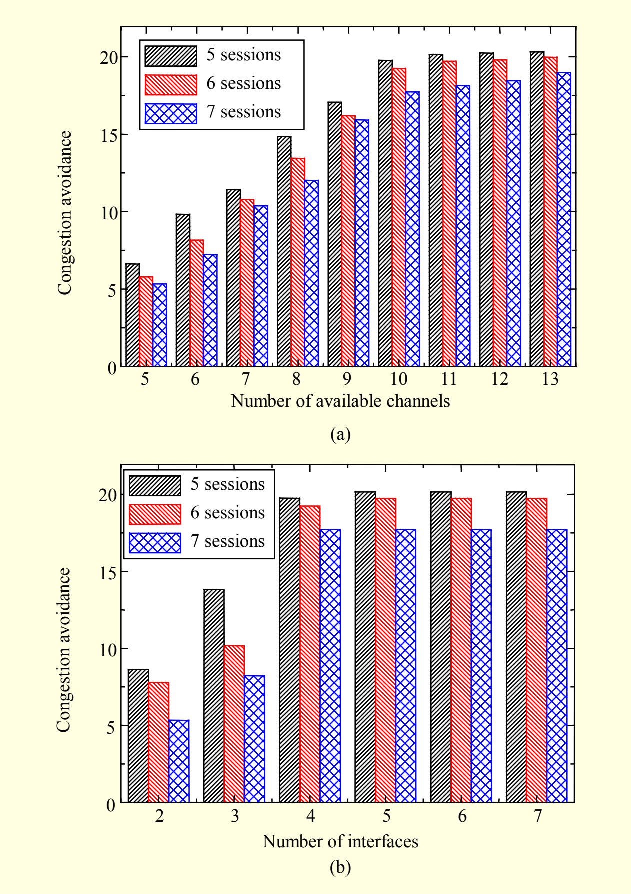

Fig. 3. Congestion avoidance comparison in (a) different channels and (b) different interfaces.

variables is $(30\times(30-1))^{10\times16}=870^{160}$, suppose one solution is executed in 10^{-6} seconds; then, the time to find the optimal $x_{ij}^{m,t}$ using the brute force approach is about $870^{160}\times10^{-6}/(365\times34\times60\times60)>10^{455}$ years.

Figure 1 shows the comparison of network congestion avoidance with different iterations. Clearly, in our algorithm, the congestion avoidance increases from a negative value to an optimal solution more rapidly. After the 300th generation, no better solutions can be found, which shows that our algorithm can converge to the optimal solution more quickly than the CPLEX method. Figure 2 shows the final route for each session. The solid line arrow shows the links in the routing tree, and the numbers beside the links represent the assigned channel and power level for each link. From Fig. 2, we can clearly see that all the interfering links in the routing tree are assigned different channels. By assigning the proper power level, we can obtain the optimal effective link capacity.

Figure 3(a) shows the comparison of congestion avoidance in different numbers of channels and routing sessions when the number of interfaces is fixed to four. Figure 3(b) shows the comparison of congestion avoidance in different numbers of interfaces and routing sessions when the number of channels is fixed to ten. Clearly, more routing sessions, fewer channels, and fewer interfaces result in lower congestion avoidance, as expected.

V. Conclusion

In this letter, we investigated the problem of joint channel allocation and routing scheduling for cognitive WMNs. This problem was formulated as a mixed integer linear programming program. We proposed an efficient nested optimization framework based on a GA to solve this problem. Simulation results show that our algorithm can achieve the maximum network congestion avoidance very quickly.

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