Joint Link Scheduling and Routing for Load Balancing in STDMA Wireless Mesh Networks

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Abstract: In wireless mesh networks, it is known to be effective to use a TDMA based MAC than a contention-based CSMA. In addition, if spatial TDMA is used, network performance can be improved further because of its spatial reuse effect. However this scheme still has a disadvantage in the system performance aspect without a load-balanced routing because the resource of links that are not used is wasted and frequently used links are out of resources. That is, the number of available flows in network is limited because load balancing is not performed. In this paper, we propose joint link scheduling and routing through a cross-layer scheme. For this, we propose a load balancing routing method to maximizes the minimum available resource under the given traffic pattern and scheduling method for maximizing link utilization on the given route. These two methods are iterated until an optimized solution can be obtained. The proposed algorithm can be formulated using a mathematical LP problem and we show that it is very effective for load balancing compared to simple adoption of IEEE 802.11s which is a standard TDMA protocol in wireless mesh network. If the proposed algorithm is applied to initial design solution such as Smart Grid, the number of available flows can be increased and the load on each link can be balanced.

Keywords: WMN, STDMA, Load Balancing, Joint Routing and Scheduling, Network Optimization, Linear Program

1. Introduction

Wireless Mesh Networks (WMNs) is a useful key technology when a wireless network is installed urgently and temporarily or when the installation of a wired network is difficult. WMNs provides easy installation, economic efficiency, flexibility, and scalability outside of a city or in disaster area and military battlefield without a wired infrastructure[1].

The backbone of WMNs consists of Mesh Routers (MRs), and the MRs are classified as Mesh Points (MPs), Mesh Access Points (MAPs), and Mesh Portals (MPPs or Gateways) according to their own function. In WMN backbone, the MP has a function of routing and forwarding, the MAP carries out an Access Point (AP) of wireless stations (STA) and the MPP operates as a gateway between the wired Internet and the WMNs[2]. The WMN backbone has load imbalance in the MPP which is connected to the wired Internet or in some MPs which are on the routing path. Therefore, load balancing is necessary for avoiding bottleneck links and causing high network utilization. Especially in the case of the MPP, because all the traffic from end users should go through it, there is high possibility for network congestion, packet loss, and buffer overflow due to bandwidth constraint, so load balancing is necessary to enhance network throughput and network scalability. When load balancing is applied to WMNs, it is possible to distribute the traffic to all the links evenly, to minimize the consumption of network resources, and to overcome the load imbalance efficiently[3][4].

Especially in the case where the topology of WMNs does not change a lot, it is very important to determine the routing and scheduling carefully at the initial network design stage. In this paper, we propose a joint routing and scheduling algorithm for load balancing, and evaluate its performance by mathematical analysis. Because WMNs can be modelled as a network graph, a network optimization solution can be applied to routing and scheduling for load balancing. The objective of the optimization problem is the maximization of the minimum available bandwidth under the given traffic.

We assume STDMA (Spatial TDMA)-based WMNs in this paper. TDMA is a time division multiple access method to provide collision free transmission, but has a shortage of no spatial reuse between non-overlapping regions. Especially in a multi-hop wireless environment, an STDMA scheme can greatly prevent a waste of resource by applying the spatial reuse scheme. Under the STDMA scheme, nodes away from three-hop and above can use the same wireless channel simultaneously. This is a principle of STDMA in a wireless ad-hoc or wireless mesh network, thus this MAC scheduling scheme can improve network performance[5].

As a standard MAC protocol in IEEE 802.11s[6], the MCCA (MCF Controlled Channel Access) which can guarantee bandwidth via a TDMA-based reservation is suggested. The MCCA scheme supports the spatial TDMA scheme, but it cannot achieve load balancing. So, an additional routing algorithm that considers current load conditions of each link should also be applied for load balancing.

In this paper, we propose a new algorithm considering joint scheduling and routing to distribute the network load over WMNs. When network flow is designed using the proposed algorithm at the initial design stage, network utilization will be maximized and available remaining network resources can be evenly distributed over all the links.

The remainder of the paper is organized as follows. In section 2, we describe the related works of load balancing routing and scheduling. In section 3, we present the proposed algorithm and LP analysis method in detail, and we show the performance of the proposed algorithm in section 4. Lastly in section 5, we conclude our paper and discuss the future directions.

2. Related Works

In this section, we describe research issues and related works about scheduling and routing for load balancing in WMNs. We introduce the IEEE 802.11s HWMP path selection protocol, which is a performance comparison target of the proposed algorithm.

An object of wireless link scheduling is to enable a transmission without collision based on the interference between links. The early wireless link scheduling research in the multi-hop wireless networks was done assuming a simple network topology graph, so that approaches have not considered full interference of the wireless medium[7].

In a multi-hop wireless mesh network environment, CSMA/CA cannot guarantee the network performance due to a variety of problems, such as a hidden/exposed node problem [8]. However TDMA-based link scheduling can improve network performance by controlling the schedule and avoiding collisions in high load conditions.

In [9], they proposed a TDMA scheduling on the given node and link topology using a physical interference model and analyzed the proposed scheduling using an LP(Linear Programming) formulation. Also, in [10], they proposed a scheduling algorithm to control traffic further. But these two proposed scheduling schemes have the disadvantage of complex calculation. According to [11], it is difficult to predict the performance of STDMA scheduling when a physical interference model is applied. For this reason, in this paper we use a protocol interference model in STDMA based WMNs and propose a joint link scheduling and routing algorithm.

The routing algorithms for load balancing have been proposed in ad-hoc networks. The proposed routing algorithms, MCR[11], LBAR[4], DLAR[12] and etc. are on-demand routing schemes. These routing protocols are suitable for an ad-hoc network where frequent link failures occur due to the movement of nodes, but they have a drawback when applied to WMNs because big overhead of control messages to set up a path occurs irrespective of almost less mobility in WMNs. Therefore the proposed routing algorithms for load balancing in ad hoc networks are inappropriate in WMNs

In WMNs, routing algorithms should reflect that the MP's mobility is less frequent and must consider interferences between MPs in the wireless environment. In this paper, we suggest link scheduling using l-distance edge coloring[13] to consider interference between MPs and also propose a routing algorithm which can find a path to distribute available resource evenly. A detailed description of l-distance edge coloring is discussed in section 3.

When the proposed joint link scheduling and routing algorithm is applied at the initial network design stage, the total amount of the remaining resource for each link can be maximized and the resources of each link can be used evenly, and thus even more flows can be accommodated than the pre-existing algorithms in a network having limited resources. Existing research has considered scheduling and routing separately, but for efficient network design cross-layer design has to be applied by sharing information between different layers in multi-hop wireless mesh networks. So in this paper, we propose a novel algorithm which improves network performance by evenly distributing flows throughout the network by applying scheduling information to the routing algorithm.

As a default routing protocol, HWMP was suggested in IEEE 802.11s. HWMP uses a combination of reactive and proactive algorithms as a routing protocol. Because the routing protocol is used in a MAC layer, HWMP is called a path selection protocol in IEEE 802.11s. In this paper, however, we use the term "routing protocol" instead of "path selection protocol" to avoid confusing the terminology.

A proactive algorithm forms a root-based tree to generate a routing path. Generally, a mesh portal or mesh gateway among all mesh routers is chosen as a root node. Unlike a proactive algorithm that discovers a path earlier even if there is no data to send, the reactive algorithm, also called the on-demand algorithm, conducts a path discovery only when there is a data just to send. In general, RM-AODV(Radio Metric-AODV) [14] is used. RM-AODV's operational procedure is the same as AODV[15], but it uses a radio metric called 'AirTime' instead of a distance metric to reach the destination.

We assume that the condition of the wireless link is the same when comparing a performance between the proposed algorithm and HWMP.

3. Joint Load Balancing Routing and Scheduling

In this section, the network model and several assumptions to be used in this proposed algorithm are explained in detail. We then formulate the joint link scheduling and routing algorithm and convert it into an LP problem which can be easily solved. Lastly, we fully describe the proposed algorithm.

3.1 Network Model and Assumptions

The network model proposed in this paper is composed of static MPs. The STDMA-based WMNs are modelled as a network graph consisting of nodes (vertices) and links (edges). In other words, the network graph G denotes $G = (N, E)$ which consists of the set of nodes N and the set of links E. A link l_{ij} stands for a link from node i to node j, its capacity(resources) is represented by C slots. Actually used resource capacity on link l_{ij} by all the flows is represented by c_{ij}, and the maximal available capacity except for resources that cannot be used because of interference from other link's transmission is denoted by u_{ij}. Under the topology of given N and E, $K = \{1, 2, 3, \dots, k\}$ means flow set, $s_k(d_k)$ means source(destination) of a flow k and λ_k means the amount of flow k.

For example, in the network topology as shown in figure 1, N, E, K, s_1, d_1 and λ_1 are as follows:

$N = \{n_1, n_2, n_3, n_4, n_5, n_6\}$
$E = \{l_{12}, l_{14}, l_{21}, l_{23}, l_{25}, l_{32}, l_{36}, l_{41}, l_{45}, l_{52}, l_{54}, l_{56}, l_{63}, l_{65}\}$
$K = \{1\}, s_1 = n_1, d_1 = n_6, \lambda_1 = 10$

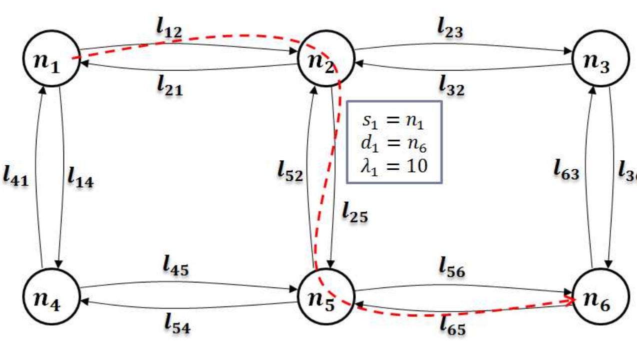

Figure 1. 2x3 Grid Network Topology

In this paper, we assume that the topology information and all the information of every flow (source, destination, and the traffic load) are given at the initial network design stage. We define the unit of the resource of link and the amount of flows as slot.

3.2 Link Coloring and Slot Allocation

Link coloring can be used for link scheduling by assigning different slots to each color. However, the scheduling algorithm in a wired network cannot be used as it apply link coloring without considering wireless interference. In wireless networks, the transmission range is not same as the interference range and hidden/exposed terminal problems can occur, so a new link coloring algorithm is needed[16]. A link coloring algorithm in a wired network decides scheduling by assigning different colors to all links which is connected to the same node. But in a wireless network, the color of a link should be decided by considering the neighbor link and interferences from within 3-hops away links as well. This coloring scheme can guarantee interference-free transmission and packet collision does not occur. In this paper, we use an l-distance edge coloring scheme proposed in [13].

First, we define l-distance as the number of links between any two links when the minimum path is decided between them. In figure 1, the minimum path between l_{12} and l_{36} is $l_{12} \rightarrow l_{23} \rightarrow l_{36}$, so the distance is 1 because there is only one link between them. According to 1-distance edge coloring, links within $distance \leq 1$ are colored with different colors, i.e. l_{12}, l_{23}, l_{36} have different colors. The links with different colors are scheduled in different time intervals in a frame. Generally, time slots allocated to each color in a frame is determined to be the 1/(number of colors) of the total slots after coloring the entire WMNs. But, if we assign more slots to highly loaded links by borrowing slots from links with less traffic, network utilization can be enhanced.

We decide the number of required colors using 1-distance edge coloring scheme assuming bi-directional link between nodes at first as shown in figure 2. But in wireless network, the bidirectional link should be colored with different colors in each direction separately because each transmission can affect packet collision. So, the number of needed colors is twice the value obtained from figure 2.

The number of colors from 1-distance edge coloring in WMNs is defined as $\chi(G)$. Link scheduling is then defined as a scheme allocating resources to each color. A set of links with the same color is represented by the independent link group $S_{\chi(G)}$.

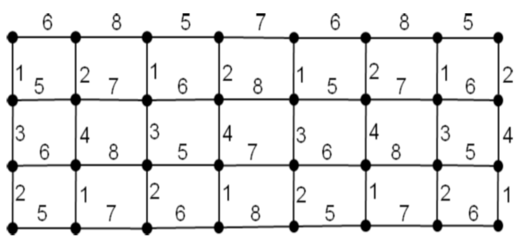

Figure 2. Example of 1-Distance Edge Coloring

If we allocate the resources having maximum capacity C to each link group S_s $(0 < s \leq \chi(G))$ with the amount of slots ϕ_s, then the constraint equation (1) is given as follows.

$$\sum_{s=1}^{\chi(G)} \phi_s \leq C \quad , \qquad 0 \leq \phi_s \leq C \tag{1}$$

ϕ_s can be formulated as following equation (2), since each group of links transmits data at the exclusive time. If link l_{ij} belongs to link group S_s, then maximum available capacity u_{ij} is equaled to ϕ_s as shown in equation (3).

$$\phi_s = \mathrm{C} \lim_{\tau \to \infty} \frac{1}{\tau} \sum_{t=0}^{\tau-1} I_{\{S_t = S_s\}} \tag{2}$$

S_t : a group which is selected at time t

$$u_{ij} = \phi_s \; , \quad \text{if } l_{ij} \in S_s \tag{3}$$

In the next section, we formulate the problem of routing algorithm with load balancing using the above mentioned slot allocation and scheduling scheme.

3.3 Routing Problem Formulation

We formulate the load-balancing scheme as an LP problem to maximize the minimum remaining capacity. By solving the LP problem, a routing path maximizing the minimum remaining resource of the link under the given traffic flow can be determined.

The objective function is formulated as a function to maximize the minimum remaining capacity between the total capacity C and the used capacity c_{ij} in each link l_{ij} as shown in equation (4). By doing so, the minimum remaining capacity of the link can be maximized.

$$Maximize \qquad min_{l_{ij} \in E_c}(C - c_{ij}) \tag{4}$$

The constraint equations of the objective function are given as follows. First, as shown in equation (5), the flow status of link l_{ij} for flow k is represented as an integer (0 or 1). In case of $x_{ij}^k = 0$, flow k passes on the link l_{ij}, on the contrary in case of $x_{ij}^k = 1$, it does not. This means that each flow takes a single routing path in network without being distributed to multiple routing paths.

$$x_{ij}^k \in \{0, 1\} \tag{5}$$

The following constraints (6) and (7) can be derived from that source and sink node should have only one outgoing / incoming link for flow k. Equation (6) means the outgoing link from node i must have one link in case that node i is a source, and equation (7) means incoming link to destination node d_k must have one link for each flow. E_C stands for a set of links for which it is possible to communicate at the node excluding interference links.

$$\sum_{j:(ij) \in E_C} x_{ij}^k = 1, \quad i = s_k \;\; for\ all\ flow\ k \in K \tag{6}$$

$$\sum_{j:(ji) \in E_C} x_{ji}^k = 1, \quad i = d_k \;\; for\ all\ flow\ k \in K \tag{7}$$

We assume a single path routing algorithm. So, for any link between intermediate nodes not being a source or a destination, the sum of x_{ij}^k (x_{ji}^k) is less than or equal to 1 as shown in equation (8) and (9).

$$\sum_{j:(ij) \in E_C} x_{ij}^k \leq 1, \quad i \neq s_k, d_k \;\; for\ all\ flow\ k \in K \tag{8}$$

$$\sum_{j:(ji) \in E_C} x_{ji}^k \leq 1, \quad i \neq s_k, d_k \;\; for\ all\ flow\ k \in K \tag{9}$$

Next, flow conservation laws from equation (10) to (12) should be applied. These laws mean flow coming to an arbitrary node must go out from that node. The equation (10) corresponds to the case of intermediate nodes and equation (11), (12) corresponds to the case of source and destination, respectively.

$$\sum_{j:(ji) \in E_C} x_{ji}^k - \sum_{j:(ij) \in E_C} x_{ij}^k = 0 \, ,$$

$$i \neq s_k, d_k \quad for\ all\ flow\ k \in K \tag{10}$$

$$\sum_{j:(ji)\in E_C} x_{ji}^k - \sum_{j:(ij)\in E_C} x_{ij}^k = -1\,,$$

$$i = s_k \quad for\ all\ flow\ k \in K \tag{11}$$

$$\sum_{j:(ji)\in E_C} x_{ji}^k - \sum_{j:(ij)\in E_C} x_{ij}^k = 1\,,$$

$$i = d_k \quad for\ all\ flow\ k \in K \tag{12}$$

The used capacity c_{ij} of a link l_{ij} is formulated as the total sum of product of λ_k and x_{ij}^k as shown in equation (13). So, c_{ij} should be less than or equal to the maximum available capacity u_{ij}.

$$c_{ij} = \sum_{k\in K} \lambda_k x_{ij}^k \ \leq \ u_{ij} \tag{13}$$

The routing path x_{ij}^k can be determined by solving an LP problem which has the objective function in equation (4) under the constraints from equation (6) to (13). Then, we calculate c_{ij} of each link using the derived x_{ij}^k, and also determine scheduling ϕ_s using c_{ij}.

In the following section, we propose a new algorithm to distribute remaining resources on each link evenly and to perform load balancing efficiently by applying the previously described scheduling and routing algorithm in section 3.2 and 3.3 recursively.

3.4 Joint Routing and Scheduling Algorithm

The goal of the proposed algorithm is to deduce joint routing and scheduling scheme for load balancing by using the iterative method, in which the routing problem is solved first and scheduling is done based on the routing information derived. The proposed algorithm is summarized in Algorithm 1. Inputs of the algorithm include maximal capacity C, the number of colors $\chi(G)$ for scheduling, the amount of flows λ_k, source node of flows s_k, and destination node of flows d_k. The criterion ε is used to stop the iteration by comparing it with the difference $\Delta\phi_{diff}$ between maximum ϕ_s and minimum ϕ_s.

In Algorithm 1, STEP 1 is a stage to initialize ϕ_s to be a value of total link capacity divided by the number of the colors in the graph. The next stages from STEP 2 to STEP 4 represent the process to iterate the proposed algorithm until $\Delta\phi_{diff}$ is less than or equal to ε. STEP 2 is a stage to solve the routing problem described in prior section. And STEP 3 is a stage of calculating the actually needed capacity uc_s by using the deduced routing information as in equation (14)

$$uc_s = \max_{l_{ij}\in E_C}\{c_{ij}\} \tag{14}$$

Finally, STEP 4 is a stage to perform an algorithm as shown in Algorithm 2 for updating ϕ_s and $\Delta\phi_{diff}$ to carry out STEP (2) ~ (4) in Algorithm 1 recursively.

Algorithm 1: Joint Routing & Scheduling Algorithm

Input: $C, \chi(G), \varepsilon, \lambda_k, s_k, d_k$
Output: Routing, x_{ij}^k, scheduling, ϕ_s
STEP 1: Initialize scheduling $\phi_s \leftarrow C/\chi(G)$
while *Iteration until the difference,* $\Delta\phi_{diff}$ *is less than or equal to* ε **do**
  STEP 2: Solve an routing problem to maximize total remained capacity $Maximize\ \min_{l_{ij}\in E_c}(C - c_{ij})$
  STEP 3: Calculate the used capacity on each link group $uc_s \leftarrow \max_{l_{ij}\in S_s}\{c_{ij}\}$
  STEP 4: Go to ϕ_s Update Algorithm
end

Algorithm 2: ϕ_s Update Algorithm

Input: uc_s, ϕ_s
Output: Updated ϕ_s, $\Delta\phi_{diff}$
STEP 1: Calculate a scheduling margin
for $s \leftarrow 1$ **to** $\chi(G)$ **do**
  $\Delta\phi_s \leftarrow \phi_s - uc_s$;
end
STEP 2: Calculate max. & min. scheduling margin and difference
$\Delta\phi_{s_{max}} \leftarrow max\{\Delta\phi_s\}$;
$\Delta\phi_{s_{min}} \leftarrow min\{\Delta\phi_s\}$;
$\Delta\phi_{diff} \leftarrow \Delta\phi_{s_{max}} - \Delta\phi_{s_{min}}$;
$\phi_{s_{max}}^{new} \leftarrow \phi_{s_{max}} - 1/2(\Delta\phi_{s_{max}} - \Delta\phi_{s_{min}})$;
$\phi_{s_{min}}^{new} \leftarrow \phi_{s_{min}} + 1/2(\Delta\phi_{s_{max}} - \Delta\phi_{s_{min}})$;

Inputs of the ϕ_s update algorithm in Algorithm 2 are uc_s and ϕ_s. In STEP 1, we calculate the scheduling margin $\Delta\phi_s$ using equation (15) for each color. The scheduling margin can be obtained by subtracting uc_s from the previously scheduled ϕ_s.

$$\Delta\phi_s = \phi_s - uc_s \tag{15}$$

In STEP 2, we calculate the maximum of the scheduling margin $\Delta\phi_{s_{max}}$ and the minimum $\Delta\phi_{s_{min}}$, and then we determine the new scheduling by applying the bisection method. That is, half of the difference between $\Delta\phi_{s_{max}}$ and $\Delta\phi_{s_{min}}$ is subtracted from $\phi_{s_{max}}$ and the same amount is added to $\phi_{s_{min}}$. By doing so, extra scheduled slots on a link having $\Delta\phi_{s_{max}}$ can be moved to a link having $\Delta\phi_{s_{min}}$, and the load can be effectively distributed. After that, using the new calculated scheduling ϕ_s, the algorithm in Algorithm 1 is repeated. If the algorithms in Algorithm 1 and Algorithm 2 carry out iteratively, then the optimal routing and scheduling is finally determined for load balancing.

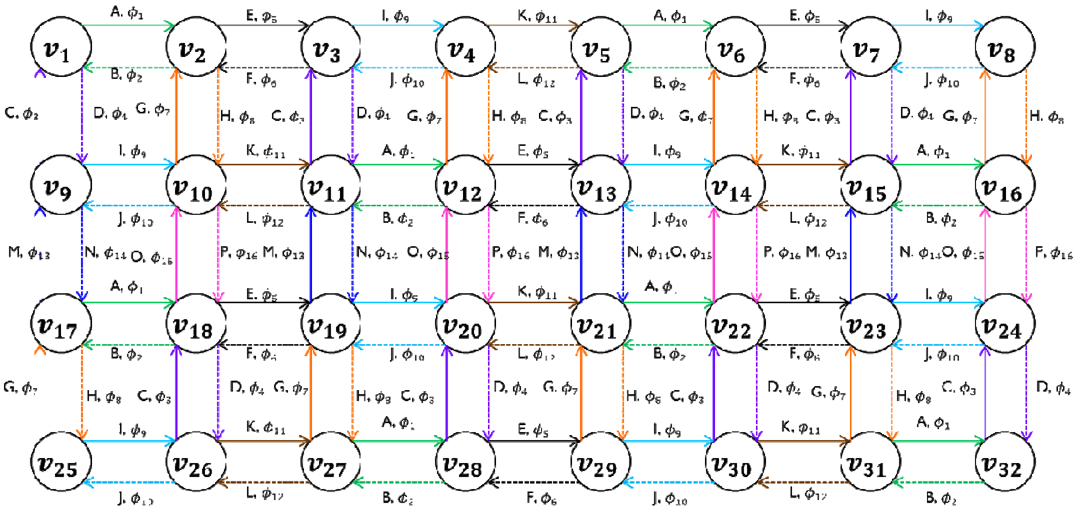

Figure 3. 4x8 Grid Network Topology

To analyze the adaptability of the proposed algorithm, we do the experiment to check how many iterations are required until the proposed algorithm ends. In grid network topology as shown in figure 3, we set source node be v_1, destination node v_{32}, and $\varepsilon = 1$ for varying λ. As shown in figure 4, when the proposed algorithm is performed repeatedly about 15 times, $\Delta\phi_{diff}$ is converged to ε or less. Therefore, we can conclude that the time of delay until the convergence at the WMNs design stage is not too large.

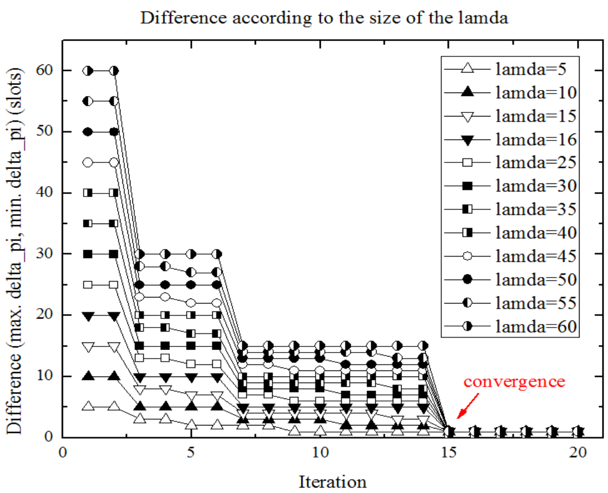

Figure 4. $\boldsymbol{\Delta\phi_{diff}}$ according to iterations of algorithms

In the next section, we analyze and compare the performance of the proposed algorithm with IEEE 802.11s HWMP routing and static scheduling. As a performance index, the balance index and the number of acceptable flows in the given WMNs is used on the assumption of fixed sources and destinations under given flows.

4. Performance Evaluation

For performance evaluation, we used open-source linear program, lpsolve. To evaluate the performance of the proposed algorithm, we configure a grid network topology consisting of 32 nodes and 104 links as shown in figure 3. In figure 3, the capital letter such as A, B, C … means the color of each link obtained from 1-distance edge coloring described in section 3.2. The total required number of colors is 16. For simplicity of calculation, we assume that the capacity of each link is 1,000 slots. In this topology, independent link groups can be mapped as shown in Table 1 for each color.

Table 1. Independent Link Set

$S_1 = \{l_{1\to2}, l_{5\to6}, l_{11\to12}, l_{15\to16}, l_{17\to18}, l_{21\to22}, l_{27\to28}, l_{31\to32}\}$
$S_2 = \{l_{2\to1}, l_{6\to5}, l_{12\to11}, l_{16\to15}, l_{18\to17}, l_{22\to21}, l_{28\to27}, l_{32\to31}\}$
$S_3 = \{l_{9\to1}, l_{11\to3}, l_{13\to5}, l_{15\to7}, l_{26\to18}, l_{28\to20}, l_{30\to22}, l_{32\to24}\}$
$S_4 = \{l_{1\to9}, l_{3\to11}, l_{5\to13}, l_{7\to15}, l_{18\to26}, l_{20\to28}, l_{22\to30}, l_{24\to32}\}$
$S_5 = \{l_{2\to3}, l_{6\to7}, l_{18\to19}, l_{22\to23}, l_{28\to29}\}$
$S_6 = \{l_{3\to2}, l_{7\to6}, l_{19\to18}, l_{23\to22}, l_{29\to28}\}$
$S_7 = \{l_{10\to2}, l_{12\to4}, l_{14\to6}, l_{16\to8}, l_{25\to17}, l_{27\to19}, l_{29\to21}, l_{31\to23}\}$
$S_8 = \{l_{2\to10}, l_{4\to12}, l_{6\to14}, l_{8\to16}, l_{17\to25}, l_{19\to27}, l_{21\to29}, l_{23\to31}\}$
$S_9 = \{l_{3\to4}, l_{7\to8}, l_{9\to10}, l_{13\to14}, l_{19\to20}, l_{23\to24}, l_{25\to26}, l_{29\to30}\}$
$S_{10} = \{l_{4\to3}, l_{8\to7}, l_{10\to9}, l_{14\to13}, l_{20\to19}, l_{24\to23}, l_{26\to25}, l_{30\to29}\}$
$S_{11} = \{l_{4\to5}, l_{10\to11}, l_{14\to15}, l_{20\to21}, l_{26\to27}, l_{30\to31}\}$
$S_{12} = \{l_{5\to4}, l_{11\to10}, l_{15\to14}, l_{21\to20}, l_{27\to26}, l_{31\to30}\}$
$S_{13} = \{l_{17\to9}, l_{19\to11}, l_{21\to13}, l_{23\to15}\}$
$S_{14} = \{l_{9\to17}, l_{11\to19}, l_{13\to21}, l_{15\to23}\}$
$S_{15} = \{l_{18\to10}, l_{20\to12}, l_{22\to14}, l_{24\to16}\}$
$S_{16} = \{l_{10\to18}, l_{12\to20}, l_{14\to22}, l_{16\to24}\}$

In order to analyze the load balancing performance of the algorithm, we define the BI (Balance Index) of links as the following equation (16).

$$BI = \frac{\left(\sum A_{ij}\right)^2}{L \sum A_{ij}^2}, \quad 0 < BI \le 1 \qquad (16)$$

BI means the fairness index of the remaining slots after all the flows use the required resources from total slots of each link. In here, A_{ij} means the available slots of link l_{ij} and is defined as in equation (17). In equation (16), L means the total number of links.

$$A_{ij} = C - c_{ij} \quad : Available\ slots\ at\ link\ l_{ij} \qquad (17)$$

First, to analyze the balance index for the given number of flows and the amount of flows, we assign the amount of flows variably within a limit of ϕ_s, and increase the number of flows by one from 1 to 4. It is assumed that $s_k = v_{10}$, $d_k = v_{23}$ as a source and destination. Also, we assume that the same amount of total load apply to the network, that is, the total traffic of 1 flow is same as that of 4 flows. For example, if the traffic of single flow is 100 slots in case of 1 flow, then that of each flow is 25 slots in case of 4 flows.

In figure 5, we can find that IEEE 802.11s HWMP has the same balance index regardless of the number of flows (K). This is because the shortest path, $v_{10} \rightarrow v_{11} \rightarrow v_{12} \rightarrow v_{13} \rightarrow v_{14} \rightarrow v_{15} \rightarrow v_{23}$, is not changed unless traffic exceeds the available capacity and all the flows go along the same path. So, even if the number of flows increases, the path is not changed within the statically scheduled bounds, and therefore the balance index is also same.

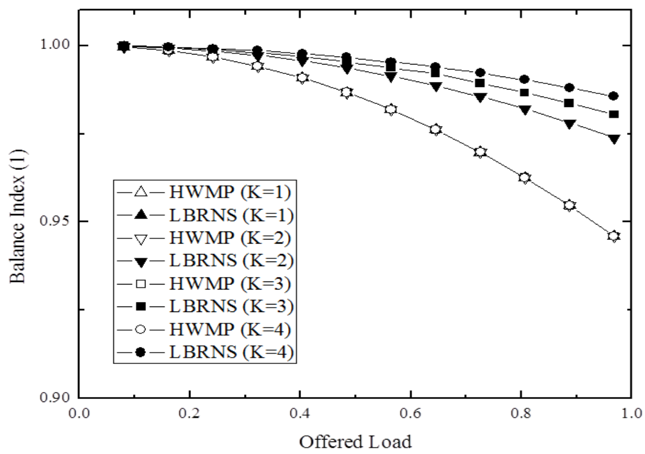

Figure 5. Balance Index as Load and the Number of Flows

However the proposed algorithm called LBRNS (Load Balancing Routing and Scheduling) can use multiple paths in case of multiple flows because the algorithm updates link scheduling and routing iteratively for load balancing. Hence, as the number of flow increases, traffic can be distributed over the whole network and the balance index also increases in the proposed algorithm.

When the offered load increases, the balance index decreases in both the legacy 802.11s and the proposed algorithm, however the proposed algorithm has a smaller decrease rate than the legacy protocol. Through the analysis results of the balance index, we can conclude that if the proposed algorithm is applied to the initial network design, then it is possible to efficiently distribute the load properly in wireless mesh networks.

We also analyze the number of flows that can be accepted between specific source and destination. In case of the legacy algorithm, only one best path is used regardless of the number of possible paths between the source and destination node, so the number of flows that can be accepted is low compared to the proposed algorithm. Also, the number of flows is the same in all the source-destination pairs.

In the proposed algorithm, however, the accepted number of flows can be changed variably based on how many links are connected to the source and destination node. In other words, because the number of wireless links is two when the source is v_1 and destination is v_{32} in a network topology as shown in the figure 3, the proposed algorithm can accept the flows twice. If the source-destination pair is v_{10}-v_{23} whose node has four connected links respectively, then the proposed algorithm can accept the flows up to four times. This is because the proposed algorithm updates link scheduling and routing iteratively for load balancing and multiple paths can be used in proportion to the number of outgoing and incoming links of source and destination. When the load is relatively small, the number of accepted flows of the legacy algorithm is about 10, but in case of the proposed algorithm it can be seen that the number is increased up to about 50 in figure 6.

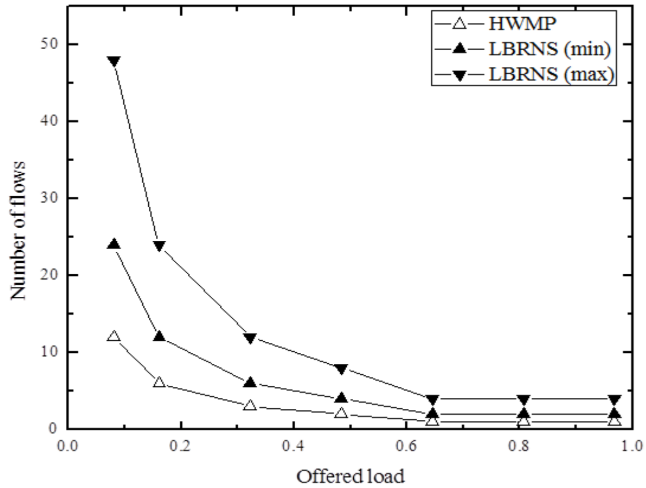

Figure 6. Analysis of number of acceptable flows

As we said before, the legacy algorithm selects a routing path having a minimum metric regardless of link load, so the selected path is not changed until the selected path cannot accept more traffic and thus load balancing is considerably difficult. But, in the proposed algorithm, we carry out an updating of link scheduling and routing path in turn recursively, thus it is possible to accept more flows and achieve a balanced use of each link in the wireless mesh networks. This proposed algorithm can be efficiently used in case of static source, destination, and flow patterns such as Smart Grid network.

5. Conclusions

In this paper, we proposed a joint link scheduling and routing algorithm for load balancing in STDMA-based wireless mesh networks, formulated the LP problem, and lastly analyzed the performance mathematically.

Lots of the existing algorithms for load balancing have tried to solve the problem of routing and scheduling separately. But we proposed a new algorithm which can achieve effective load balancing using shared information between different layers. According to the proposed algorithm, the routing path is determined first to maximize the available capacity of each link using LP problem, and then the scheduling of the selected link on the determined path is performed based on the link utilization to efficiently transmit data traffic. These two steps are iterated until load is fully distributed over the networks.

We consider that the proposed algorithm can help link scheduling and routing for load balancing at the initial design stage of STDMA-based wireless mesh networks.

Recently, the IEEE 802.11s wireless mesh network has been considered to be a promising backbone structure of a Smart Grid. The type and amount of traffic over Smart Grid is generally known to have a static property and require high reliability and bandwidth guarantee [17]. Therefore, if we design a Smart Grid network using the algorithm proposed in this paper, then the performance of each flow can be guaranteed due to the TDMA reservation characteristic and the load can be balanced and maximized due to the joint link scheduling and routing scheme. In other words, we can design an effective Smart Grid network that is possible to ensure reliability of flow, and also can accommodate more flows by load balancing.

For future work, we will plan to study extended joint link scheduling and routing algorithms continually in multi-interface multi-channel wireless mesh networks. Also we have assumed the routing path of each flow is single in this paper, but will extend to the multi-path routing.

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