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Distributed Joint Channel and Routing Assignment for Multimedia Wireless Mesh Networks

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***Abstract*—Wireless mesh networks (WMNs) have been increasingly used to carry multimedia traffic with flow requirements. The performance of multi-radio multi-channel (MRMC) WMNs largely depends on the routing and channel assignment. Because routing and channel decisions are coupled, they need to be *jointly* optimized to achieve the best performance. This is the so-called routing and channel assignment (RCA) problem, which is known to be NP-hard. There has not been sufficient consideration on *joint* RCA optimization which takes into account multimedia traffic demands in the network.**

In this paper, we propose and study CRAFT (Channel and Routing Assignment with Flow Traffic) for MRMC WMNs. CRAFT is distributed, cooperative, computationally efficient and simple to implement. It *jointly* optimizes routing and channel assignment by using a properly designed objective function to meet the flow demands of the mesh nodes. Simulation results based on NS3 show that CRAFT performs much better than other state-of-the-art schemes in terms of convergence, delay, loss rate and throughput.

***Keywords*-flow traffic, routing, channel assignment, multimedia wireless mesh**

I. Introduction

Multi-radio Multi-channel Wireless Mesh Network (MRMC WMN) is a multihop communication network made up of radio nodes equipped with multiple IEEE 802.11 standard radios. In a MRMC network, mesh nodes can transmit and receive packets simultaneously by communicating with their neighbors via different orthogonal frequency channels. Hence, it can achieve higher system throughput than the traditional single-channel single-radio mesh network. Due to its promising performance, multihop wireless network has aroused much interest in both academia and commercial sectors [1], [2].

Multimedia traffic has been increasingly carried in WMNs. In such a network, there are (possibly heterogeneous) traffic demands between pair of nodes in the network. Meeting the traffic demands is challenging due to the co-channel interference among the communication links. Such interference is caused by simultaneous transmissions of neighbors on the same frequency channels and largely affects the performance of the MRMC WMN.

In a multimedia wireless mesh network, channel and route decisions largely affect the performance of the network. They are coupled with each other because given a channel assignment there is an optimal route assignment, and vice versa. Such inter-dependence between the routing and channel assignment means that they should be designed *jointly* to achieve the best performance, the so-called joint Routing and Channel Assignment (RCA) problem. Note that for efficiency consideration due to the channel switching overhead, channel assignment should not be done on the per-packet basis. Therefore, RCA should usually run at an interval of a longer time scale (say several times in a day), taking into account the longer-term traffic demands in the network.

Optimizing RCA is known to be NP-hard [3]. Most of the recent works are often centralized in nature or considers CA and routing separately or independently. There has been insufficient consideration on *joint* RCA with flow demands. In this paper, we present CRAFT (Channel and Routing Assignment with Flow Traffic), which is a novel, simple and scalable scheme to optimize the RCA according to the traffic demands in MRMC WMNs. In CRAFT, each mesh node cooperatively seeks to maximize an objective function which models the interference and traffic demands of all the nodes by choosing a joint routing and channel assignment.

The main contributions of this work are:

- *A novel RCA algorithm with flow requirements*: We propose CRAFT, which *jointly* optimizes the routing and channel assignment based on flow demands of nodes in MRMC WMNs. CRAFT is distributed, implementable and computationally efficient.
- *A properly designed objective function to cooperatively and distributively improve the network performance*: We propose an objective function which properly captures the network throughput due to the interference of the traffic flows in the network. Therefore, the optimization of the objective function leads to the maximum throughput of the whole network. With the objective function, the RCA can be optimized in a distributed and cooperatively manner.
- *Extensive simulation studies on NS3*: We evaluate our scheme through extensive simulation based on NS3. CRAFT substantially outperforms proposed RCA ap-

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proaches in terms of convergence, loss rate, delay, and throughput.

The rest of the paper is organized as follows. We first discuss the related works in Section II. The problem is formulated in Section III. We present CRAFT, our approach for joint RCA in Section IV. In Section V, we present the illustrative simulation results based on NS3. We conclude in Section VI.

II. Related works

Much work has been done on channel assignment and routing in wireless networks. Because of the NP-hard nature of RCA, the work often considers CA and routing separately or independently [1]. Some game-based approaches presented recently focus on CA only [4], [5]. The work in [4] proposes a state-of-the-art game-based CA approach called GBCA (Game Based Channel Assignment). It first forms a tree structure of the network topology (through, for example, the shortest-path-first tree (SPF)). Each non-leaf node is in charge of assigning channel for links towards its children.

Some approaches jointly consider scheduling, routing and channel assignment with QoS requirements [6], [7]. However, the algorithms require high-precision clock synchronization among the mesh nodes. They choose the routing and channel decision according to the synchronized time slots, in which it is often impractical for reasons of cost in commodities nowadays.

Some distributed RCA algorithms have been proposed recently [8]. The work in [8] proposes a joint and distributed RCA for ad-hoc networks called J-CAR. J-CAR is load-aware and efficient, but the CA may not be optimal on a global scale. CRAFT is a joint, novel, distributed and simple RCA scheme with the consideration of traffic demands in its optimization. We will show that CRAFT can substantially improve system performance (convergence, throughput, loss rate, etc.).

III. Throughput Analysis and Problem formulation

A. Interference Analysis

We consider there are certain flow traffic demands between pair of nodes in the multimedia mesh network. From a mesh node i's point of view, whether its transmission is interfered or not depends on whether others in its interference range are transmitting packet in the same channel at that time. If so, i's transmission will not be successful. (For simplicity, we consider using the same transmission power in this work. This can be extended to the case with power control, after taking into account some fairness issues [9].)

Assume node i is using channel c. Denote $I(i)$ the set of nodes in i's interference range. Let $|.|$ be the cardinality of a set, and $|I(i)| = n$. Let x_j^c indicate whether channel $c \in C$

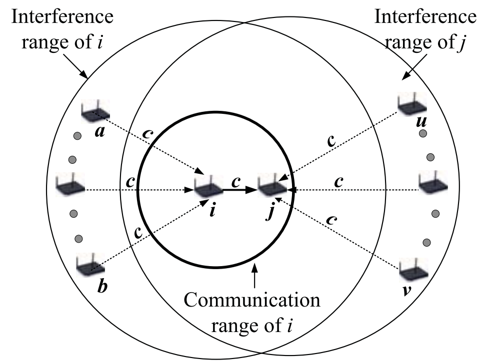

Figure 1. Link interference model.

is in use at node j at the moment, where $j \in I(i)$, i.e.,

$$x_j^c = \begin{cases} 1, & \text{if channel } c \text{ is in use at node } j \\ & \text{at the moment;} \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Let f_j^c be the total traffic in channel c at node j at the moment, and K be the transmission capacity of channel c. The probability p_j^c that node j is using channel c is given by f_j^c/K. Therefore, we have $P(x_j^c = 1) = p_j^c$ and $P(x_j^c = 0) = 1 - p_j^c$.

Let $X_i^c = (x_1^c, x_2^c, ..., x_j^c, ...x_n^c)$ be the event vector indicating which nodes in i's interference range are using channel c and which are not. By independence assumption, the probability that X_i^c occurs can be written as

$$P(X_i^c) = \prod_{j=1}^{n} P(x_j^c). \quad (2)$$

From the above we can see that higher traffic load at node j on channel c leads to higher probability to interfere with node i. Since the traffic load on a link depends on routing, we need to jointly consider CA and routing to minimize the system interference.

B. Problem Formulation

We seek to maximize the throughput by assigning a channel for each link and allocating traffic on it properly. Such success probability depends on the network interference, which can be divided into two parts, for edge $(i, j) \in E$: i) Interference at the sender i, due to the interference by the nodes in $I(i)$ using the same channel as (i, j); and ii) Interference at the receiver j, due to the interference of nodes in $I(j)$. This link interference model is shown in Figure 1. The directed link (i, j) is assigned channel c. If any nodes from a to b on the left hand side transmit traffic on channel c, they will interfere the transmission of node i. Similarly, nodes u to v will interfere the receiving of node j.

The probability of successful transmission of a link is closely related to the signal to interference plus noise ratio

(SINR) [10], which is given by

$$SINR(i,c) = \frac{\Theta(i,i,c)}{\sum\limits_{k \in I(i), k \neq i} \Theta(k,i,c) + \Delta}, \quad (3)$$

where $\Theta(k,i,c)$ is the signal strength of node k at node i using channel c and Δ is the background noise constant.

Therefore, each state X_i^c mentioned in Section III-A has a SINR value at node i given by

$$SINR(i,X_i^c) = \frac{\Theta(i,i,c)}{\sum\limits_{k \in I(i), k \neq i} (x_k^c \cdot \Theta(k,i,c)) + \Delta}. \quad (4)$$

Using conditional probability, the SINR at sender i, denoted by $SINR_{se}$, can be written as

$$SINR_{se}(i,c) = \sum_{X_i^c} P(X_i^c) \cdot SINR(i, X_i^c). \quad (5)$$

The SINR at receiver j, denoted as $SINR_{re}(i,j,c)$, can be calculated similarly by replacing the $\Theta(i,i,c)$ in Equation (4) with $\Theta(i,j,c)$. A link (i,j)'s successful transmission probability is related to the SINR at the sender i and the receiver j, which is defined as

$$P(i,j,c) = \Psi(SINR_{se}(i,c), SINR_{re}(i,j,c)), \quad (6)$$

where Ψ is a function of $SINR_{se}(i,c)$ and $SINR_{re}(i,j,c)$ that maps $SINR$ of link (i,j) to the probability of successful transmission of the link. Clearly, Ψ is a monotonically increasing function, and its detailed expression can be found in [11]. From Equations (2), (4), (5) and (6), we see that the success probability of a link's transmission depends on the routing and CA.

Let F be the matrix representing the traffic demands between source and destination pairs, i.e., $f_{ab} \in F$ is the traffic demand from nodes a to node b. Let $path_{ab}$ be the routing path from a to b. Let s be a routing and CA decision of the network. The utility of s, denoted as $U(s)$, can be defined as the successful transmission traffic given the traffic demand F.

The joint CA and routing problem in a MRMC WMN is hence to maximize the throughput of network, stated as follows:

$$\max_s \quad U(s) = \sum_{f_{ab} \in F} \left(f_{ab} \cdot \prod_{(i,j) \in path_{ab}} P(i,j,s) \right). \quad (7)$$

IV. CRAFT: Distributed Joint Channel and Routing Assignment with Flow Traffic

A. CRAFT Framework

In CRAFT, all the nodes try to maximize the objective function $U(s)$ given in Equation 7. Each node i maintains a RCA decision table given in Table I. Here, α_j is the destination node of the incoming flow, β_j is the next hop to the destination, and c_j is the channel assigned to the outgoing link (i, β_j). N represents the number of nodes in the WMN.

Table I
RCA decision table of a mesh node.

Routing		Channel
Destination	Next-hop	Channel
α_1	β_1	c_1
$\vdots$	$\vdots$	$\vdots$
α_{N-1}	β_{N-1}	c_{N-1}

CRAFT is an adaptive approach. In each adaptation, node i decides its RCA decision to improve $U(s)$. CRAFT can be implemented with the following phases:

- *Start phase*: Routing of the network is established by a link state routing protocol. The channel of each link is randomly assigned by each node. After the RCA decision table is formed, each node will distribute it to the network. The RCA decision tables of all the nodes form the initial RCA decision of the whole network, s^0.
- *Improvement phase*: A node waits for random period of time to start its improving procedure after the start phase is over. When node i is in Improvement phase, it will compute a RCA decision table that can maximize the objective function $U(s)$ without changing the others decisions. After the computation, the node will distribute its new RCA decision to the network and wait for random period of time to enter the Improvement phase again.
- *End phase*: When no one can improve $U(s)$ in the improvement phase, the algorithm is converged and CRAFT ends.

The RCA decision tables of all the nodes are used as the final solution of the scheme.

B. Routing and Channel Assignment

We study and compare the following two approaches in CRAFT to efficiently assign routes and channels jointly in the RCA decision table:

- *CRAFT-RD*: It is called random decision (RD). It randomly chooses a RCA decision from node *i*'s decision space. The decision is adopted if it improves $U(s)$. In practice, the random approach can execute several times to finalize on the best RCA decision table that improves $U(s)$.
- *CRAFT-TP*: It is called traffic-prioritized decision (TP). Since links with higher traffic load have larger probability to interfere with each other and are the main factors that can affect the overall performance, the high traffic should be routed a better path and assigned a channel which is more idle. Thus, CRAFT-TP considers the

destinations with high traffic to have the priority to be handled first.

C. Complexity Analysis

In this section, we analyze the complexities of CRAFT approaches in big-Oh, i.e., CRAFT-RD and CRAFT-TP. Let $|T(i)| = D$ be the average number of neighbors of each node. Because $|X^c| \leq D$, the complexity of computing Equation 2 is $O(D)$. The possible value of X^c is less or equal to 2^D. Thus, the complexity of computing Equations 5 and 6 is $O(2^D D)$. Assume there are P flows in the network. Since the maximum hops of a path in a N-node network is $N-1$, according to Equation 7, the complexity of computing $U(s)$ is hence given by $O(2^D DPN)$.

CRAFT-RD and CRAFT-TP have low run-time complexity and their complexity analysis is described as follows:

- *CRAFT-RD*: The algorithm requires computing and comparing the $U(s)$ for the newly chosen decision only. Thus, the complexity of CRAFT-RD is given by $O(2^D DPN)$.
- *CRAFT-TP*: There are DH choices for each destination and $DH \times (N-1)$ comparison steps, where H is the number of orthogonal channels. Therefore, the complexity of CRAFT-TP can be presented as $O(2^D D^2 PN^2)$.

In WMNs, the values of D and H are usually small. Hence, the complexity of CRAFT-RD and CRAFT-TP can be presented as $O(PN)$ and $O(PN^2)$ respectively.

V. Illustrative Simulation Results

In this section, we present illustrative simulation results to show the performance of CRAFT. We describe simulation environment and metrics first. Then, we compare CRAFT with other RCA schemes and illustrate the results.

A. Simulation Environment and Metrics

Mesh nodes are randomly put into an area (of size 500m$\times$ 500m). The WMNs in our setting use IEEE 802.11b radio and NS 3.10 is used as our simulator.

The performance metrics in the simulation are itemized as follows:

- *Loss rate (UDP)*: We inject UDP traffic into the network according to the traffic demands. We take the average loss rate of all the flows at steady state.
- *Delay (UDP)*: We inject UDP traffic into the network according to the traffic demands. At steady state, we take the average end-to-end delay of all the successfully received packets.
- *Throughput (TCP)*: TCP traffic is injected into the network according to the traffic demands. At steady state, the aggregated throughput of all the flows is then measured.
- *Convergence*: Convergence is measured by the steps it takes for the system to reach the steady state.

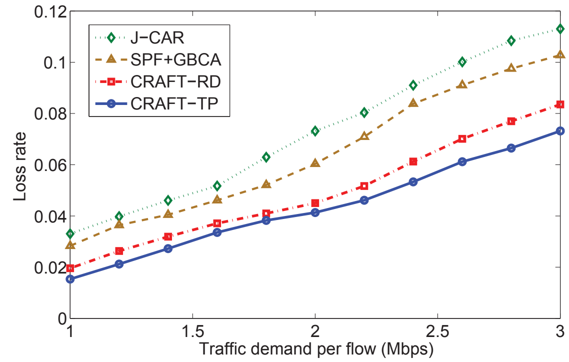

Figure 2. UDP loss rate comparison.

We compare CRAFT with a state-of-the-art distributed RCA scheme (J-CAR [8]) and a game-based scheme (GBCA [4]). J-CAR improved the AODV protocol to do the RCA in a distributed manner. The game-based scheme uses GBCA for channel assignment and shortest path first (SPF)for routing. Although GBCA was proposed for wireless sensor network, the algorithm can be applied to WMN. GBCA can be easily implemented and has been shown to achieve high performance. Unless otherwise stated, we use the following baseline parameters: communication range is 120m, interference range is 240m, 3 orthogonal channels are avaiable, each node is equipped with 3 radios, traffic demand is 2Mbps per pair of nodes, total number of node-pairs is 10, the CSMA is enabled, and total number of mesh nodes is 20.

B. Illustrative Results

Figure 2 shows the loss rate versus the traffic demand per flow. The loss rate increases with the traffic demand because higher traffic demand leads to higher interference. From the low loss, we see that the traffic demands have been met. CRAFT performs better than SPF+GBCA and J-CAR and CRAFT-TP performs better than CRAFT-RD. This is because GBCA does not always converge while J-CAR is not adaptive to the changing of traffic. These may cause high interference leading to a higher loss rate than CRAFT. CRAFT-TP is better than CRAFT-RD because CRAFT-TP minimizes the interference of the links that have heavy traffic. This effectively reduces the probability of interference, hence the loss rate.

The cumulative percentiles versus loss rate in UDP given different schemes is shown in Figure 3 The cumulative percentile is the percentage of flows that are lower than the loss rate. Given a certain loss rate, the cumulative percentile of CRAFT is higher than the other two schemes, which means that more flows using CRAFT have lower loss rates. The reason is the same as explained in Figure 2.

The UDP loss rate versus the number of nodes is shown in Figure 4. The loss rates is low for a network with small

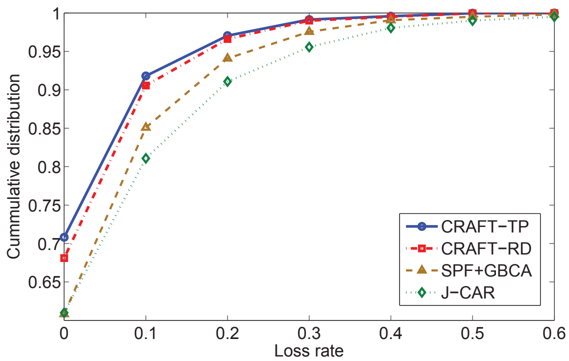

Figure 3. Cummulative percentile versus loss rate in UDP.

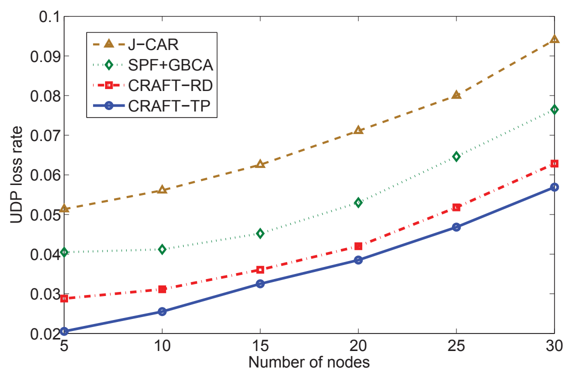

Figure 4. UDP loss rate versus the number of nodes

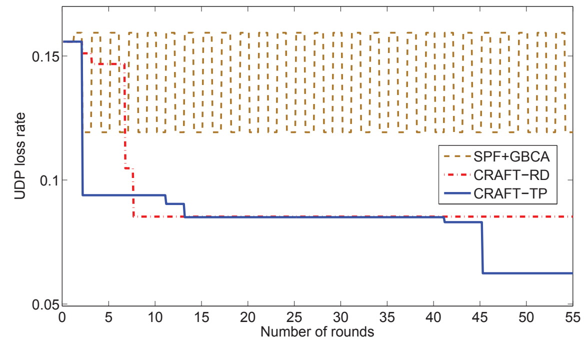

Figure 5. Convergence comparison between CRAFT and GBCA.

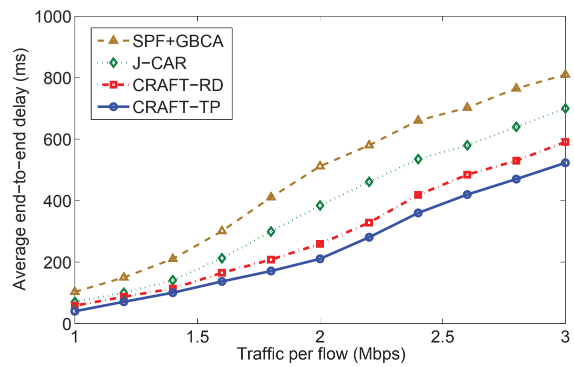

Figure 6. Average end-to-end delay of UDP comparison.

number of nodes because of lower interferences and number of hops among the nodes. The loss rate increases with the network size (and hence density) increase. Both CRAFT-TP and CRAFT-RD outperform the other schemes significantly due to its better RCA.

We compare the convergence time (in terms of UDP loss rate) of CRAFT-TP and CRAFT-RD with SPF+GBCA. Figure 5 shows the average loss rate versus the number of rounds of each scheme. Clearly, CRAFT converges after several rounds while SPF+GBCA can hardly converge. The convergence time of CRAFT-TP is shorter than CRAFT-RD. Meanwhile, the final result of TP is better than RD. CRAFT-TP optimizes the links with higher traffic demand first, which eliminates the main factor that will affect the interference. This makes TP converge faster than RD. When links with higher probability to interfere with each other are first optimized in each iteration, clearly it may get better final results.

Figure 6 presents the average end-to-end UDP delay versus the traffic demand per flow. The end-to-end delay increases with the traffic demand. This is because when a node detects the sending of others in the interference range, it delays its sending. High traffic demand leads to long queuing delay for each packet, which increases the end-to-end delay. CRAFT performs better than J-CAR and SPF+GBCA because their better channel assignment can reduce the queuing delay significantly. CRAFT-TP performs better than CRAFT-RD, because links with higher traffic will be assigned to an idler channel first. This reduces most of the packet's queuing delay.

Figure 7 shows the aggregated TCP throughput versus the traffic demand per flow. In TCP, the situation is similar to UDP. More per flow traffic leads to higher throughput. TCP throughput is highly co-related with the loss rate and delay, hence can be explained in the same way as in Figures 6 and 2.

In Figure 8, the cummulative percentile versus TCP throughput is presented. The cumulative percentile of CRAFT is lower than the other two schemes. Given a certain TCP throughput, which means that more flows using CRAFT have higher throughputs. The reason is the same as explained in Figures 3 and 7.

VI. Conclusion

Wireless mesh networks (WMNs) have been increasingly used to carry multimedia traffic. In order to meet flow

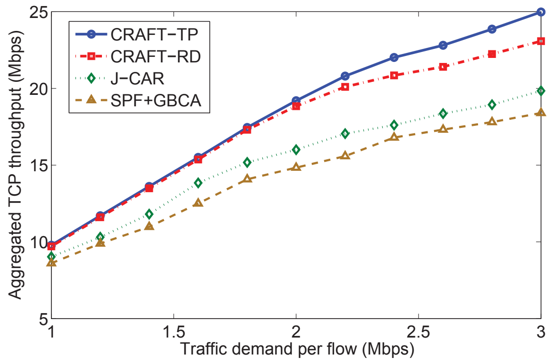

Figure 7. TCP throughput comparison.

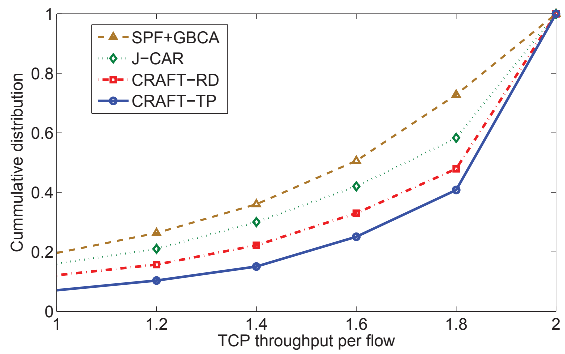

Figure 8. Cummulative percentile versus TCP throughput.

requirements between pairs of nodes in the network, we need to address how to optimally assign channels and routes, the so-called Routing and Channel Assignment (RCA) problem. The RCA problem of a MRMC WMN is generally known to be NP-hard. In this paper, we have studied distributed and cooperative optimization of RCA for multimedia mesh networks. We have proposed CRAFT (Channel and Routing Assignment with Flow Traffic) to assign channels and routes meeting traffic demands between pair of nodes. In order to reduce the computational complexity, we have proposed efficient traffic-prioritized (TP) and random (RD) selections to choose the RCA decisions.

We have compared CRAFT with other traditional and state-of-the-art approaches using NS3 network simulations. CRAFT achieves much faster convergence, lower packet loss rate (UDP), lower end to end delay, and higher TCP throughput.

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