Optimal Joint QoS Routing and Channel Assignment in Multi-Channel Multi-Radio WMNs

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Abstract

We study the problem of finding a performance bound on joint QoS routing and channel assignment in multi-channel multi-radio wireless mesh networks, which is a fundamental issue in performance evaluation of joint QoS routing and channel assignment algorithms. To our best knowledge, this is the first time that the problem is addressed. A simple version of the problem is formulated as a mixed integer linear programming model, the model is relaxed to get an easier to solve model. The original problem is modeled by the relaxed model. Our simulations show that the relaxed model provides a tight upper bound while improves solution time up to 3.0e+5 times.

Keywords: Joint QoS Routing and Channel Assignment, Optimization Model, Relaxation, Upper Bound, Multi-Channel Multi-Radio Wireless Mesh Networks

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1. Introduction

QoS of Service (QoS) support is an essential component in broadband Wireless Mesh Networks (WMN). Supporting QoS is challenging in WMNs, since the multi-media services are bandwidth intensive while the capacity of WMNs is shrunk by the interferences arise from the shared nature of the wireless media. Multi-channel multi-radio networking is a promising approach to mitigate the interferences and boost network capacity.

In these networks, the main problem is to maximize network performance while maintaining QoS requirements of flows. Contrary to the traditional throughput maximization problem, in which the objective is to maximize the achievable rate of each flow, in presence of traffic with QoS requirements, the network performance is measured in terms of the number of *admitted QoS sensitive traffic demands*. A demand is accepted if the network can meet the QoS requirements. Since bandwidth is the most important QoS requirement for multimedia applications [1], we focus on this requirement; a demand is accepted if there is a path with sufficient bandwidth that is named as *feasible path*.

Existence of the feasible path depends on available bandwidth of links, which is specified by channel assignment pattern and routing path of flows. This bandwidth depends on channel assignment because each link has to share its physical channel capacity with other interfering links, which are determined by the channel assignment. Routing path of flows affects links available bandwidth as it specifies the load on each link. Hence, to maximize the network performance, routing path of flows and channels of links should be jointly optimized that leads to the *joint QoS routing and channel assignment* problem.

Each subproblem of this joint problem has been separately studied in previous work. The authors in [2–12] have studied the QoS routing problem and dynamic channel assignment problem has been investigated in [13–18]. These existing studies have two major drawbacks: (i) they don't treat the joint problem in spite of the fact that it is known the joint optimization of routing and channel assignment is beneficial [19] and

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Table 1: Notations

Notation	Description
V	Set of nodes, $\lvert V\rvert = n$.
E	Set of edges, $\lvert E\rvert = m$.
F	Set of demands, $F = \{(s_i, d_i, b_i, t_i, e_i)\}$.
K	Set of channel, $\lvert K\rvert = \kappa$.
c	Physical channel capacity
TR	Transmission range
IR	Interference range, $IR = TR \times q$ and $q > 1$.
r_u	The number of radios of node u
Ψ	Channel assignment pattern
(u, v)	Link $(u, v) \in E$
$I_{(u,v)}$	Interference set of link (u, v) in case of common channel assignment
$l_{(u,v)}$	Total load on link (u, v)
$l^k_{(u,v)}$	Load on link (u, v) on channel k
$f^i_{(u,v)}$	Flow of demand i on link (u, v)

(ii) these are heuristic methods; they cannot guaranty optimality of solution and in some cases, the solutions obtained from these algorithm may be far from the optimal one.

In this paper, we study the problem of obtaining a performance bound on joint QoS routing and channel assignment. In this problem, it is assumed that each demand arrives at a particular time and requires a specific bandwidth. The demand is accepted if we can find a path with sufficient bandwidth, otherwise it is rejected. The primary goal is to maximize acceptance rate of the demands by jointly optimizing routing and channel assignment. Our contributions to the problem are as following.

- We develop an optimal Mixed Integer Linear Programming (MILP) model for a simple version of the problem, in which demands are static.
- We relax the MILP model to get an upper bound that gives a tight bound while improves solution time up to 3.0e+5 times.
- The original problem, the case of dynamic demands, is formulated by the relaxed model which is an upper bound on the performance of joint QoS routing and channel assignment algorithms.

The remaining of this paper is organized as follows. System model and problem statement are presented in Section 2. In Section 3 we obtain an upper bound on the network performance. In Section 4, we present the simulation results. Finally, Section 5 concludes this paper.

2. System Model and Problem Statement

In this section, we describe the assumptions and models; then, the problem considered in this paper is formulated. Notations used through the paper are denoted in table 1.

2.1. Assumptions

We consider IEEE 802.11 based multi-channel multi-radio wireless mesh networks. In the network, all nodes are static, have multiple radios and all radios have the same transmission range TR and the same interference range IR. It is supposed that the RTS/CTS mechanism is enabled. There are κ orthogonal channels in the network and the physical channel capacities are the same value c Mb/s. We assume that each link can transmit only on one channel at any given time.

2.2. 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. $\forall v \in V$ corresponds to a node in the network. Let $d(u, v)$ be the Euclidean distance between nodes u and v. For a given pair of nodes u and v, there is a link $(u, v) \in E$ iff $d(u, v) \leq TR$.

2.3. Interference Model

We use the *interference range model* [20] which is an special case of the protocol model [21]. 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 if the sender or receiver of one of them is in the interference range of the sender or receiver of the other one [11], [19]; more specifically, $d(u_1, u_2) \leq IR$ or $d(u_1, v_2) \leq IR$ or $d(v_1, u_2) \leq IR$ or $d(v_1, v_2) \leq IR$. $I_{(u,v)}$ is the set of the links that interfere with (u, v) when *a common channel is assigned to all links.* Note that by definition (i) $(u, v) \in I_{(u,v)}$, (ii) $(u_1, v_1) \in I_{(u_2,v_2)}$ iff $(u_2, v_2) \in I_{(u_1,v_1)}$, and (iii) $I_{(u,v)}$ corresponds to neighbors of (u, v) in the link interference/contention graph.

2.4. Available Bandwidth Model

The authors in [22] proposed two sufficient conditions for feasibility of bandwidth allocation in multi-hop wireless networks: the *row* constraint and the *scaled clique* constraint. The row constraint implies that the aggregate load of the links in the interference set of each link must be less than the physical channel capacity. On the other hand, the scaled clique constraint imposes that the aggregate load of the links in each maximal clique of interference graph does not exceed the scaled physical channel capacity. We use the row constraint in the optimal for joint QoS routing and channel assignment, Section 3.1.1, and the scaled clique constraint in the relaxed model, Section 3.1.2.

2.5. Problem Statement

The problem studied in this paper is the optimal joint QoS routing and channel assignment for performance optimization in multi-channel multi-radio WMNs, which is measured in terms of the number of accepted demands with QoS constraints. In the problem, there is a set of demands $F = \{(s_i, d_i, b_i, t_i, e_i)\}$ in which, demand i arrives at time t_i, needs a path with bandwidth b_i from node s_i to node d_i. If it is admitted, it will leave the network at time e_i. We seek the optimal QoS routing and channel assignment — or at least a tight performance upper bound — which can be used as the reference point to evaluate practical algorithms.

3. Performance Bound

In this section, first we consider a simple version of the joint QoS routing and channel assignment problem in which the QoS demands are static. We develop an optimal model for this problem and then relax it to get an upper bound. Next, we consider the dynamic demands case and develop an optimization model for it.

3.1. Static Demands Performance Bound

The static demands performance bound problem is as following. A multi-channel multi-radio WMN, which is modeled by a digraph, and a set of *static* QoS demands are given. By the static QoS demands we mean all demands arrive at time 0, all have a same lifetime, and the required bandwidth of demands does not vary over the time. The question is *what the maximum number of admissible demands is.*

For this problem, first, we develop an optimal MILP model. The model is extremely difficult, so we relax it and obtain a relaxed model that is tremendously easier and provides a tight bound for the problem.

3.1.1. Optimal Model

In the optimal MILP model, we assume that each link can only use one channel and there is not fast channel switching capability in radios. In this model, the capacity constraint is modeled by the row constraint. In addition to the notations in table 1, following variables are used. Binary variable $x^k_{(u,v)}$ is the channel assignment variable,

$$x^k_{(u,v)} = \begin{cases} 1, & \text{if link } (u,v) \text{ transmits on channel } k \\ 0, & \text{otherwise.} \end{cases}$$

To model admission of demands, binary variable a_i is used,

$$a_i = \begin{cases} 1, & \text{if demand } i \text{ is accepted} \\ 0, & \text{otherwise.} \end{cases}$$

Tuning radios to channels is modeled by variable y_u^k,

$$y_u^k = 1, \text{ if channel } k \text{ is assigned to a radio in node } u.$$

The optimal model is as following. The objective function of the model is maximizing the number of admitted demands,

$$\text{maximize} \sum_{i \in F} a_i. \tag{1}$$

Since at most one channel can be assigned to each link, we have

$$\sum_{k \in K} x_{(u,v)}^k \leq 1 \qquad \forall (u,v) \in E. \tag{2}$$

Obviously, the variable y_u^k cannot be greater than 1, so

$$y_u^k \leq 1 \qquad \forall k \in K,\ \forall u \in V. \tag{3}$$

If link (u,v) uses channel k, the channel must be assigned to a radio in both nodes u and v, therefore

$$x_{(u,v)}^k \leq y_u^k,\ x_{(u,v)}^k \leq y_v^k \qquad \forall k \in K,\ \forall (u,v) \in E. \tag{4}$$

The radio constraint forces that the total number of channels assigned to links of a node to be at most the number of radios of the node; in other words,

$$\sum_{k \in K} y_v^k \leq r_v \qquad \forall v \in V. \tag{5}$$

If link (u,v) transmits a load on channel k, the channel must be assigned to the link. So, we have

$$l_{(u,v)}^k \leq x_{(u,v)}^k c \qquad \forall k \in K,\ \forall (u,v) \in E. \tag{6}$$

For each link, the load transmitted by the link must be equal to the load offered by flows in the network,

$$\sum_{i \in F} f_{(u,v)}^i = \sum_{k \in K} l_{(u,v)}^k \qquad \forall (u,v) \in E. \tag{7}$$

Capacity constraint is modeled as

$$\sum_{(a,b) \in I_{(u,v)}} l_{(a,b)}^k \leq (1 - x_{(u,v)}^k)M + c \qquad \forall k \in K,\ \forall (u,v) \in E. \tag{8}$$

This conditional constraint imposes the physical channel capacity restriction iff channel k is assigned to link (u,v), $x_{(u,v)}^k = 1$. It is easy to show that the value of M must be larger than $(\hat{I} - 1)c$ where $\hat{I}$ is the size of the largest interference set. Finally, the routing and flow conservation constraint must be satisfied *if demand is accepted*, which is modeled as following

$$\sum_{(u,v) \in E} f_{(u,v)}^i - \sum_{(v,u) \in E} f_{(v,u)}^i = \begin{cases} a_i b_i, & \text{if } u = s_i \\ -a_i b_i, & \text{if } u = d_i \\ 0, & \text{otherwise} \end{cases} \qquad \forall u \in V,\ \forall i \in F. \tag{9}$$

The last constraints are the bound constraints,

$$x_{(u,v)}^k \in \{0,1\},\ a_i \in \{0,1\},\ l_{(u,v)}^k \geq 0,\ f_{(u,v)}^i \geq 0,\ y_u^k \geq 0. \tag{10}$$

Putting (1)–(10) altogether gives an optimal model for the static demands performance bound problem as follows.

Table 2: The Number of Maximal Cliques

Node #	Link #	Interference Graph Maximal Clique #
25	126	8
50	234	107
100	656	204

Model: OptimalStaticDemands
Objective: (1)
Subject to: (2)–(10)

Whereas solving the OptimalStaticDemands model gives an optimal feasible QoS routing and channel assignment, it is extremely difficult. The model cannot be solved easily even for small networks and a few number of demands. The complexity arises from the binary variables $x^k_{(u,v)}$ and a_i. In the following, we deal with this complexity by relaxing this optimal model.

3.1.2. Upper Bound

The binary variable $x^k_{(u,v)}$ used for channel assignment is the source of the difficulty of OptimalStaticDemands. To tackle this complexity, we assume that *radios are capable to do fast switching.* Using this assumption, variable $x^k_{(u,v)}$ is relaxed as

$$x^k_{(u,v)} = \text{ Fraction of time that link } (u,v) \text{ transmits on channel } k.$$

However, this relaxation causes a problem. The capacity constraint (8) is a conditional constraint and needs the *binary* variable $x^k_{(u,v)}$. To deal with this issue, we replace the constraint by another one. Note that (8) is based on the *sufficient* row constraint. We replace the row constraint by the *scaled clique* constraint [22]. While the unscaled clique constraint is not generally a sufficient condition for feasibility of bandwidth allocation[1], the scaled version is. The scaled clique constraint imposes that the aggregate load of the links in each *maximal* clique in the interference graph does not exceed the *scaled* physical channel capacity. There are two issues about the scaled clique constraint. The first one is finding the maximal cliques. Theoretically, the number of maximal cliques in an arbitrary graph can be exponential; but, in practice, in the interference graphs of multi-hop wireless networks, the number is limited and all maximal cliques can be found very easily. Table 2 shows the number of maximal cliques in the interference graph of three random topologies. The maximum time to find all maximal cliques is less than one second in our experiments on an Intel Pentium IV 3.0GHz machine[2].

The second issue is the value of the scale. The authors in [22] showed that the value depends on the *imperfection ratio* of the interference graph and stated that in unit disk graphs, the value is bounded by 0.46. But 0.46 is too loose bound; for example, in small topologies with large interference rages, the interference graph is a single clique that implies scale = 1.0. A recent simulation based study of the imperfection ratio of the interference graphs provided two conclusions [24]. First, as the number of nodes increases the value of scale decreases. Second, scale = 1.0 is a good approximation but to be more conservative, we can use scale $= \frac{1}{1.21} = 0.826$. Based on this study, we use both these values to find two bounds.

Let γ be the scale, Q_i be a maximal clique in the interference graph when a common channel is assigned to all links, and set $\Phi = \{Q_1, Q_2, \ldots\}$ be the set of the maximal cliques. The relaxed model for the static demands performance bound problem is as following. Obviously, the variable $x^k_{(u,v)}$ is bounded by 1,

$$x^k_{(u,v)} \leq 1 \qquad \forall k \in K,\ \forall (u,v) \in E. \tag{11}$$

[1] In fact it is sufficient condition iff the interference graph is *perfect*.
[2] We used MACE program to enumerate maximal cliques [23].

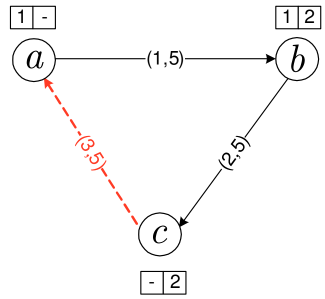

Figure 1: An example of unschedulable solution. The physical channel capacity is 10. Each node has one radio. Label of each link is (channel, load). Label of each node is the schedule of channel activation on the radio of the node. Whereas all the constraints of RelaxedStaticDemands are satisfied, there is not any feasible schedule.

Load transmitted by link (u, v) on channel k is proportional to the fraction of time that the link is active on the channel, so

$$l^k_{(u,v)} = x^k_{(u,v)} c \qquad \forall k \in K,\ \forall (u, v) \in E. \tag{12}$$

As $x^k_{(u,v)}$ also equals to utilization of a radio in both nodes u and v on channel k, the radio constrain will be as

$$\sum_{k \in K} \Big(\sum_{(u,v) \in E} x^k_{(u,v)} + \sum_{(v,u) \in E} x^k_{(v,u)} \Big) \leq r_v \qquad \forall v \in V. \tag{13}$$

The scaled clique constraint is

$$\sum_{(u,v) \in Q_i} l^k_{(u,v)} \leq \gamma c \qquad \forall k \in K,\ \forall Q_i \in \Phi. \tag{14}$$

The bound constrains are

$$x^k_{(u,v)} \geq 0,\ a_i \in \{0, 1\},\ l^k_{(u,v)} \geq 0,\ f^i_{(u,v)} \geq 0. \tag{15}$$

Combination of these constraint and objective function (1) gives the relaxed model as

Model:	RelaxedStaticDemands
Objective:	(1)
Subject to:	(7), (9), (11)–(15).

It is important to note that this relaxed model is an upper bound because the solution of this model may not be *schedulable*. An example of unschedulable solution is depicted in Fig. 1. In this example, in the first time-slot, nodes a and b active channel 1 on their radios to transmit the load on link (a, b), the length of this time-slot is half of the scheduling frame since the load on the link is 5 and the physical channel capacity is 10. In the second time-slot, channel 2 is activated on radios of nodes b and c to transmit the load on link (b, c), the length of this time-slot is also half of the scheduling frame. However, there is not any time-slot to transmit the load on link (c, a) on channel 3 even though all the constraints of the RelaxedStaticDemands model are satisfied. Our simulation results presented in the next section show that this issue is not an important matter and RelaxedStaticDemands provides a tight bound.

3.2. Dynamic Demands Performance Bound

Dynamic demands performance bound problem is in fact the performance bound of the joint QoS routing and channel assignment problem in which each demand i arrives at time t_i and has a limited lifetime $e_i - t_i$. However, the required bandwidth b_i does not vary over the time. Again, the question is the maximum number of admissible demands.

In addition to the fast switching capability, if we assume that flows in the network can be *rerouted*, there would be a *static demands* performance bound subproblem at the arrival time of each demand. However, the major complexity to model the dynamic demands performance bound problem is that the static subproblems are **not** independent. In each subproblem, which corresponds to the arrival of a new demand, the static demands set contains all the previously arrived demands that overlap with the new one; which implies each demand is considered in multiple subproblems. Therefore, if a demand is accepted in a subproblem, it must be accepted in all other subproblems that implies the subproblems cannot be solved independently. In fact, the dynamic demands performance bound problem is a combination of $|F|$ static demands performance bound subproblems which should be solved altogether simultaneously. In the following, we develop an optimization model for the problem.

3.2.1. Upper Bound Model

As mentioned, we need to consider all the static demands performance bound subproblems altogether. For this propose, we introduce a time set T which is $T = \{t_1, t_2, \ldots, t_{|F|}\}$. All variables except a_i are indexed by the time variable; e.g., $x^k_{(u,v)}$ is converted to $x^k_{(u,v),t_i}$, $f^i_{(u,v)}$ is converted to $f^i_{(u,v),t_i}$, and so on. Moreover, the required bandwidth of demand j is defined as

$$b_{j,t_i} = \begin{cases} b_j, & \text{if } t_j \leq t_i \leq e_j \\ 0, & \text{otherwise.} \end{cases}$$

The constraints of all the static subproblems must be satisfied, so (7), (9), and (11)–(15) are respectively changed as the following.

$$\sum_{i \in F} f^i_{(u,v),t_i} = \sum_{k \in K} l^k_{(u,v),t_i} \qquad \forall t_i \in T,\ \forall (u,v) \in E. \tag{16}$$

$$\sum_{(u,v) \in E} f^j_{(u,v),t_i} - \sum_{(v,u) \in E} f^j_{(v,u),t_i} = \begin{cases} a_j b_{j,t_i}, & \text{if } u = s_j \\ -a_j b_{j,t_i}, & \text{if } u = d_j \\ 0, & \text{otherwise} \end{cases} \qquad \forall t_i \in T,\ \forall u \in V,\ \forall j \in F. \tag{17}$$

$$x^k_{(u,v),t_i} \leq 1 \qquad \forall t_i \in T,\ \forall k \in K,\ \forall (u,v) \in E. \tag{18}$$

$$l^k_{(u,v),t_i} = x^k_{(u,v),t_i} c \qquad \forall t_i \in T,\ \forall k \in K,\ \forall (u,v) \in E. \tag{19}$$

$$\sum_{k \in K} \Big(\sum_{(u,v) \in E} x^k_{(u,v),t_i} + \sum_{(v,u) \in E} x^k_{(v,u),t_i} \Big) \leq r_v \qquad \forall t_i \in T,\ \forall v \in V. \tag{20}$$

$$\sum_{(u,v) \in Q_i} l^k_{(u,v),t_i} \leq \gamma c \qquad \forall t_i \in T, \forall k \in K,\ \forall Q_i \in \Phi. \tag{21}$$

$$x^k_{(u,v),t_i} \geq 0,\ a_i \in \{0,1\},\ l^k_{(u,v),t_i} \geq 0,\ f^i_{(u,v),t_i} \geq 0. \tag{22}$$

The upper bound model for the dynamic demands performance bound problem is

Model:	UpperBoundDynamicDemands
Objective:	(1)
Subject to:	(16)–(22).

4. Simulation Results

In this section, we present simulation results to show efficiency and tightness of the RelaxedStaticDemands model. We conducted the simulations in three 10, 15, and 25 nodes random topologies with parameters shown in table 3. In each experiment, 50 random demands were offered to the network. The required bandwidth of each demand was a uniform random variable in $[0, B_{max}]$Mb/s. To solve the models, we used CPLEX 11.0 [25]. Time limit to solve the model was 10 hours. If a model was not solved in the time limit, we got the best integer solution as the result. We present optimality gap for the problems which were not solved optimally. The machine used in these simulations was an Intel Pentium IV 3.0GHz with 2 Gigabytes RAM. The results presented in this section are the average of five experiments.We use two evaluation metrics which are defined as following.

Table 3: Parameters of the Topologies Used in Simulations

Parameter	Values		
Name	T-10	T-15	T-25
Area	$500\times500m^2$	$600\times600m^2$	$750\times750m^2$
Node #	10	15	25
TR	$200m$	$200m$	$200m$
IR	$400m$	$400m$	$400m$
Radio #	Random [2,5]	Random [2,5]	Random [2,5]
Channel #	12	12	12
c	100Mb/s	100Mb/s	100Mb/s

Table 4: Simulation results of OptimalStaticDemands and RelaxedStaticDemands. The parameters of the simulation topologies are shown in table 3.

Topology		T-10		T-15		T-25	
B_{max}		20	30	20	30	20	30
Accepted #	Optimal	48.8	44	49.4	44.4	46.6	40
	Not Scaled	49.3	45.4	49.4	45	49.9	44.8
	Scaled	48.5	42.8	48.8	42.6	48.8	42
Bound Gap	Not Scaled	1.09e−2	3.13e−2	0	1.35e−2	7.09e−2	1.20e−1
	Scaled	−6.15e−3	−2.84e−2	−1.21e−2	−4.05e−2	4.68e−2	5.00e−2
Time(sec)	Optimal	2.17e+4	3.60e+4	1.09e+4	3.60e+4	3.60e+4	3.60e+4
	Not Scaled	9.50e−2	1.73e−1	4.74e−1	6.24e−1	8.71e−1	3.38e+0
	Scaled	1.20e−1	1.12e−1	4.62e−1	8.90e−1	2.16e+0	5.71e+0
Time Ratio	Not Scaled	2.28e+5	2.08e+5	2.30e+4	5.77e+4	4.13e+4	1.07e+4
	Scaled	1.81e+5	3.22e+5	2.36e+4	4.04e+4	1.67e+4	6.31e+3
Exceed #		2	5	1	5	5	5
Optimality Gap		1.66e−2	1.13e−1	6.38e−2	1.27e−1	7.46e−2	2.08e−1

Definition 1. *Bound Gap of a relax model is*

$$\frac{\textit{Relaxed Model Accepted Demands \# } - \textit{ Optimal Model Accepted Demands \#}}{\textit{Optimal Model Accepted Demands \#}}.$$

Definition 2. *Time Ratio of a relax model is*

$$\frac{\textit{Optimal Model Solution Time}}{\textit{Relaxed Model Solution Time}}.$$

Table 4 shows the simulation results. In this table, rows “Optimal,” “Not Scaled,” and “Scaled” are the results of OptimalStaticDemands and RelaxedStaticDemands with scale = 1.0 and scale = 0.826, respectively. The “Exceed #” row is the number of times that OptimalStaticDemands was not solved in the specified time limit and “Optimality Gap” is the average optimality gap of the best integer solutions in these cases.

Following conclusions can be derived from these results. First, RelaxedStaticDemands is a tight relaxation of the optimal model as the bound gap is very small. Second, RelaxedStaticDemands is incredibly, up to 3.22e+5 times, faster than OptimalStaticDemands. Third, the best integer solution is a fairly good approximation of the optimal solution since the optimality gap of the solutions of OptimalStaticDemands is quite small. Forth, these results confirm the conclusions in [24] that the scale value 0.826 is too conservative for small topologies, the bound gap is negative for T-10 and T-15, but as the number of nodes increases the scale value 1.0 becomes looser while the scale value 0.826 gets more tighter.

5. Conclusion

In this paper, we approached the problem of finding an upper bound on the maximum number of admissible demands with bandwidth requirement in multi-channel multi-radio WMNs. In this problem, demands are dynamic — demands arrive one-by-one and each demand has a finite life-time. Since modeling this problem is rather difficult, in the first step, we simplify it and assume all demands are static — all demands arrive at time 0. We developed an optimal model for the static case and then relax it. The relaxation improves solution time tremendously and gives a tight upper bound on the optimal solution. The dynamic demands case is modeled by the relaxed model. The solution obtained from the dynamic model, can be used as the benchmark to evaluate heuristic algorithms for the joint QoS routing and channel assignment problem.

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