QoS Driven Channel Assignment in Multi-Channel Multi-Radio Wireless Mesh Networks

Bahador Bakhshi
Computer Engineering Department
Amirkabir University of Technology
Tehran, Iran
bbakhshi@aut.ac.ir

Antonio Capone
Department of Electronics and Information
Politecnico di Milano
Milan, Italy
capone@elet.polimi.it

Siavash Khorsandi
Computer Engineering Department
Amirkabir University of Technology
Tehran, Iran
khorsand@aut.ac.ir

***Abstract*—Channel assignment in multi-channel multi-radio wireless mesh networks is a powerful management tool to exploit available resources efficiently. In this paper, we study the problem of dynamic channel assignment in the presence of traffic with QoS constraints to optimize network performance, which is measured in terms of demand acceptance rate. We propose an on-line on-demand dynamic algorithm for the problem. It reassigns channels only when a demand cannot be accepted using current channel assignment and keeps the number of channel reassignments small by changing only the channel of the links in a vicinity of the route of each demand. Comparisons with other algorithms, including the optimal static channel assignment, show that the proposed algorithm outperforms existing solutions and can efficiently exploit available channels.**

***Index Terms*—Wireless Mesh Networks, Dynamic Channel Assignment, Quality of Service (QoS).**

I. Introduction

Multimedia services as an integral ingredient of broadband wireless mesh networks (WMN) require end-to-end quality of service (QoS) support, and because they are resource intensive need a high network capacity. However, the capacity of WMNs is shrunk due to interferences. In recent years, multi-channel multi-radio networking is used as a promising approach to boost the capacity. The problem of performance optimization of multi-channel multi-radio WMNs in the presence of QoS requirements is an interesting open problem. In this problem, the network performance is measured in terms of the acceptance rate of traffic demands as if the network cannot guarantee the QoS requirement of a demand, the user is not admitted to enter to the network.

Channel assignment is the key issue needs to be addressed in multi-channel multi-radio WMNs. It can be used to manage network resources *dynamically* since the available bandwidth on each link is determined by the level of interference on it, which depends on its assigned channel. In the presence of traffic with QoS constraints, the main problem is *to dynamically assign channels in order to optimize the network performance in terms of acceptance rate of traffic demands*.

The existing dynamic channel assignment schemes attempt to optimize different metrics as a measure of network performance. These solutions can be viewed in three categories: (i) approaches designed to mitigate external interferences [1]–[3], (ii) methods that reoptimize whole channel assignment periodically [4]–[6], and (iii) solutions that reassign channels according to local load measurements [7]–[9]. In the first category, it is assumed that there is an external source of interference, e.g., coexisting network, each node measures interferences periodically, and switch to the least interfered channel. Although minimizing the external interference improves network performance, this category does not explicitly take into consideration the network traffic and its dynamics. The studies in the second category are load-aware channel assignment; channels are assigned according to link loads. In these approaches, the channel assignment algorithm, which needs global network information, reruns every time network traffic pattern changes. Hence, the major drawbacks of these schemes are the requirement of global information and a significant overhead due to the possibility of many channel reassignments in each iteration. Schemes proposed in the third category are localized reassignment approaches, in which each node periodically checks the load on its links and reassigns channels in the case of detecting an overloaded link. Although these schemes have not the drawbacks of the second category, they do not consider the end-to-end throughput of each flow explicitly. These schemes attempt to improve the one-hop capacity of the network but cannot guarantee the end-to-end bandwidth requirement of flows, which is the main constraint in supporting quality of service. In summary, the existing solutions neither consider end-to-end QoS requirements of flows nor aim to maximize demand acceptance rate.

In this paper, we study the problem of dynamic channel assignment in presence of traffic with end-to-end bandwidth requirement to maximize the acceptance rate of the demands. The channel assignment algorithm can be used with any arbitrary routing strategy to provide the required resources. It is assumed that each QoS demand arrives at a particular time and requires a specific bandwidth. The demand is accepted if and only if the network can provide sufficient bandwidth along the routing path of the demand through appropriate channel assignments; otherwise, it is rejected. We assume channel assignment is a part of network management tools. It is a centralized algorithm, which runs on the call admission control (CAC) server.

Our contributions to the problem are as follows. First, we formulate it and identify the requirements of an efficient algorithm for it. Second, we design an on-line on-demand channel assignment algorithm. Finally, we evaluate the algorithm in terms of demand acceptance rate and study the effect of various parameters, including demand arrival rate, the number of available channels, and the number of radios per node.

The remaining of this paper is organized as follows. Assumptions, models, and problem formulation are presented in Section II. In Section III, we present the QoS Driven Channel Assignment (QDCA) algorithm and analyze its computational complexity. Simulation results are presented in Section IV and Section V concludes this paper.

II. System Model and Problem Formulation

A. Assumptions

We consider IEEE 802.11 based multi-channel multi-radio WMNs. In the networks, all nodes are static, node u has r_u radios, and all radios have the same transmission range T_R and the same interference range I_R. It is supposed that the RTS/CTS mechanism is enabled. There are κ orthogonal channels with the same c Mb/s physical capacity.

B. Network Model

Network is modeled by a digraph $G = (V, E)$, where V is a set of n vertices and E is a set of m edges. Each $v \in V$ corresponds to a node in the network. Suppose $d(u, v)$ is the Euclidean distance between u and v. For a given pair of nodes u and v, there is a link $(u, v) \in E$ iff $d(u, v) \leq T_R$.

C. Interference Model

We use the *interference range* model [10]. This model, in conjunction with the RTS/CTS mechanism, yields that links (u_1, v_1) and (u_2, v_2) interfere with each other if a same channel is assigned to both of them and $d(u_1, u_2) \leq I_R$ or $d(u_1, v_2) \leq I_R$ or $d(v_1, u_2) \leq I_R$ or $d(v_1, v_2) \leq I_R$. The set of the links interfering with (u, v) is denote by $I_{(u,v)}$.

D. Available Bandwidth Model

In multi-hop wireless networks, links interfering with each other have to share the physical channel capacity. To model the available bandwidth of each link, we use the *row constraint* model [11]. Let $l_{(u,v)}$ be the load on link (u, v), the row constraint imposes that $\sum_{(a,b)\in I_{(u,v)}} l_{(a,b)} \leq c$. Consequently, the available bandwidth of a link is defined as $ALB(u, v) = c - \sum_{(a,b)\in I_{(u,v)}} l_{(a,b)}$. To satisfy bandwidth requirement of flows we need $ALB(u, v) \geq 0$ for all links in the network.

E. Problem Statement

The problem studied in this paper is to maximize network performance, which is measured in terms of the acceptance rate of QoS constrained demands. There is a set of demands $F = \{(s, d, b, t, e)\}$. Demand i arrives at time t_i, it requires bandwidth b_i from node s_i to node d_i, and if accepted, it leaves the network at time e_i. A demand is accepted if and only if there is a channel assignment where allocating the required bandwidth through the path found by a routing algorithm does not violate capacity constraint of any link. If such path exists under an appropriate channel assignment, it is named *feasible path*. Therefore, the problem is to develop a channel assignment algorithm that can be used with every routing algorithm to maintain feasibility of paths found by the routing algorithm. In this problem, since there is not any information about a demand before its arrival time, the channel assignment algorithm must be *on-line*.

In addition to adapting channels to maximize demand acceptance rate, two further requirements should be met. First, the number of channel reassignments should be minimized, which is necessary to reduce the signaling traffic for updating channels in the network. Second, the solution should use local information and have a local impact because using the whole global network information for a channel reassignment leads to high computational complexity, and if its impact is not local, the reassignment may propagate in the network, which is known as the ripple effect problem [7].

III. Proposed Solution

In this section, we first clarify design choices, next, explain how the choices help us to achieve the design goals, and finally, present the QDCA algorithm and its computational complexity analysis.

A. Design Choices

There are four design decisions in the channel assignment algorithm: channel reassignment strategy, best channel selection metric, group channel change technique, and resource utilization strategy. Our choices for these decisions are clarified in the following.

1) On-demand Channel Reassignment: Our channel reassignment strategy is on-demand; channels are changed only if the path found by the routing algorithm is not feasible under current channel assignment. Infeasibility of path p implies that allocating bandwidth b through it violates the capacity constraint of at least one link, $\exists(u, v) \in E$ s.t. $ALB(u, v) < 0$. The link for which its capacity constraint is violated is referred as *violated link*. Note that violated links are not necessarily in path p, allocating bandwidth b through path p may cause $ALB(u, v) < 0$ where $(u, v) \notin p$.

For a given demand (s, d, b, t, e) and path p, the on-demand channel reassignment strategy checks feasibility of the path, if it is not feasible, violated links are found and their channels are changed to resolve the violations. The *best feasible* channel is selected as the new channel for each violated link. Satisfying feasibility and finding the best channel are explained in the following.

2) Feasibility Satisfaction: A feasible channel assignment needs to satisfy *capacity* and *radio* constraints. The capacity constraint is defined by the row constraint that needs $ALB(u, v) \geq 0$ $\forall(u, v) \in E$. The radio constraint imposes that the number of channels assigned to the links of node u does not exceed r_u. Suppose link (u, v) is violated, and we want to assign a new channel to the link. It is easy to see that the radio constraint at node u is satisfied if at least one of the following conditions holds: (i) there is a radio in u that is already tuned to the new channel, or (ii) there is a free radio, or (iii) the radio tuned to the old channel can switch to the new channel; to avoid the ripple effect [7] this condition holds only if no link except (u, v) uses the old channel. According to these constraints, we define two types of channels as follows.

Definition 1. *Candidate channel for a link is a channel that satisfies the radio constraint in both nodes of the link.*

Definition 2. *Valid channel is a candidate channel that also satisfies the capacity constraint.*

3) Best Channel Selection: Resource availability in the network is the main factor that affects admission of demands. Selecting a new valid channel for a violated link should provide resources for the upcoming demands. We define the resource of the network under channel assignment Ψ as $R(G, \Psi) = \sum_{(u,v)\in E}(ALB(u, v)/|I_{(u,v)}|)$. Therefore, the best channel is the one that maximizes $R(G, \overline{\Psi})$, where $\overline{\Psi}$ is the new channel assignment. If $\overline{\Psi}$ is obtained from Ψ by changing the channel of (u, v), it is easy to show that

$$R(G, \overline{\Psi}) = R(G, \Psi) + \sum_{(a,b)\in I_{(u,v)}\cup\overline{I}_{(u,v)}} \frac{\overline{ALB}(a, b)}{|\overline{I}_{(a,b)}|} - \sum_{(a,b)\in I_{(u,v)}\cup\overline{I}_{(u,v)}} \frac{ALB(a, b)}{|I_{(a,b)}|}, \quad (1)$$

where, $\overline{I}_{(u,v)}$ and $\overline{ALB}(u, v)$ are the interference set and available bandwidth of (u, v) after channel reassignment. In (1), the second term is the aggregate resource of the links in $I_{(u,v)}$ and $\overline{I}_{(u,v)}$ after changing the channel of (u, v) and the third term is these resources before the reassignment. This equation implies that we need to compute the difference between these two aggregate resources, and the best channel maximizes the difference. Note that this computation needs only the information of the links in $I_{(u,v)}$ and $\overline{I}_{(u,v)}$, which are local.

4) Group Channel Change: There are situations in which there is not any valid channel for a violated link (u, v), but changing the channel of other links in $I_{(u,v)}$ increases $ALB(u, v)$, and consequently, can resolve the violation. This strategy of is called *Group Channel Change*.

Our *recursive* procedure is as follows. We distinguish between the in-path violated links and the out-of-path ones. If violated link (u_2, v_2) is out-of-path, $(u_2, v_2) \notin p$, we change the channel of links $(u_3, v_3) \in I_{(u_2,v_2)}$ one-by-one that reduces the number of interfering links with (u_2, v_2) and, as a result, increases $ALB(u_2, v_2)$. When violated link (u_1, v_1) is in-path, for each *candidate channel* of (u_1, v_1), we assign the channel to the link; since it is not a *valid channel*, this assignment violates the capacity constraints of some links $(u_2, v_2) \in I_{(u_1,v_1)}$. Now, we have a new set of violated links and attempt to resolve them. However, this procedure creates a loop because if there is not any valid channel for a new violated link, the group channel change procedure is reapplied on it, and if it is in-path, the procedure creates another new set of violated links and so on. To avoid the loop, we treat all the new violated links as out-of-path links even if they are in-path. Note that this procedure limits channel reassignments in range $2I_R$ of path p because at most, it changes the channel of link (u_3, v_3) if $\exists(u_2, v_2), (u_1, v_1)$ such that $(u_3, v_3) \in I_{(u_2,v_2)}$, $(u_2, v_2) \in I_{(u_1,v_1)}$, and $(u_1, v_1) \in p$.

5) On-demand Resource Utilization: Available channels and radios are scarce resources in multi-channel multi-radio WMNs. To utilize these resources efficiently, we assign a channel to each link only if it is in the path of a flow. When a flow leaves the network, we check all the links in the routing path of the flow. If there is not any flow routed through link (u, v) on channel i, we remove the channel from the link and check radios of nodes u and v; at each node, if no link uses channel i, we free the radio tuned to the channel. In the initial channel assignment, when there is not any load, no link has any assigned channel. In real applications, we need to maintain network connectivity; thus, to remove the channel of a link, we *temporarily* assign a *default channel* to it. If it is not possible due to the radio constraint, it implies that some channels are assigned to the links of the node; hence, the node is already connected to the network.

B. Achieving Design Goals

The aforementioned design choices fulfill the design requirements mentioned in Section II-E. Acceptance rate is boosted by the on-demand resource utilization, which frees channels and radios, group channel change that offers more opportunity to resolve violations, and selecting the best channel that provides resources for upcoming demands. The number of channel reassignments is kept small by the on-demand strategy as it reassigns channels only if needed. The solution is localized since the best channel is selected according to local information and the group channel change mechanism limits channel reassignments in range $2I_R$ of routing paths.

C. QDCA Algorithm

These design choices are integrated in the QDCA algorithm. Pseudo-code of the algorithm is shown in algorithms 1–3. In these algorithms, LINKCHANNELCHANGE(u, v) assigns the best valid channel to (u, v) if it exists. Note that since a channel reassignment can resolve violation of multiple links, after each successful resolve in RESOLVEVIOLATION, remaining violated links are rechecked in line 9.

D. Worst Case Computational Complexity

The worst case running time of the QDCA algorithm is the case that all links in path p are violated and LINKCHANNELCHANGE cannot resolve the violations. In this case, for each link, GROUPCHANNELCHANGE is called, wherein lines 5–9 run and RESOLVEVIOLATION is called for the newly generated violated links, NVL. In the worst case, RESOLVEVIOLATION calls GROUPCHANNELCHANGE for the new violated links. However, in this case, lines 2–3 run that breaks the recursive function calls.

Let $\hat{I}$ be the size of the largest interference set, $\hat{r}$ denotes the maximum number of radios per node, and GCC_1 and GCC_2 be

Algorithm 1 : QDCA$((s, d, b, t, e), p)$

Check allocating bandwidth b through path p
if path p is feasible **then**
    return Accept
else
    $VL \leftarrow$ Violated Links
    RESOLVEVIOLATION(VL)
    if violations were resolved **then**
        return Accept
    else
        return Reject

Algorithm 2 : RESOLVEVIOLATION(VL)

while VL is not empty **do**
    $(u, v) \leftarrow VL[0]$
    LINKCHANNELCHANGE(u,v)
    if violation was *not* resolved **then**
        GROUPCHANNELCHANGE(u,v)
    if violation was *not* resolved **then**
        return Reject
    else
        Remove unviolated links from VL

Algorithm 3 : GROUPCHANNELCHANGE(u, v)

1: **if** (u, v) is out-of-path **or** $(u, v) \in NVL$ **then**
2:     **while** (u, v) is violated **and** there is unvisited $(a, b) \in I_{(u,v)}$ **do**
3:         LINKCHANNELCHANGE(a,b)
4: **else**
5:     $CC \leftarrow$ Candidate channels for (u, v)
6:     **for** $\forall i \in CC$ **and** if (u, v) is violated **do**
7:         Change channel of (u, v) to i
8:         $NVL \leftarrow$ New Violated Links
9:         RESOLVEVIOLATION(NVL)

respectively lines 2–3 and 5–9 of GROUPCHANNELCHANGE. We have $O(\text{LINKCHANNELCHANGE}) = O(\kappa(\hat{r} + \hat{I}))$ as we need to check the radio and capacity constraints per channel. $O(\text{GCC}_1) = O(\text{LINKCHANNELCHANGE})\hat{I} = O(\kappa\hat{I}(\hat{r} + \hat{I}))$. $O(\text{GCC}_2) = O(\kappa\hat{r} + \kappa(\hat{I} + \hat{I}(O(\text{LINKCHANNELCHANGE}) + O(\text{GCC}_1)))) = O(\kappa^2\hat{I}^2(\hat{r} + \hat{I}))$ as the radio constraint must be checked for κ channels to find the candidate channels and at most there would be $\hat{I}$ new violated links that RESOLVEVIOLATION is called for. The length of path can be at most n, so $O(\text{RESOLVEVIOLATION}) = n(O(\text{LINKCHANNELCHANGE}) + O(\text{GCC}_2)) = O(n\kappa^2\hat{I}^2(\hat{r} + \hat{I}))$, and finally $O(\text{QDCA}) = O(n\hat{I}) + O(\text{RESOLVEVIOLATION}) = O(n\kappa^2\hat{I}^2(\hat{r} + \hat{I}))$.

It should be noted that our simulations, presented in Section IV-F, show that this worst case occurs very rarely in practice.

IV. SIMULATION RESULTS

In this section, after describing the simulation setup, we evaluate the performance of QDCA under various network loads and configurations.

A. Simulation Setup

We used a flow-level event-driven simulator developed in Java. All simulations except Section IV-E were performed in a random topology, in which 100 nodes were spread in $1000 \times 1000m^2$ area, $T_R = 150m$, $I_R = 350m$, $c = 100$Mb/s, $\kappa = 12$, and r_u was a uniform random variable in $[2, 5]$. In each run of the simulations, a set of 500 random traffic demands was used, in which the arrival rate was a Poisson random variable, holding time was an exponential random variable with mean 10 min., and the required bandwidth was a uniform random variable in $[1, 20]$ Mb/s. We used the minimum-hop algorithm as the routing algorithm.

In these simulations, **QDCA-LCC** is the version of QDCA in which group channel change is not used; **QDCA-GCC** is the full version; **Random-Static** and **Greedy-Static** are the static random and greedy minimum interference [12] channel assignment algorithms, respectively. Moreover, we implemented the dynamic channel assignment algorithm proposed in [9] that needs an initial channel assignment. **Random-Dynamic** and **Greedy-Dynamic** are two versions of the dynamic algorithm with the initial channel assignment as the random and greedy algorithms, respectively.

B. Effect of Demand Arrival Rate

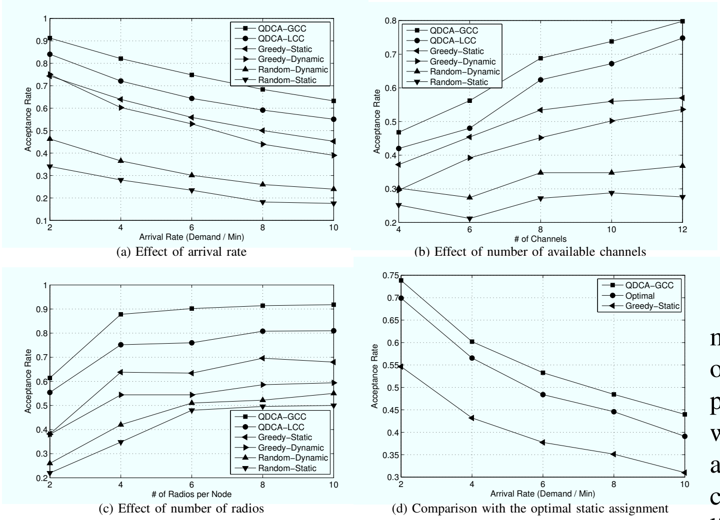
Acceptance rate versus demand arrival rate is shown in Fig. 1(a). As seen, both versions of QDCA outperform other static as well as dynamic approaches. Group channel change improves the acceptance rate of QDCA-GCC up to 10% in comparison to QDCA-LCC. There are two points about the approach proposed in [9]: first, its performance depends on the initial channel assignment—the Greedy-Dynamic has much better performance than Random-Dynamic. Second, Greedy-Static outperforms the Greedy-Dynamic especially in high loads that implies the decisions made by the dynamic algorithm have negative effects on acceptance of the upcoming demands.

C. Effect of Number of Available Channels

An efficient channel assignment algorithm should be able to exploit available channels. Fig. 1(b) shows the performance of the algorithms versus the number of available channels. This figure shows that QDCA has the maximum increase of acceptance rate per additional channel; more precisely, the average slope of the curves for QDCA based, Greedy based, and Random based algorithms is, respectively, 0.041, 0.03, and 0.005. The higher slope implies that QDCA has more ability to exploit additional channels.

D. Effect of Number of Radios per Node

Radios in each node are scarce resources. Efficient algorithms should be capable to provide good performance even with a limited number of radios. Fig. 1(c) depicts the performance of the algorithms versus the number of radios. This figure shows that a limited number of radios per node, about 4, is sufficient for QDCA-GCC to achieve the maximum performance. This figure also indicates that the number of radios is an important parameter in the random based algorithms since providing more radios improves the performance of these algorithms.



(a) Effect of arrival rate

(b) Effect of number of available channels

(c) Effect of number of radios

(d) Comparison with the optimal static assignment

Fig. 1. Simulation results to evaluate QDCA.

The results in Fig. 1(b) and Fig. 1(c) show that providing many channels with a very few radios per node is sufficient for QDCA-GCC to achieve good performance. This is also the situation in the real-life mesh networks, in which there are 12 orthogonal channels in IEEE 802.11a, and each node usually has 2–4 radios.

E. Comparing with Optimal Static Channel Assignment

To show the superiority of the QDCA algorithm, we compared it against the *optimal* static channel assignment, which is obtained by an integer linear programming model proposed in [12]. Since, the model is not solvable for large networks, we conducted these simulations in a 25-node network, in which nodes were spread in $750 \times 750m^2$ area, $T_R = 200m$, $I_R = 400m$, $c = 100$Mb/s, $\kappa = 10$, and r_u was a uniform random variable in $[2, 5]$. Fig. 1(d) shows the results in this topology. As seen, whereas the optimal model has significantly better performance than Greedy-Static, it is outperformed by the QDCA-GCC algorithm. These results show that an efficient dynamic approach can be better than every possible static algorithm. It must be noted that whereas the difference between the acceptance rate of QDCA-GCC and the optimal model is at most 5%, complexity of the optimal model is much higher than QDCA-GCC; this model is not a practical solution for real-life large/medium networks.

F. Complexity and Overhead

The average case complexity of QDCA is proportional to the average number of violations per demand and its overhead to update channels in the network is influenced by the number of channel reassignments per resolved violation. These statistics are reported in Table I. It is seen that the average case complexity is much less than the worst case as the number of violations per demand is much less than n. Moreover, the overhead is not significant as the average number of channel reassignment per resolved violation is less than one.

TABLE I
COMPLEXITY AND OVERHEAD OF QDCA

	Arrival Rate (demands per min.)				
	1	2	3	4	5
Violations per Demand	3.94	3.95	4.05	4.38	4.88
Channel Changes per Resolve	0.97	0.92	0.87	0.83	0.81

V. CONCLUSIONS AND FUTURE WORK

We studied the problem of performance optimization of multi-channel multi-radio WMNs, which is measured in terms of acceptance rate of QoS constrained traffic demands. We proposed an on-line dynamic channel assignment solution which can be used with any arbitrary routing strategy. When a demand arrives, if the path found for it is not feasible under current channel assignment, the algorithm detects violated links. If there is at least one valid channel for each violated link, it assigns the best one to the link; otherwise, it changes channels in the interference range of the violated link to provide additional bandwidth for it. Our simulation results show that this algorithm, which adapts channel assignment according to traffic requirements, outperforms even the best static approach. The proposed solution in this paper is decoupled from routing, we plan to study the joint QoS routing and dynamic channel assignment problem in the future work.

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