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Joint Channel Assignment and Multi-path Routing in Multi-radio Multi-channel Wireless Mesh Network

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ABSTRACT

Multi-radio multi-channel Wireless Mesh Network requires an effective management policy to control the assignment of channels to each radio. We concentrated our investigation on modeling method and solution to find a dynamic channel assignment scheme that is adapted to change of network traffic. Multi-path routing scheme was chosen to overwhelm the unreliability of wireless link. For a particular traffic state, our optimization model found a specific traffic distribution over multi-path and a channel assignment scheme that maximizes the overall network throughput. We developed a simple heuristic method for channel assignment by gradually removing clique load to obtain higher throughput. We also presented numerical examples and discussion of our models in comparison with existing research.

Key words: Wireless mesh network, routing, channel assignment, multi-channel, multi-radio.

1. INTRODUCTION

Recently, development of Wireless Mesh Network (WMN) [1-2] and supporting technology has gains a lot of attention. More than four hundred of the cities in the world have plans to deploy this network and deployments exist in some cities for public use. The term of Wireless Mesh Network refers to a new wireless network architecture that can provide low up-front cost, easy network maintenance, and reliable service coverage. Network nodes are composed of mesh clients and mesh routers that can dynamically self-organize, self-configure, and automatically establish and maintain mesh connectivity. The mesh client, which can be any kind of conventional nodes (Desktop, laptop, mobile, sensors…), can connect directly to mesh routers forming the network backbone. WMN architecture expressively extends network connectivity and coverage of conventional wireless network. Moreover, WMN also allows interconnection between different wireless technologies to enhance their interoperability. As a result, WMN has a wide range of applications from broadband home networking, enterprise networking, and metropolitan area networks to health and care networking, to the transport system.

In order to enhance aggregated capacity and network performance, multi-radios and multi-channels are integrated into WMN. In multi-channel networks [3-4], network nodes can operate on a predefined set of channels. Different nearby links are assigned to different channel to reduce incurred interference. On other hand, multi-radio network nodes [5-6] are equipped with multiple network interface cards (radios) that simultaneously work on different channels. Links between network nodes can be composed of multi-

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ple links between interfaces to increase the capacity of logical links.

In the multi-radio and multi-channel networks, each network interface has multiple choices of operating channel and this dramatically affects interference, and, as a result, network capacity. This fact raises a question how to find the optimal operating channel for each available radio. Those operating channels should minimizes the interference and directly provide support for current traffic states. This problem is called *Channel Assignment* (CA) problem. Channel assignment can be categorized into two types [7]: Fixed assignment and dynamic assignment. In the fixed assignment, channel and interface are almost unchanged while in the dynamic assignment, they are continuously changed to improve the performance. The dynamic scheme brings more difficulty in management, higher complexity in computation and greater delay in channel switching. Regarding the stability of mesh router topology, fixed channel assignment schemes are preferred because it avoids the unnecessary control overhead and the bottlenecks found in dynamic channel switching.

Interference level between links relies on commodities on each logical link which, however, is assigned by the network routing policy or routing protocols. This recursive dependency necessitates a need for joint design between routing and channel assignment (JCAR) to leverage network performance. Unfortunately, the JCAR problem is well-known as NP-hard [7]. An exact solution is quite expensive regarding the current state of practical wireless network environment. The current approach to overwhelm this problem is that it is divided into several solvable sub-problems. Those sub-problems can be worked out mathematically or heuristically.

Major research results have been published mainly in [8-11] and [12]. In the [8] and [10-11], mathematical models are formulated to obtain the maximum network through subject to interference constraints and available radios. In the reference [8], the authors formulated the JCAR to optimize network throughput subject to interference constraints, number of channels, number of radios, and fairness constraints among concurrent commodities. The references [10-11] are a series of papers of the same authors researched on the multi-channel multi-radio WMN. The authors modeled the problem as linear-mixed binary problems and solved it based on centralized binary optimization. Perhaps the main disadvantage of this approach is the use of centralized implementation schemes. In another approach, researchers used the heuristic approaches [9], [12] to try to allocate channels considering current commodities so that interference within the network is minimized. Reference [9] presented a more practical method regarding the distributed implementation of the algorithm. The authors introduced Channel Cost Metric (CCM) which reflects the interference level and used CCM as a key for performance measures to propose a distributed heuristic algorithm that produces a near-optimal JCAR solution. This approach has a simple implementation but cannot guarantee the convergence. It is suitable to use for the mesh client tier where network topology suffers from a high dynamic.

Traditionally, we can formulate CA problems as integer optimization problems. Depending on other factors in the model, these maybe mixed integer optimization problems [8] and become very hard to solve for a realistic scenario. It is important to notice that we can leverage network throughput by decreasing the interference level between nearby links while keeping support current traffic. When interference level is decreased, radios related to that network node can support more traffic; then, network throughput can automatically increase. Hence, instead of solving the integer optimization problem, we can perform a channel switching that reduces the interference level. Interestingly, that procedure can be performed simultaneously and independently at different network nodes. This observation is key idea for realization of our heuristic protocol in section IV.

Wireless network environments are well-known as being filled with uncertainties caused by various phenomena such as link fluctuation, mobility, or topology changes. A trivial solution but an effective one for this problem is to use many backup paths, called multi-paths, to support one commodity. This solution has been widely used not only in theoretic study but also in practical protocol design. In comparison with single-path routing, obviously, multi-path routing can easily recover from network disruption. This method also shows advantages in comparison to the routing method those results from the Multi-Commodity Flow Algorithm (MCFA), which has been used in [8]. MCFA leads to a division of every network commodity over all network links. This leads to difficulties in controlling message order and protocol implementation. Moreover, from the point of view of resource allocation, the multi-path routing method exploits resource and balance loads from different network areas. Generally, multi-path routing is a tradeoff between single path and MCFA.

The above interesting features in JCAR are not fully addressed by any existing related works. This paper exploits those features and integrates them into a single framework:

1) We propose a modeling method and algorithm to obtain near-optimal solution for JCAR in multi-path routing schemes. Network traffic is optimally distributed over the multi-path and then channel assignment is performed to optimize the network throughput.

2) We develop a simple channel assignment algorithm following the observation discussed above. This algorithm enables distributed implementation of CA. Discussion and details are presented in section III.

3) The JCAR using multi-path has proved its performance in comparison with the one using MCFA in reference [8]. This comparison and discussion we show in the section IV.

The rest of the paper is organized as follows. In the section II, we describe the system model the assumption of our model. In the section III, we present the modeling method and algorithm to solve the JCAR problems. In the section IV, we present a numerical analysis of our method on a specific network.

2. SYSTEM MODEL

In this section, we define the basic concepts and notation that we used in this paper and then we discuss the assumptions and constraints for our wireless network model.

2.1 System model

We consider a multi-hop wireless mesh router network with n node denoted by $N=\{N_1,\dots,N_n\}$ and l wireless links denoted by $E=\{e_1,e_2\dots,e_l\}$. Each node has multi-radio, or, said differently, each node has a number of network interface denoted by vector K. Each element $K(N_i)$ denotes the number of radios at node N_i. Nodes in the network can choose to operate on a set of C orthogonal channels.

Let us assume that there are H commodities denoted as $f=(f_{1\dots},f_H)$. Each commodity is defined by a source node, a destination node, and a demand value. The value of each commodity is considered as known before performing the optimization procedure. We also assume that each commodity has a set of multi-path that is also defined in advance using any traditional routing method [13-14]. Let $r_i=\{r_i^1,r_i^2,\dots,r_i^{M_i}\}$ be the set of the multi-path of commodity f_i where M_i is number of multi-paths. Commodity f_i is able to divide its traffic into multi flow over all its available paths. Let f_i^j be the faction of f_i on path r_i^j. We have $\sum_{j=1}^{M_i} f_i^j = f_i$.

To assure the fairness between the commodities, we use a scaling factor λ to scale commodities to fit all network conditions. Demand of commodity f_i, thus, becomes $\lambda . f_i$.

2.2 Interference constraints and link capacity constraints

In this network, we assume a network model with two-hop interference. Link e_{ij} cannot be active if there is other active transmission on link e_{mn} whose endpoint is the neighbor of link e_{ij}'s endpoint. The two-hop interference model considerably reduces the complexity in the construction of the interference relationship between links. We call that relationship interference clique [15]. A set of logical links in two-hop distance, which may potentially cause interference each other if they are in the same channels, calls logical interference clique.

Considering the interference-free scheduling scheme, with the two-hop interference model, links within a two-hop distance cannot be active simultaneously. Let $c(e_{ij})$ be the link capacity of link e_{ij}, and $F(e_{ij})$ be the total traffic rate on e_{ij}. So, the proportion of time in which link e_{ij} is active is $F(e_{ij})/c(e_{ij})$. The interference constraint of nearby links of link e_{ij} defined as following [4,8]

$$\sum_{e_{mn} \in I(e_{ij})} \frac{\lambda . F(e_{mn})}{c(e_{mn})} \leq \varepsilon \quad \text{With } \forall e_{ij} \in E \tag{1}$$

Where $I(e_{ij})$ denotes the set of the link that interferes with e_{ij}, $0 \leq \varepsilon \leq 1$ denotes the clique capacity. This constraint guarantees that all the commodity rates in all the maximal cliques are feasible for any scheduling schemes. The value of ε depends on some specific characteristic of the contention graph.

Moreover, regarding link capacity, we also have the following constraints for each link e_{mn}

$$F(e_{mn})/c(e_{mn}) \leq 1 \tag{2}$$

The number of radios decides number of available link at each node; therefore, it decides how much traffic can be accepted at each node. This will be referred to as link capacity constraints in this paper.

3. JOINING BETWEEN CHANNEL ALLOCATION AND MULTI-PATH ROUTING

We have so far defined the assumptions and discussed the constraints involved in the modeling process; in this section, we will elaborate on our proposed optimization procedures.

3.1 Overview of optimization procedure

When we use the scaling factor λ to keep the fairness between users, we can consider our problem as maximization of scaling factor λ. There are two kinds of variables in our network that involve in finding λ. These variables are the distribution of each commodity over its multi-path and the channel assignment scheme. At the higher abstraction level, the optimal distribution of network traffic over the multi-path depends on total traffic in cliques, or, in other word, on the interference level, and on the number of radios on involved nodes. This conclusion is directly derived from constraints (1) and (2). For that reason, we can approximately separate the optimal multi-path problem from the channel assignment schemes. Our approach includes two steps:

- *Solve optimal multi-path routing*: Find the optimal scaling factor and traffic distribution over multi-path that fits the interference constraints and link capacity constraints.
- *Solve the CA*: CA is a heuristic method that gradually removes the congestion and offers a larger scaling factor λ. The first problem is solved every time we have changes in the traffic state. After that, we start running the second problem to obtain a higher scaling factor. The second stops only when network demands changed.

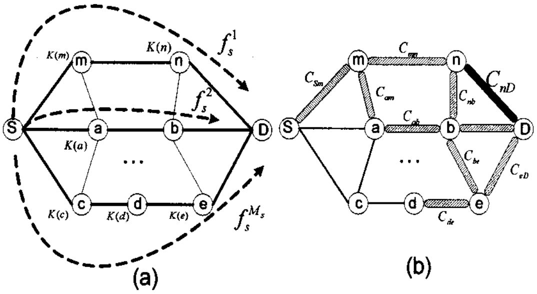

Fig. 1. Two step in optimization procedure. (a) Step1: Optimal multi-path routing. (b) Step 2: Channel assignment involving link (n,D) over flows from step 1.

Fig. 1 presents an illustration of the two steps in optimization procedure. In step one, the optimization procedure involves in finding the optimal distribution of commodity f_s over its M_s paths. The number of radios at each node, which defines the number of possible link between nodes, thus, imposes the amount of traffic supported by each node. The total traffic in a logical clique also defines the potential interference level at that clique. This step takes those two factors as constraints for optimization procedures. In step two, we perform CA based on the traffic distribution of step one. For example, CA at link (n,D), in black, considers only the links in two-hop distance. New CA is chosen when it is feasible all other concerned links.

3.2 Solve optimal multi-path routing

Allocation of multi-path can follow some policies in order to distribute a commodity fairly on the network. When we increase the number of available path, commodity can also increase its coverage over network. Studying further about the set of path is out of the scope of our research. In this research, we use the multi path routing for each commodity. However, uses of a single path or a disjoin path are also feasible choices. Linear programming problem to find the distribution of commodities over multi-path is described as follows.

$$\begin{aligned}
&\underset{f,\lambda}{\text{maximize}} \quad \lambda \\
&\text{s.t} \sum_{e_{ij}\in I(e_{pq})} \frac{\lambda.F(e_{ij})}{c(e_{ij})} \le C.\varepsilon \text{ with } \forall e_{pq}\in E \\
&\sum_{e_{\text{mk}}\in S(N_m)} \frac{\lambda.F(e_{\text{mk}})}{c(e_{mk})} \le K(N_m) \text{ with } \forall \text{N}_\text{m} \in N \qquad \text{(A)} \\
&\sum_{j=1}^{M_i} f_i^j = f_i \text{ with } \forall N_i \in N \\
&\lambda \ge 0
\end{aligned}$$

Where $S(N_m)$ denotes the set of link involved in node N_m. The first constraint is defined by interference constraint between nearby links, which derived from (1) in the case with C available channel. Similarly, derived from (2), the next constraint represents the maximum traffic that can be transmitted over one node. This amount of traffic is limited by the capacity of each link and also by the number of available radios on that node.

To this end, we have shown how to obtain the flows over multi-paths through problem (A). Those flows will be used as parameters in the channel assignment procedure in the next step.

3.3 Solve the CA

We derived following the modelling method from reference [9]. Let x_{mn}, a vector of size $1\times c$, be channel allocation vector for the link (m,n) . $x_{mn}(i)=1$ if the link $e=(m,n)$ is allocated with channel i. Let y_{mn}, a vector of size $1\times I$, be interface assignment vector for the link $e = (m,n)$. We have the constraints of the channel and interface assignment.

$$m,n,p \in N \text{ and } (m,n),(m,p)\in L$$

$$x_{mn}, x_{mp} \in \{0,1\}^C \quad y_{mn}, y_{mp} \in \{0,1\}^I$$

$$x_{mn} = x_{nm}, \; x^T{}_{mn}.x_{mp} = y^T{}_{mn}.y_{mp}$$

The channel and interface assignment is written as follows.

$$\begin{aligned}
&\underset{x,y}{\text{maximize}} \quad \lambda \\
&\text{s.t} \sum_{e_{ij}\in I(e_{pq})} x_{ij}x_{pq} \frac{\lambda.F(e_{ij})}{c(e_{ij})} \le C.\varepsilon \text{ with } \forall e_{pq}\in E \\
&\sum_{e_{\text{mk}}\in S(N_m)} \frac{\lambda.F(e_{\text{mk}})}{c(e_{mn})} \le K(N_m) \text{ with } \forall \text{N}_\text{m} \in N \qquad \text{(B)} \\
&x_{mn}, x_{mp} \in \{0,1\}^C \quad y_{mn}, y_{mp} \in \{0,1\}^I \\
&x_{mn} = x_{nm}, \; x^T{}_{mn}.x_{mp} = y^T{}_{mn}.y_{mp}
\end{aligned}$$

Regarding the hardness of the problem (B), we prefer a heuristic method to gradually improve the scaling factor of the network. Notice that the scaling factor λ only linearly depends on the load of every clique on the network; then, if we can reduce the load on every clique, we can gradually increase the scaling factor. Moreover, this process can be done simultaneously on the overloaded clique. From that notice, we develop a heuristic algorithm to solve the problem (B). We describe it as follows.

At first, we solve the channel allocation locally at one node to obtain the lowest possible load on every clique. Then, that node informs its neighbors to perform the local minimization while keeping supporting the current traffic. Finally, the iteration is stopped when all cliques are changed. Every network node will compute the maximum λ scaling factor. Another process is performed again to minimize the clique load. The clique load of link e_{pq} is computed as follows

$$\Gamma(e_{pq}) = \sum_{e_{ij} \in I(e_{pq})} x_{ij} x_{pq} \frac{\lambda.F(e_{ij})}{c(e_{ij})} \leq C.\varepsilon \text{ with } \forall e_{pq} \in E$$

We can also use any binary search method regarding constraints of connectivity, and channel allocation on the neighbor nodes.

Algorithm 1: Channel allocation and interface assignment

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Input: $(N,E),K,f$ and current global scaling factor $\lambda_i$
For all $e \in E(N_i)$, get the link $e_0 = \arg(\max_{e \in E(N_i)} \Gamma(e))$
For all channels, get the channel $c_0$ with highest clique load.
If there exists $r_s, r_d$ free radios on $N_S, N_d \in e_0$
Use it for $e_0$ on channel $c_0$
If there exists only $r_0$ free radios on $N_S$ or $N_d$
Use it for $e_0$ if it can produce lower $\max_{e \in E(N_i)} \Gamma(e)$
Calculate the $new\_\lambda_{N_i} = \lambda_i * \frac{\varepsilon}{\max_{e \in E(N_i)} \Gamma(e)}$
If $\lambda_{i+1} = \lambda_i$
If there exists $r_s, r_d$ free radios on $N_S, N_d \in e_0$
Create a new link $e_0'$ use $c_0$ with $f(e_0') = \arg(\min_{e \in E(N_i)} \Gamma(e))$
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4. NUMERICAL ANALYSIS

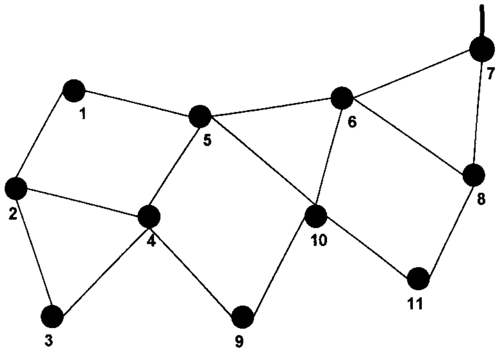

Fig. 2. Logical topology of the numerical analysis

In this section, we present a numerical analysis of the specific topology (Fig. 2). The aim is to demonstrate the performance of our algorithm and compare the computation results with existing results. The evaluation, using numerical analysis, shows performance in two parts. In the first part, we perform an algorithm on an example network and analyze the results of JCAR while comparing it with the current results from the multi-channel multi-radio network capacity regarding the sensitivity of network capacity with number of channels and radios. The purpose of this step is to show the compliance with and correctness of other results. In the second part, we run another example to compare the performance of the algorithm with existing algorithms in terms of network performance.

Our algorithm is implemented on Matlab. First, we solve the problem (A) and use output parameters f_i^j as input of Algorithm 1. The network simulation environment is defined as follows. WMN is assumed to use 802.11a. A simple network channel model is chosen to model the link capacity basing on the common characteristics of 802.11a. The link capacity depends only on the distance between nodes. That is 54 Mbps if the two nodes are within 30m, 48 Mbps they are within 32 m, 36 Mbps if they are within 37 m, 24 Mbps if they are within 45 m, 18 Mbps if they are within 60 m, 12 Mbps if they are within 69 m, 9 Mbps if they are within 77m, 6 Mbps if they are within 90m. Transmission range is 90m and interference range is twice of transmission range, or 180m.

4.1 Impact of multi-radios multi-channel on network capacity

We evaluate the impact of the number of radios and channels on the total network work throughput. By varying the number of radios and number of available channel and calculating the total network throughput we can inspect the impact of the number of radios and channel on the work capacity. The demand in table 1 is assigned on a random topology of 11 network nodes with one gateway, node 7, on an area of 150m x 210m. Clique capacity is assumed to be ε=0.9.

Applying our algorithm to that parameter and varying the number of radios and channel, we found the dependency of the network capacity over the number of radios and channels as in Fig. 3. We notice that when increasing the number of channels and radios the network throughput will also increase. The increment of network throughput can only be done with both increment of number radios and channels. For example, when we have four radios, but small a number of available channels, network throughput cannot increase. This result conforms with other existing results on the dependency of network throughput on the network resources, channel and radios [4,5].

Table 1. Parameters used in numerical analysis

Source nodes	Destination nodes	Demand (Mbps)
2	7	22
3	7	33
10	7	44
11	7	55

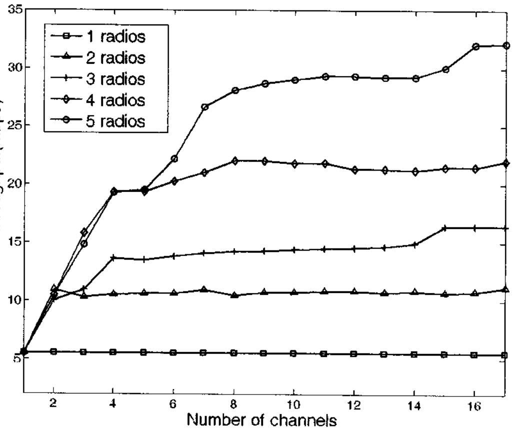

Fig. 3. Effects of varying the number of radios and number of channels

In order to investigate the efficiency of our algorithm in using channel and radios, we compare the total throughput of our proposal method with that of the method proposed in [8]. In [8], the authors used a grid topology to evaluate their methods. In the case of a grid topology with 2 gateway and 20 nodes, 4 radios and 12 channels per node, link capacity is 18Mbps, per node throughput calculated is about 1.6Mbps. Then, the total network throughput of 20 nodes is 32Mbps. When we compare this to our case of 1 gateways, 4 radios and 12 channel, link capacity is 11Mbps, we get the network throughput at around 22Mbps. Because in these two cases link capacity is uniform, we can compare the efficiency using the ratio of network throughput over link capacity. In our case, this ratio is around 2. In [8], this ratio is 33/18. This comparison shows the advantage of our algorithm in compare with the one in [8].

4.2 Comparison of network performance

In this evaluation, we compare the network performance produced by our algorithm with existing algorithm. The chosen algorithm is a join channel and assignment and routing algorithm in WMN in the reference [8]. We chose an equivalent scenario to the scenario used in the [8] so that we can evaluate correctly performance of our proposal. We use a random topology of 60 nodes. Twenty nodes have traffic to 8 gateways. We fixed the number of radios is 3; the number of channels is 12. After numerous of experiments, the results is shown in the Fig. 4. We can see that per-node network throughput falls at around 2 to 6 Mbps. This throughput is similar to the per-node throughput generated from the experiment results of [8]. Hence, using

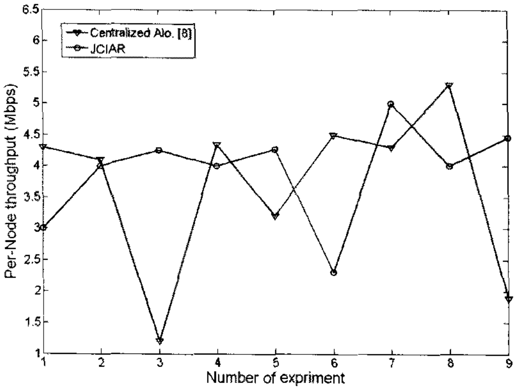

Fig. 4. Comparison of Per-Node throughput between JCAR and Algorithm in (8).

the multi-path we still achieve the network performance similar with the algorithm presented in the [8].

5. CONCLUSION

In this paper, we studied joint design between channel assignment and routing. We argued that multi-path routing could provide better performance the single path routing. Moreover, channel assignment also can be done simpler by lowering the congestion level at each clique. We developed a two-step algorithm. The first step of the algorithm is to obtain the optimal distribution of traffic over the multi-path. The next one is for channel assignment to achieve to maximal throughput. Finally, we showed the correctness and convergence of our proposed algorithm in the numerical examples.

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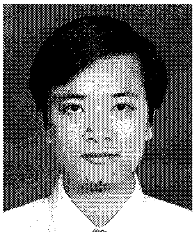

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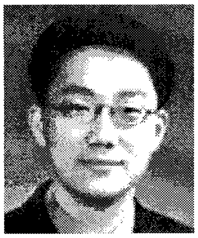

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