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Being Opportunistic or Being Concurrent

— On Designing Channel Assignment Algorithms in Multi-Radio, Multi-Channel Wireless Mesh Networks

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I. Introduction

Wireless mesh networks provide an alternative way to deploy broadband network infrastructures to local communities at low cost [1], [2], [10], [12]. However, the deployment of wireless mesh networks has a major challenge, which is throughput scalability. Due to the highly unpredictable and lossy wireless channels, the throughput achieved by traditional deterministic routing protocols in wireless mesh networks can be quite poor. This problem is particularly serious in urban areas, where exist many sources of interference from various wireless applications [1], [7], [9].

To cope with the highly unpredictable and lossy wireless channels, opportunistic routing emerged as a novel technique to allow any node that overhears the packet to participate in packet forwarding, which is different from the traditional deterministic routing techniques. In an early work, Biswas and Morris [4] introduced the ExOR opportunistic routing protocol and showed that it can achieve superior end-to-end throughput than the traditional deterministic forwarding. Recently, Chachulski et al. [5] proposed the MORE opportunistic routing protocol to address issues in ExOR and achieve even higher throughput in wireless mesh networks.

However, the existing opportunistic routing protocols only consider single-radio wireless nodes, and assume that all the nodes work on the same channel, without exploiting possible concurrent transmissions by multi-radio nodes over orthogonal channels provided by IEEE 802.11 protocols (3 in 802.11b and 12 in 802.11a). Although a considerable amount of work has been done on multi-radio, multi-channel assignment in wireless mesh networks (*e.g.* , [3], [6], [8], [13]–[15]), there are important questions remaining unsolved. For example, will simply integrating the existing channel assignment schemes and the opportunistic routing technique produce a higher end-to-end throughput? If not, in what scenarios a opportunistic routing technique is preferred? Can we design an algorithm to compute the optimal channel assignment, considering the support of opportunistic routing technique? The objective of this work is to present a systematic study to address the above questions.

II. Technical Preliminaries

In this section, we present our network model and assumptions, and formulate the channel assignment problem for wireless mesh networks.

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A. Network Model and Assumptions

We consider a wireless mesh network with stationary wireless nodes (routers), denoted by N, where each node $i \in N$ is equipped with r_i radio interfaces. Let K denote the set of orthogonal (non-interfering) and homogenous channels. For simplicity, we assume that all the nodes use the same transmission rate over their radios, and we normalize the transmission rate as a unit constant.

We assume that there is no power control scheme. Let $\epsilon_{i,j}$ be the link loss probability from node i to node j on any channel; that is, if a packet is transmitted from node i to node j on a common channel shared by them, then with probability $\epsilon_{i,j}$ the packet cannot be decoded.

For simplicity, we do not consider the throughput loss caused by nodes' contention for communication medium. We also do not consider the hidden terminal problem, which has not been fully resolved in opportunistic routing.

B. Problem Formulation

Given a static wireless mesh network of router nodes with multiple radio interfaces, we wish to assign one or multiple channels to each node, such that the number of different channels assigned to a node is not more than the number of radios on the node. The objective of the channel assignment problem for wireless mesh network is to maximize the end-to-end throughput between a source node and a destination node.

Formally, the problem of static channel assignment for a multi-radio wireless mesh network over a set of N nodes, given a set of K channels, is to compute a function $f : N \rightarrow \mathcal{P}(K)$, to maximize the end-to-end throughput between a given source-destination pair (src, dst).

III. A Multi-radio, Multi-channel Opportunistic Routing Protocol

Opportunistic routing is an emerging technique to achieve high throughput despite lossy wireless links. Instead of deterministically choosing the next hop before transmitting a packet, opportunistic routing allows multiple nodes that overhear the packet to participate in forwarding. MORE is a representative and efficient opportunistic routing protocol. Due to limitation of space, we do not review the detail of MORE in this abstract. Unfortunately, MORE was originally designed for a single-radio, single-channel setting. In this section, we describe a simple extension for MORE to work in a multi-radio multi-channel setting.

We allow nodes that are equipped with multiple radio interfaces to work on more than one channels simultaneously. We assume that there is no throughput gain when a node

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has more than one radio on the same channel. Therefore, we require that every node should tune at most one radio on a channel. Now, let's assume that there is an optimal channel assignment profile. It is possible that the number of channels assigned to a node in an optimal channel assignment be less than the number of radios on that node, in which case the node can use redundant radios to serve other flows in the network. However, we focus on maximizing the end-to-end throughput of a single flow in this work. The problem of maximizing the total throughput of multiple flows will be considered in our future work.

Every node can use its assigned channels for packet transmission and reception. Let $X_i^k \in \{0,1\}$ denote whether a radio of node $i \in N$ is assigned to channel $k \in K$[1].

$$X_i^k = \begin{cases} 1 & \text{if a radio of node } i \text{ is assigned to channel } k, \\ 0 & \text{otherwise.} \end{cases}$$

Given $\mathcal{X} = \{X_i^k | i \in N, k \in K\}$, the expected number of packets that node i must forward for delivering one packet from source to destination is:

$$L_i = \sum_{k \in K} \left(X_i^k \sum_{j>i} \left(Z_j^k (1 - \epsilon_{j,i}^k) \prod_{h<i} \left(1 - X_h^k (1 - \epsilon_{j,h}^k)\right) \right) \right), \tag{1}$$

where Z_j^k is the workload of node j on channel k. Let $\mathcal{L} = \{L_i^k | i \in N, k \in K\}$.

Since a node may be assigned multiple channels for transmitting packets, we split the node's duty to different channels. Let L_i^k denote the duty of node i on channel k. Then the sum of the duties should be equivalent to L_i.

$$L_i = \sum_{k \in K} X_i^k L_i^k. \tag{2}$$

Thus, the expected number of transmissions that node i needs to make on channel k is:

$$Z_i^k = \frac{X_i^k L_i^k}{1 - \prod_{j<i} \left(1 - X_j^k (1 - \epsilon_{i,j})\right)}. \tag{3}$$

Let $\mathcal{Z} = \{Z_i^k | i \in N, k \in K\}$. Here an arithmetic error may be raised and the node's workload goes to infinity on channel k, if there is no node, who has smaller ETX than node i, working on channel k, and node i's duty on channel k is not 0. Therefore, we require that when distributing nodes' duties, the channel assignment should be taken into account to avoid the arithmetic error.

Noting that some of the nodes may inject more than enough packets into the network, such that their next hop nodes cannot deliver the packets in time, we introduce a variable, λ_k, to indicate the effective ratio of transmission time for channel k. In other words, λ_k is the minimal percentage of time that channel k is used, in order to guarantee the optimal end-to-end throughput. Let $\Lambda = \{\lambda_k | k \in K\}$. We assume that node i's expected transmission rate on channel k is proportional to its Z_i^k among the nodes in its collision domain. Then, the normalized effective transmission rate of node i, denoted by T_i, is:

$$T_i = \sum_{k \in K} T_i^k, \tag{4}$$

where T_i^k is the normalized effective transmission rate of node i on channel k:

$$T_i^k = \lambda_k \cdot \frac{X_i^k Z_i^k}{\sum_{j \in N \wedge (\epsilon_{i,j} < 1 \vee \epsilon_{j,i} < 1)} X_j^k Z_j^k}. \tag{5}$$

Finally, the end-to-end throughput can be calculated as follows:

$$Throughput = \sum_{k \in K} \left(X_{dst}^k \sum_{i \in N} T_i^k (1 - \epsilon_{i,dst}) \right). \tag{6}$$

In the above equations, there are three unknown set of variables: channel assignment $\mathcal{X}$, duty distribution $\mathcal{L}$, and vector of effective channel usage ratio Λ. In section V, we will present algorithms to compute them.

IV. Infeasibility of Traditional Channel Assignment Schemes

In this section, we use examples to show that the optimal channel assignment, computed by existing channel assignment schemes, cannot still achieve optimal end-to-end throughput when opportunistic routing technique is provided.

In the following examples, we consider the same wireless mesh network with 4 nodes, in which every node is equipped with 2 radio interfaces. The number of available orthogonal channels is 3. We show the "optimal" channel assignment computed by traditional channel assignment algorithms (that do not consider opportunistic packet reception), and the optimal channel assignment for our multi-channel opportunistic routing protocol — EMORE. We also compare the end-to-end throughput achieved by the two channel assignments, when EMORE is used. In the examples, colored lines show data flows on different channels.

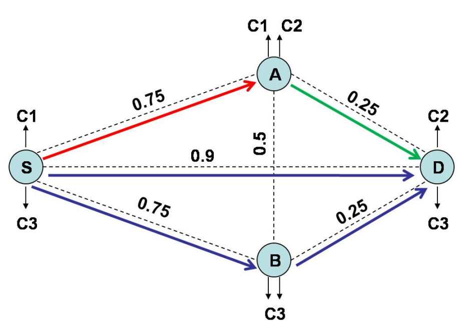

Fig. 1. "Optimal" channel assignment computed by the traditional channel assignment algorithm. Every node has 2 radio interfaces, the number of available orthogonal channels is 3, and the loss probability is indicated on each link.

Figure 1 and Table I jointly show the channel assignment computed by the traditional channel assignment algorithm, and routing strategy for EMORE. The total normalized end-to-end throughput calculated through Equation(5) and (6) is 0.5.

Figure 2 and Table II jointly show the optimal channel assignment, when opportunistic routing protocoal EMORE is

[1]We do not distinguish which radio is assigned to channel k.

TABLE I

CHANNEL ASSIGNMENT $\mathcal{X}$, WORKLOADS $\mathcal{Z}$, AND EFFECTIVE CHANNEL USAGE RATIOS Λ FOR THE CASE SHOWN IN FIGURE 1.

X_i^k	S	A	B	D
k=1	1	1	0	0
k=2	0	1	0	1
k=3	1	0	1	1

	λ_k
k=1	1.0
k=2	0.3333
k=3	1.0

Z_i^k	S	A	B
k=1	2.1429	0.0	0.0
k=2	0.0	0.7143	0.0
k=3	1.4286	0.0	0.4286

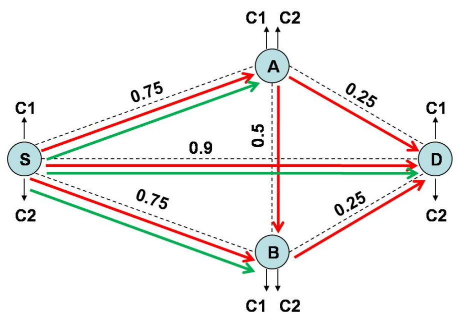

Fig. 2. Optimal channel assignment for multi-channel opportunistic routing protocol EMORE. Every node has 2 radio interfaces, the number of available orthogonal channels is 3, and the loss probability is indicated on each link.

TABLE II

CHANNEL ASSIGNMENT $\mathcal{X}$, WORKLOADS $\mathcal{Z}$, AND EFFECTIVE CHANNEL USAGE RATIOS Λ FOR THE CASE SHOWN IN FIGURE 2.

X_i^k	S	A	B	D
k=1	1	1	1	1
k=2	1	1	1	1
k=3	0	0	0	0

	λ_k
k=1	1.0
k=2	1.0
k=3	0.0

Z_i^k	S	A	B
k=1	0.4810	0.3906	0.6727
k=2	1.5443	0.0	0.0
k=3	0.0	0.0	0.0

provided. We can observe that the optimal channel assignment in this case is fundamentally different from the previous one. The total normalized end-to-end throughput calculated through Equation(5) and (6) is 0.6475, which is higher than the one achieved by traditional channel assignment by 29.5%.[2] Furthermore, the new channel assignment uses only 2 channels. It saves 1 channel compared with the traditional channel assignment.

The above examples show that traditional channel assignment may not achieve optimal end-to-end throughput or uses more than enough channels, when opportunistic routing technique is provided. Therefore, it is highly needed to design new channel assignment algorithms, taking advantages from both opportunistic throughput gain and multi-channel throughput gain.

V. WORKLOAD-AWARE CHANNEL ASSIGNMENT AND ROUTING ALGORITHM

We proposed a workload-aware channel assignment and routing algorithm. Our algorithm is composed of three major modules:

1) Workload-aware channel assignment: Compute a channel assignment $\mathcal{X}$ based on nodes' workloads.
2) Workload distribution: Given a channel assignment $\mathcal{X}$, compute the optimal workload distribution for each of the nodes on the assigned channels $\mathcal{Z}$.
3) Effective channel usage ratio computation: Given nodes' workloads $\mathcal{Z}$ over the channels K, compute the effective channel usage ratios Λ, that maximize end-to-end throughput.

Due to limitation of space, we do not present the detail of the algorithm in this abstract.

VI. CONCLUSION

In this abstract, we have studied the problem of channel assignment in multi-radio, multi-channel wireless mesh networks, considering the support of opportunistic routing technique. First, we have formally modeled the channel assignment problem. Second, we have presented our multi-channel opportunistic routing protocol. Third, we have shown the infeasibility of traditional channel assignment schemes, in the context of opportunistic routing. Finally, we have proposed a workload-aware channel assignment and routing algorithm, which can take advantages from both opportunistic throughput gain and multi-channel throughput gain.

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[2] We note that in the optimal channel assignment, optimal distribution of workload Z is not unique. However, the optimal end-to-end throughput can be achieved by any of these optimal workload distributions.