QoS Routing in Wireless Mesh Networks with Cognitive Radios

Roberto Hincapie, Jian Tang, Guoliang Xue and Roberto Bustamante

Abstract— **In this paper, we study QoS routing in wireless mesh networks with cognitive radios, which involves route selection, channel allocation and scheduling. It turns out to be a hard problem because of the impact of interference and channel heterogeneity. We formally model it as an optimization problem and present an Integer Linear Programming (ILP) formulation to provide optimal solutions. We then present a distributed routing protocol which can select a route and allocate resources for a connection request to satisfy its end-to-end bandwidth requirement. NS2 based simulation results show the performance given by our protocol is close to that of the optimal solution.**

Index Terms– **Cognitive radio, wireless mesh network, routing, QoS.**

I. Introduction

Various multimedia and real-time applications, such as neighborhood gaming, Video-on-Demand (VoD) and emergency communications, are expected to be provided by Wireless Mesh Networks (WMNs) in the future [2]. In order to provide those services, end-to-end Quality of Service (QoS) must be well supported. Bandwidth is a basic QoS parameter and the focus of this paper. A QoS connection request should be admitted if there exists a path with required bandwidth. Otherwise, it should be rejected. Such a bandwidth guaranteed path in a wired network can be easily obtained by simply ignoring those links without enough bandwidth and applying a shortest path algorithm in the residual network. However, QoS routing in a multihop wireless network is much harder due to the impact of interference. Communications between a pair of nodes may consume the bandwidth of neighboring nodes. The available bandwidth in each node/link is related to interference caused by its neighbors within the interference range. Therefore, QoS routing schemes proposed for wired networks are not applicable for multihop wireless networks.

The emerging cognitive radio technology enables unlicensed users (a.k.a secondary users) to sense and access the under-utilized spectrum bands dynamically as long as the communications among licensed users (a.k.a primary users) in such spectrum bands are not affected. The cognitive radio is desirable for a WMN in which a large volume of traffic is expected to be delivered since it is able to utilize spectrums more efficiently, therefore improve network capacity significantly. However, it introduces additional complexities to QoS routing. With cognitive radios, each node can access a set of available spectrum bands which may spread a wide range of frequencies. Different spectrum bands (a.k.a channels) can support quite different transmission ranges and data rates, both of which have a significant impact on route selection and end-to-end bandwidth.

In this paper, we study the QoS routing problem in WMNs with cognitive radios, which involves not only route selection but also channel allocation and scheduling. We formally define the problem and present an Integer Linear Programming (ILP) formulation to provide optimal solutions. We then present a novel distributed routing protocol which can select a route and allocate channels and timeslots for a connection request to satisfy its end-to-end bandwidth requirement. The efficiency of the proposed protocol is justified by NS2 based simulation. To our best knowledge, we are the first to study QoS routing in the context of wireless mesh networks with cognitive radios.

II. Related Work

Even though cognitive radio came into being a long time ago, research on networking with cognitive radios is still in its infancy [3]. In [19], Zheng *et al.* developed a graph-theoretic model to characterize the spectrum access problem and devised a set of heuristics to find high throughput and fair solutions. The authors of [16] introduced the concept of a time-spectrum block and proposed the protocols to allocate such blocks. In [18], the authors derived optimal and suboptimal distributed strategies for the secondary users to decide which channels to sense and access under a framework of Partially Observable Markov Decision Process (POMDP). In [14], Wang *et al.* considered the joint design of dynamic spectrum access and adaptive power management, and proposed a power-saving multi-channel MAC protocol. However, the above works concentrated on the physical and MAC layers and did not address routing and end-to-end issues, especially end-to-end QoS provisioning which is the focus of this paper.

QoS routing has been well studied for single-channel wireless ad hoc networks. QoS routing protocols have been proposed for wireless ad hoc networks with a TDMA-over-CDMA based MAC layer [8], [9], a TDMA-based MAC layer [13], [20] or a 802.11-based MAC layer [15]. In [12], Tang *et al.* proposed an algorithm to compute a low-interference channel assignment as well as a QoS routing algorithm to compute a route for a connection request with bandwidth requirement in a 802.11-based multi-channel WMN. However, a cognitive radio WMN is different from single-channel wireless networks since different non-overlapping channels can be assigned to cognitive radios in a common neighborhood to mitigate the interference. Moreover, a WMN with cognitive radios which

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can be tuned to a large number of heterogeneous channels is also quite different from the WMNs studied before [2], [12], in which several homogeneous channels on a certain spectrum band are always available to each node.

III. Problem Formulation

In this section, we will describe our system model first. Then we formally define the problem to be studied and present an ILP formulation.

We consider a WMN composed of a set of stationary nodes with locations known, each of which is equipped with a cognitive radio. The available spectrum is divided into a set of non-overlapping spectrum bands, which are also called *channels*. A cognitive radio can dynamically access a channel to deliver its packets. Any proposed spectrum sensing scheme can be used to detect the locally available channels [3]. A TDMA scheme is used in the MAC layer for cognitive radios, i.e., time domain is divided into timeslots with fixed durations and they are further grouped into frames of T timeslots each. A timeslot-channel pair (t, h) is defined as a *transmission block*, which can be considered as a resource unit. The *capacity of a transmission block* $c(t, h) = C_h/T$, where C_h is the capacity of channel h. The resource allocation problem in the MAC layer is actually to determine how to allocate available transmission blocks to links subject to the interference constraints. There also exists a common control channel on a relatively low frequency, which can support a large transmission range. Each node is also assumed to have a low-cost control radio (no need to be a cognitive radio) which is used for exchanging control messages over the common control channel.

During a certain period, there will be a set H_v of channels available to a particular node v. The channel availability may change over the time due to the impact of primary users in the same area [3]. We assume every transmitter always transmits at a fixed transmission power level. Hence, there are a fixed transmission range R_h and a fixed interference range I_h (which is typically 2 to 3 times of the transmission range [11]) for each channel h. Note that the transmission and interference ranges are both channel-dependent. We model the network using a *communication graph* $G(V, E)$, where each node $v \in V$ corresponds to a wireless mesh node and there is a link $e \in E$ between nodes u and v if there exists a channel $h \in H_u \bigcap H_v$ and $||u - v|| \leq R_h$, where $||u - v||$ represents the Euclidean distance between nodes u and v. We address wireless interference based on the protocol model [7]. Two links e_1 and e_2 are said to interfere with each other if 1) e_1 is incident to e_2 (due to constraints enforced by half-duplexing, unicast communications or collisions) or 2) they work on the same channel h, and $||T(e_1) - T(e_2)|| \leq I_h$ or $||T(e_1) - R(e_2)|| \leq I_h$ or $||R(e_1) - T(e_2)|| \leq I_h$, $||R(e_1) - R(e_2)|| \leq I_h$. Without confusions, $T(\cdot)/R(\cdot)$ represent both the transmitter/receiver of the given link, and their locations. Similar to IEEE 802.11 [1], both the transmitter and receiver of a link need to be free of interference because we assume that an ACK packet will be sent back to the transmitter by the receiver whenever receiving a data packet.

Suppose that channel $h \in H_v$. The status of transmission block (t, h) on node v, $S(v, t, h)$, is said to be *transmitting* (TX) if node v transmits on (t, h); *receiving* (RV) if v receives on (t, h); *interfered* (IR) if v is interfered by another transmission(s) on (t, h); or *free* (FR) otherwise. These four states are disjoint. A transmission block (t, h) is said to be *free* for link $e = (u, v)$ if $h \in H_u \bigcup H_v$, $||u - v|| \leq R_h$, $S(u, t, h) = FR$, $S(v, t, h) = FR$ and $S(x, t, h) = IR/FR, \forall x \in (D_h^u \cup D_h^v) \backslash \{u, v\}$, where $D_h^u = \{x : ||x-u|| \leq I_h\}$ and $D_h^v = \{x : ||x - v|| \leq I_h\}$. Note that if the existing traffic and the corresponding resource allocation are known, then we can easily identify all the free transmission blocks for each link based on this definition.

We consider a dynamic traffic model in which connection requests arrive randomly. Each connection request has a bandwidth requirement B. When a *new* connection request arrives, we have to find a path for routing and reserve resources (transmission blocks) along the path to satisfy its bandwidth requirement. We assume that a connection always uses a single path for packet delivery, i.e., no traffic splitting is allowed. There are two kinds of potential contentions associated with a routing path: interflow contention and intraflow contention [17]. Interflow contentions are the contentions caused by the interference between a link selected for the new connection request and another link used for an existing flow. Intraflow contentions are the contentions caused by the interference between two different links selected for the new connection request. Interflow contentions can be easily resolved if we always assign aforementioned *free* transmission blocks (which can be identified beforehand) to each link on the routing path we plan to select for the new connection request. Intraflow contentions are much harder to address because we have to make sure that a free transmission block is not shared by any two links interfering with each other on the selected path, which might even be several hops apart.

We now are ready to define the problem to be studied. Suppose that we are given a connection request with a source node s, a destination node d and a bandwidth requirement B.

Definition 1: A *feasible transmission schedule* for a single $s - d$ path P is a transmission block assignment that allocates transmission blocks for every link on the path such that it does not introduce any interflow contentions or intraflow contentions, and the bandwidth requirement B is satisfied on each link of the path. The path P is said to be an *admissible* path if there exists such a feasible transmission schedule.

Definition 2: The **Bandwidth Aware Routing (BAR)** problem seeks a single $s - d$ path along with a feasible transmission schedule such that the hop count of the path is minimum among all admissible $s - d$ single paths.

Next, we present an ILP formation for the BAR problem. We define two decision variables.

- x_e: $x_e = 1$ if link e is selected for routing; $x_e = 0$, otherwise.
- $y_e^{(t,h)}$: $y_e^{(t,h)} = 1$ if transmission block (t, h) is allocated to link e; $y_e^{(t,h)} = 0$, otherwise.

We also introduce the following notations.

- F_e is the set of free transmission blocks on link e.

- E_v^{out} is the set of outgoing links of node v.
- E_v^{in} is the set of incoming links of node v.
- $L_e^{(t,h)}$ is the set of links which have (t,h) as a free block and interfere with link e over channel h. Note that $e \in L_e^{(t,h)}$.

ILP: BAR

$$\min \quad \sum_{e \in E} x_e \tag{1}$$

subject to:

$$\sum_{e \in E_s^{out}} x_e = 1; \tag{2}$$

$$\sum_{e \in E_v^{out}} x_e - \sum_{e \in E_v^{in}} x_e = 0, \qquad \forall v \in V \setminus \{s,d\}; \tag{3}$$

$$y_e^{(t,h)} \le x_e, \quad \forall (t,h) \in F_e, \forall e \in E; \tag{4}$$

$$\sum_{(t,h) \in F_e} c(t,h) \cdot y_e^{(t,h)} \ge x_e \cdot B, \qquad \forall e \in E; \tag{5}$$

$$\sum_{e' \in L_e^{(t,h)}} y_{e'}^{(t,h)} \le 1, \quad \forall e \in E, \forall (t,h) \in F_e; \tag{6}$$

$$x_e \in \{0,1\}, \qquad \forall e \in E; \tag{7}$$

$$y_e^{(t,h)} \in \{0,1\}, \quad \forall (t,h) \in F_e, \forall e \in E. \tag{8}$$

The objective function (1) is set to minimize the total cost (hop count) of the path. Constraints (2) and (3) are flow constraints which guarantee that a single s-d path is chosen. Constraint (4) establishes a connection between two variables and ensures that free transmission blocks are only allocated to the links on the chosen path. Constraint (5) guarantees that the bandwidth requirement is satisfied on each link of the chosen path. Note that $c(t,h)$ is a constant and represents the capacity of block (t,h). Constraint (6) is the interference constraint which makes sure there are no intraflow contentions among the chosen links. Note that based on the definition of the *free* transmission block, the interflow contentions can be prevented if we always allocate free transmission blocks to the selected links. Solving the ILP can provide optimal solutions for the BAR problem, however, it may take a very long time to solve it for large cases. Hence, we will present an effective distributed protocol to find the route and the corresponding transmission block assignment in the next section.

IV. The Proposed Routing Protocol

In order to enable the transmission block allocation, every node needs to keep track of some necessary information of all the other nodes in its interference neighborhood, such as channel availability and transmission block status. In our protocol, each node will broadcast these information to its two-hop neighbors over the common control using the control radio whenever there are any changes. Note that we assume the common control channel can support a large transmission range. Hence, every node can obtain these information from all nodes which can potentially interfere with it. In our protocol, all the routing control packets are exchanged over the common channel using the control radios.

Due to the ad hoc feature and highly dynamic properties of the target network, we propose an on-demand routing protocol. Similar to Dynamic Source Routing (DSR) [6] and AODV [4], the route is discovered upon the arrival of a connection request. Furthermore, the proposed protocol is essentially a source routing protocol, i.e, the complete or partial routing path is always included in every control or data packet. In the DSR, when a connection request arrives at the source node, it broadcasts an RREQ (Route REQuest) packet to its neighbors. When an intermediate node receives an RREQ, it must decide if it should discard or re-broadcast it. Note that for a particular connection request, it may receive multiple RREQs from different neighbors, which include different routing paths. The intermediate node simply re-broadcasts the first one and discards all the following. Similarly, the destination node replies to the source node with an RREP (Route REPly) packet along the path included in the first RREQ it receives and discards all the following.

However, this route discovery procedure cannot well support end-to-end QoS because it is possible that there does not exists a feasible transmission schedule along the routing path included in the first RREQ arriving at the destination node. We need to identify more alternative source-destination paths during the route discovery to increase the chances for the QoS connection request to be accepted by the network. In our protocol, an intermediate node v starts a timer whenever it receives the first RREQ. For each RREQ received from a neighbor u before the timer fires, node v runs an allocation algorithm to find out good feasible transmission blocks for link $e = (u,v)$. The window size is set to 4ms in the simulation. If it fails to find a feasible allocation, it drops the corresponding RREQ. Otherwise, it attaches itself to the current partial path, includes it along with the selected blocks in the header, and re-broadcast it. The details of the proposed transmission block allocation algorithms will be discussed later.

Similarly, the destination node sets up a window to collect multiple RREQs for a connection request. It will run the same allocation algorithm to select transmission blocks for the last hop. It then chooses an *admissible* path with minimum hop count and reply to the source node with an RREP along the selected path. Accordingly, the transmission blocks selected for each link along this path will be reserved for transmission. Moreover, all the other nodes in the neighborhoods of the nodes in the selected path will be notified that these transmission blocks are going to be used by the new incoming connection. After the RREP packet arrives at the source node, data transmission begins. However, if our protocol cannot find an admissible path, it will reject the connection request. When the source or the destination node decides to terminate a connection, a special control packet RREL (Route RELease) will be forwarded along the routing path to release the reserved resources and update the transmission block statuses in the affected nodes. In addition, similar to DSR, the RERR (Route ERRor) based failure recovery scheme will be used to notify the source node and initiate a new route discovery after node failures and/or link failures (usually caused by channel availability change).

Next, we present two heuristic algorithms to allocate transmission blocks for the link $e = (u,v)$. We use B' to denote the remaining bandwidth requirement. Initially, $B' = B$.

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Capacity based algorithm: We sort all the free transmission blocks in the descending order of their capacities. If the capacity of the unselected free block with the largest capacity (the first one in the sorted list) $c(t_{max}, h_{max}) \leq B'$, then it is selected. Otherwise, the transmission block with the minimum capacity among all the free unselected blocks whose capacities are no less than B' is selected. Then the selected blocks are removed from the list and B' is updated. This procedure continues until the bandwidth requirement is satisfied.

The capacity based algorithm is a simple greedy algorithm whose design philosophy is to select minimum number of free transmission blocks to satisfy the given bandwidth requirement. However, the algorithm does not address the impact of interference. Therefore, we propose another heuristic algorithm with consideration for both capacity and interference in the following.

Capacity-interference based algorithm: The basic idea is to select high capacity transmission blocks, but to avoid using those transmission blocks which are the only free blocks on the other links within the interference range. We define the satisfaction ratio as $I_{cap}(t,h) = \max\{1, \frac{c(t,h)}{B}\}$, which indicates how much bandwidth requirement is satisfied if transmission block (t,h) is chosen. For a link $e' \in L_e^{(t,h)}$, where $e = (u,v)$ and $L_e^{(t,h)}$ denotes the set of links which have (t,h) as a free block and interfere with e over channel h, we compute the total capacity of its free transmission blocks as $C_{e'} = \sum_{(t,h)\in F_{e'}} c(t,h)$. We also compute $\delta_{e'}(t,h) = \frac{c(t,h)}{C_{e'}}$, which indicates the impact of selecting block (t,h) for link e on a link interfering with e. Furthermore, we define the interference impact ratio as $I_{int}(t,h) = \max\{0, 1 - \frac{\sum_{e'\in L_e^{(t,h)}} \delta_{e'}(t,h)}{|L_e^{(t,h)}|}\}$, to indicate the impact of selecting block (t,h) for link e on its interference neighborhood. A relatively small value indicates that block (t,h) is one of few free transmission blocks in the neighborhood, i.e., if block (t,h) is chosen for link e, those links will not be able to accept more flows, which is obviously not preferred. On the contrary, a relatively large value indicates that selecting block (t,h) for link e would not seriously affect the availability of free blocks on the neighboring links. We now define our weight function for the free transmission blocks as follows.

$$w(t,h) = \alpha \cdot I_{cap}(t,h) + \beta \cdot I_{int}(t,h) \quad (9)$$

In the equation, α and β are tunable parameters which are used to achieve a selection tradeoff between capacity and the impact of interference. Moreover, $\alpha + \beta = 1$. We sort free transmission blocks in the descending order of their weight values and select the first k transmission blocks whose total capacity is no smaller than B to serve the new incoming connection request on link $e = (u,v)$.

V. SIMULATION RESULTS

We evaluated the performance of the proposed protocol via simulation using *Network Simulator 2 (NS2)* [10]. In the simulation, the interference ranges were always set to 2 times of the corresponding transmission ranges [11] for all channels. The common control channel can support a transmission range of 600m. In all simulation scenarios, we randomly placed 10 primary users in the region. Each of them randomly chose a channel to use, which was then considered to be unavailable for all the nodes within the corresponding interference range. In all simulation runs, we injected 500 connection requests with random source nodes and destination nodes. The mean inter-arrival time is set to 10. The *acceptance ratio* is used as the performance metric, which is defined as the ratio between the number of accepted connection requests and the total number of connection requests (i.e., 500).

In the first scenario, we randomly placed 10 nodes in a $1000\text{m} \times 1000\text{m}$ region. The number of channels (H) was set to 12 and the number of timeslots in a frame (T) was set to 10. We divided those channels into three groups with equal sizes. The corresponding block capacities were normalized to $3, 1$ and 0.5 respectively, and the transmission ranges were set to 200m, 250m, and 500m respectively. The connection duration was set to a random integer uniformly distributed in $[1, D_{max}]$, where $D_{max} = 250$ in this scenario. The bandwidth requirement of a connection request was set to a random number in $[1, B_{max}]$, where B_{max} was changed from 1.25 to 12.5. In scenarios $2-4$, we tested larger cases by setting the region size to $2000\text{m} \times 2000\text{m}$, $H = 24$ and $T = 20$, which give 480 different transmission blocks. Block capacity and transmission range settings were the same as those in scenario 1. In scenario 2, we fixed the number of nodes $n = 40$ and $D_{max} = 250$. Bandwidth requirements were generated in the same way as in scenario 1. In scenario 3, $n = 40$, $B_{max} = 5$, and D_{max} was changed from 150 to 550. Finally, in scenario 4, $D_{max} = 250$, $B_{max} = 5$ and we changed n from 10 to 90. All the results are presented in Figs. 1–4. In the figures, Cap and $Cap - Interf$ stand for our capacity based and capacity-interference based algorithms respectively. The optimal solutions are provided by solving the ILP presented in Section III using CPLEX 9.0 [5].

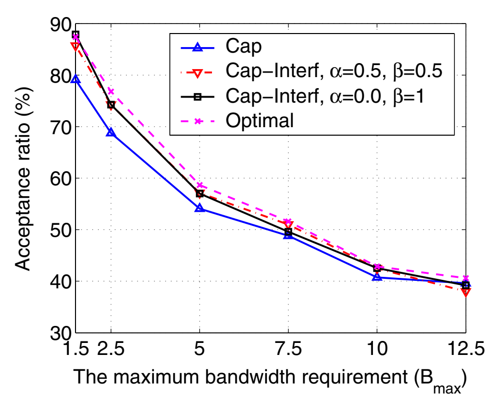

Fig. 1. Scenario 1: The proposed protocol VS. the optimal solution

We make the following observations:

1) From Fig. 1, we can see that the performance given by our protocol is very close to that of the optimal solution. Our capacity-interference based algorithm performs slightly better than our capacity based algorithm. By setting $\alpha = 0.5$ and $\beta = 0.5$, it achieves an average acceptance ratio of 58.09%,

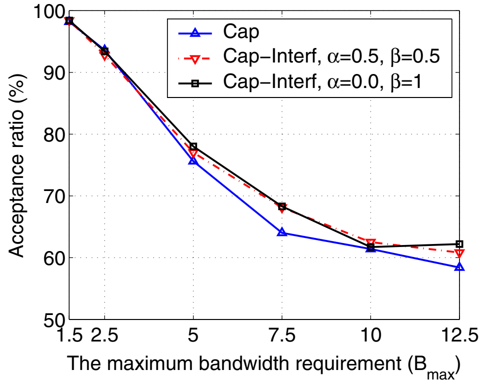

Fig. 2. Scenario 2: The impact of bandwidth requirement

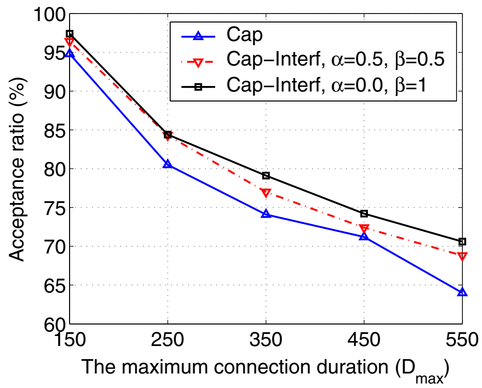

Fig. 3. Scenario 3: The impact of connection duration

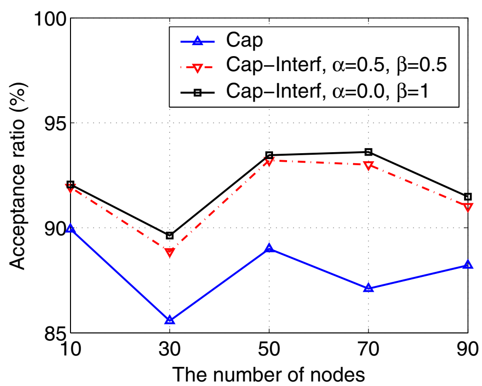

Fig. 4. Scenario 4: The impact of network size

compared to 59.66% given by solving the ILP. The difference is only 1.57%.

2) The capacity-interference based algorithm outperforms the capacity based algorithm by more than 3% on average. Interestingly, setting $\alpha = 0.0$ and $\beta = 1.0$ gives slightly better performance than setting $\alpha = 0.5$ and $\beta = 0.5$, which indicates that the interference plays a key role.

3) As expected, we find out that the acceptance ratio decreases with the increase of bandwidth requirement and connection duration. Higher bandwidth requirements (longer durations) lead to more resource consumption (longer resource occupation) for the accepted connections. Therefore, it is more likely that the system rejects more future connection requests. However, we observed from Fig. 4 that the acceptance ratio does not necessarily increase with the network size. On the positive side, with more nodes in the network, there will exist more alternative paths for a connection request. On the negative side, more nodes lead to a denser network, therefore stronger interference.

VI. Conclusions

In this paper, we studied QoS routing in wireless mesh networks with cognitive radios. We formally modeled it as an optimization problem. We presented an Integer Linear Programming (ILP) formulation as well as a distributed routing protocol to solve it. NS2 based simulation results have showed the performance given by our protocol is close to that of the optimal solution.

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