A Traffic-Demand-Aware Routing and Scheduling for CSMA-based Wireless Mesh Networks

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***Abstract*—With variety of Wireless Mesh Networks (WMNs) services and applications, seeking optimized network performance and traffic delivery become increasingly important. In this paper, we focus on the CSMA(Carrier Sense Multiple Access)-based wireless mesh networks loaded by given traffic demands, and design a reasonable routing schedule to cope with the demands without collision. Because this problem is NP-hard, we mathematically formulate it as a mixed-integer linear optimization problem (MILP) to solve it. In doing this work, we choose a slotted CSMA model and propose a new scheduling algorithm called DA-CATBS (Demand-Aware CATBS). DA-CATBS can generate reasonable routing schedules according to different traffic patterns. Compared with CATBS(CSMA-Aware Time-Boundable Scheduling), DA-CATBS has better performance, which has flexibility against variety of traffic patterns and improves the capacity of networks under real traffic.**

***Index Terms*—WMNs, CSMA, optimal, traffic demand, MILP**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are currently on the transition from a popular research topic to the application in real-world scenarios in the industry [1] [2] [3]. Aiming at wide applications utilized by general users, commodity IEEE802.11 devices are preferably used in WMNs [4] [5]. Taking advantages of CSMA MAC(Media Access Control), the precious frequency resource can be shared with many devices, which enable us to build WMNs on the shared bands such as 2.4 and 5 GHz. However, CSMA-based WMNs cannot guarantee the network performance due to a variety of problems, such as packet collisions especially due to hidden terminals [6] [7]. Therefore, an essential solution should be made to prevent hidden-terminal problem as a MAC technique in a framework of single channel CSMA-based WMNs. The best-known mechanism would be RTS/CTS(Request To Send/Clear To Send) handshake that is adopted in IEEE802.11 standards [8]. However, it is known that RTS/CTS yields limited performance due to collision of RTS/CTS themselves, or due to so called exposed terminal problems [9]. A schedule called CATBS [10] (CSMA-Aware Time-Boundable Scheduling) had been studied that significantly reduces collisions due to hidden terminals. In CATBS, a slotted CSMA is adopted as a MAC scheme, in which a single frequency channel is divided into several relatively large time slots and CSMA MAC such as IEEE802.11 runs in every slot. Simulation results showed that it has good performance and prospects for application. The downside is that CATBS only focuses on the topology of the network, without considering the traffic demands. It is easy to cause a link to become a hot spot for traffic contention, increase the probability of network congestion.

As we know, in order to increase the performance of the network, a network administrator may regulate network traffic by adjusting various parameters. A set of demands is essential for planning, designing, engineering, and operating networks [11]. Thus, to improve the communication performance of CSMA-based WMNs, a technique that cope with various traffic patterns without collision is important. However, to the best of our knowledge, no such promising technique has been presented yet. Although in [12] the proposed schedule is somewhat similar to our study, but it does not aim at achieving collision-free transmission and the scheme is suitable for multi-channel WMNs.

For solving this problem, we consider a traffic-aware joint routing and scheduling problem. However, in general, the problem for collision-free scheduling is NP-hard [10]. Thus, we mathematically formulate it as a mixed-integer linear optimization problem and solve it. We call this scheduling method DA-CATBS (Demand-Aware CATBS). The novelty of this scheme is that under the given traffic demand matrix we can compute a schedule without collision of transmissions. For any different traffic demand set given, this scheme can quickly find out whether it can be satisfied or not, and then generates reasonable routing schedule to cope with the demand. Therefore, this scheme could provide important reference in planning and managing of wireless mesh networks, such as network topology adjustment, various parameter settings, etc. This is important for improving the network performance.

The rest of the paper is organized as follows. We present related work in Section II. We describe our system model and formulate the scheduling problem in Section III. Performance evaluations are given in Section IV. Conclusions are given in Section V.

II. RELATED WORK

In order to improve the communication performance of CSMA-based WMNs up to a practical level, a wide variety

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of approaches have been presented so far.

However, as mentioned earlier, CSMA-based WMNs still suffers from heavy interference due to hidden terminals. Although the mechanism of RTS/CTS is widely known, [9] [13] showed that the effect of RTS/CTS against hidden terminals is quite limited in WMNs.

In [10], the authors proposed the schedule CATBS that successfully solves the hidden terminal problem and achieves collision-free transmission. In CATBS, the single frequency channel of CSMA is divided into several relatively large time slots. Each link recognizes the slot in which it is allowed to transmit frames. Therefore, the network topology is essentially regarded as a mapping between nodes and slots. Collisions between neighbor nodes are avoided due to CSMA. In order to solve the hidden terminal problems, CATBS excludes a part of links from a set of links that forward packets, while simultaneously guaranteeing feasible paths for any pair of source and destination nodes. Compared to the minimum hop path, it possibly causes the path length between the source and the destination node to increase. For preventing largely increasing the path length, CATBS uses a factor to control it. Through regulating of the control factor, CATBS efficiently achieves zero interference transmission. This is important for achieving the practical level performance of CSMA-based WMNs. However, CATBS has two shortcomings: the first is that traffic patterns have not been considered while achieving collision-free end-to-end transmissions, which makes CATBS always output the same schedule regardless of traffic demand. The second is that the link-state routing scheme with shortest-path computation incorporated with CATBS causes to generate bottleneck links, which makes CATBS lack flexibility against variety of traffic patterns and degrades the capacity of networks under real traffic.

Mohsenian-Rad et al. [12] proposed the TiMesh MC-WMN architecture by formulating the topology design, interface assignment, channel allocation, and routing as a joint linear mixed-integer optimization problem. The scheme balances the load among links and provides higher effective capacity for the bottleneck links. Experiment showed that the scheme actually improved the network communication performance. However, in that scheme each node needs to be equipped with multiple interface cards (NICs) and each interface card needs to be configured with a different channel, whereas the number of available channel and the number of available NICs are limited in general. Furthermore, same as CATBS, TiMesh outputs the same schedule for any different traffic demand, i.e., demand matrix. In order to avoid interference, TiMesh uses RTS/CTS. However, as shown previously, it could not effectively solve the hidden terminal problem.

In contrast, we introduce the scheduling method DA-CATBS that flexibly deals with different traffic patterns, and achieves interference-free transmissions over the network.

III. DEFINITION AND FORMULATION

In this section, the network model and several assumptions to be used in the scheme are explained in detail, then we give a detailed definition of them and convert the problem which we proposed into MILP [14].

A. *Network Model and Assumptions*

We are given directed network $G = (V, E)$, where V is the set of nodes and E is the set of directed links. Each link $\ell \in E$ has a capacity C which is a measure for the amount of traffic flow it can take. We assume a slotted CSMA as a MAC scheme in which a single frequency channel is divided into N relatively large time slots and CSMA MAC such as IEEE802.11 runs in every slot. N independent slots are available for communications between every pair of neighbor nodes u and v, where $u, v \in V$. A link $\ell \in E$ that goes from node u to node v using slot $s \in S$ is written as $\ell = (u, v, s)$, where S is a set of slots and $|S| = N$. Fig.1 illustrates the case of $N = 3$. We essentially regard this network topology as a mapping between nodes and slots. Each link recognizes the slot in which it is allowed to transmit traffic flows. It is necessary to assign a suitable slot to link ℓ. We call link ℓ is active if it is assigned a slot and being used for traffic flow transmission. A variable $Z_\ell \in \{0, 1\}$ is defined, where $Z_\ell = 1$ indicates link ℓ is active, and $Z_\ell = 0$ indicates link ℓ is inactive.

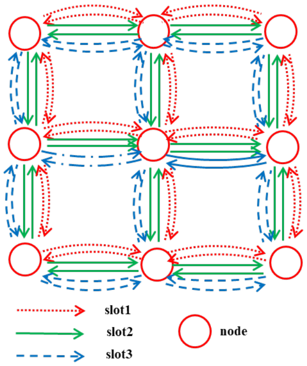

Fig. 1. Network topology G

Traffic demand matrix D is given that represents the amount of traffic demand from s to d for each pair $(s, d) \in V \times V$. The demand from s to d is written as $D(s, d)$, in which $D(s, d) = 0$ denotes there is no traffic demand from s to d. Let M denote the number of non-zero traffic demand pairs (s, d). With each pair (s, d) and each link ℓ, we associate a variable $f_\ell^{(s,d)}$ telling how much of the traffic flow from s to d goes over link ℓ and $f_\ell^{(s,d)}$ is always non-negative. We sometimes denote it by $f_{(i,j)}^{(s,d)}$, when $\ell = (i, j)$.

In order to achieve collision-free transmission, interference model which to apply is important. Several interference models are known such as single/double disk model [15], SINR model [16], and k-hop model [17]. In this paper we used the CSMA-aware interference model which is presented in [10]. In CSMA-aware interference model the link pairs based on the single disk model. It only considers the collision between hidden terminals, and ignore from them the link pairs between which carrier-sensing is possible.

We assume each node in the network has only one radio interface and shares a common channel. The capacity of each link equal to C. A central entity runs this scheduling algorithm to generate schedules for the nodes in the network.

B. Flow Conservation at Each Node

Flow in the network must meet the conservation conditions [18], for each demand pair (s,d) we refer to s and d as the source and destination of the demand. Therefore, the total volume of flows sent by s must be equal to which received by d, and the total input and output volume on the intermediate node must be equal. We have,

$$\sum\nolimits_{i:(i,j)\in E} f_{(i,j)}^{(s,d)} - \sum\nolimits_{z:(j,z)\in E} f_{(j,z)}^{(s,d)} = \begin{cases} -D(s,d), \text{if } j=s, \\ D(s,d), \text{if } j=d, \\ 0, \text{otherwise.} \end{cases} \quad i,j,s,d,z \in V \tag{1}$$

In (1), $f_{(i,j)}^{(s,d)}$ and $f_{(j,z)}^{(s,d)}$ denote the rate from node i to j, and node j to z, respectively. If node j is the source node, the value of (1) equal to $-D(s,d)$. If node j is the destination node, the value is equal to $D(s,d)$. Otherwise, the node is intermediate node, and the value equals to 0. This constraint ensures that the desired traffic flow is routed from s to d. It also guarantees that there is at least one routing path available between each source and destination pair (s,d).

C. Load on each link

Many of the entries of D may be zero if there is no requirement from s to d. If paths of flows are determined, the load on a link coming from each flow is determined. Here, the total traffic load on each link ℓ, i.e., the sum of the flows going over ℓ, cannot exceed the link capacity C. As mentioned previously, if link ℓ is used for traffic flow transmissions, then $Z_\ell = 1$ must be held. We have,

$$\sum\nolimits_{(s,d)\in V\times V} f_\ell^{(s,d)} \leq Z_\ell C \qquad \ell \in E \tag{2}$$

Note that $Z_\ell = 0$ when link ℓ is inactive, and in that case constraint (2) can be written as $\sum_{(s,d)\in V\times V} f_\ell^{(s,d)} \leq 0$. This implies $\sum_{(s,d)\in V\times V} f_\ell^{(s,d)} = 0$, there is no traffic flow going over ℓ. In contrast, if $Z_\ell = 1$, $\sum_{(s,d)\in V\times V} f_\ell^{(s,d)}$ can be greater than zero, and link ℓ is assigned a slot for traffic flow transmission. Note that, since we minimize the number of active links in our optimization problem, $Z_\ell = 1$ always means that link ℓ is active and loaded with flows.

D. Shared capacity

Since each node in the network shares a common channel, all other nodes within a node's sensing range will share the link capacity with it. See Fig.2. For node $a \in V$, $u \in V$ is a node within the sensing range of a, while node $v \in V$ is not included in the sensing range of a, but within the sensing range of u. Then three links $(a,u),(u,a),(u,v)$ at the same fraction of time share the link capacity C under CSMA. We write it as $F_a = \{(u,v)|u,v \in V,(a,u) \in E,(u,v) \in E\} \cup \{(a,u)|u \in V,(a,u) \in E\}$, where F_a is a set of potential competing links within node a sensing range. We have,

$$\sum\nolimits_{(s,d)\in V\times V} \sum\nolimits_{\ell\in F_a} f_\ell^{(s,d)} \leq C \tag{3}$$

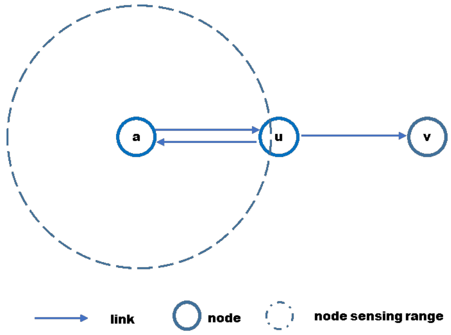

Fig. 2. Shared capacity schematic diagram

Formula (3) means that the total traffic loads of the all shared capacity links of node a must not exceed the link capacity C.

E. Interference

In order to set up collision-free end-to-end transmission schedules, we need to understand the interference model that is used to judge whether communication frames collides or is successfully transmitted and received. As mentioned before, in this paper, we use the CSMA-aware interference model. This model is based on single-disk interference model, in which the communication range and the interference range are the same. R is defined to denote the distance. The network G is structured by R. Only the link $(u,v,s) \in E$ if the distance between nodes u and v is smaller than R is defined. Let $\ell_1 = (u_1,v_1,s_1)$ and $\ell_2 = (u_2,v_2,s_2)$ be arbitrary two links in E. Then, communication on ℓ_2 is prevent by ℓ_1 due to the hidden terminal effect if $\{s_1 = s_2, (u_1,v_2,s_1) \notin E, and \quad (u_1,v_2,s_1) \in E\} \vee \{s_1 = s_2, (u_1,u_2,s_1) \notin E, and \quad (v_1,v_2,s_1) \in E\}$. Since the interference between link pairs within carrier-sensing range are avoided due to CSMA, we regard that two directed links interfere with each other only if they are located in the hidden-terminal position, i.e., the receiver node of one link is a neighbor of the other transmitter node, and the two transmitter nodes are not within the carrier-sense range of CSMA. Thus, we suppose the interference in this study is asymmetric: if a transmission on link $\ell_1 \in E$ prevents that of $\ell_2 \in E$, i.e., a transmission on ℓ_2 fails when ℓ_1 is transiting a frame simultaneously, we regard that ℓ_1 interferes ℓ_2 and write $\ell_1 \to \ell_2$. Accordingly ,we define that $I_G = \{(\ell_1,\ell_2)|\ell_1,\ell_1 \in E, \ell_1 \to \ell_2\}$ is a set of interference link pairs. We have,

$$Z_{\ell_1} + Z_{\ell_2} \leq 1 \quad \ell_1,\ell_2 \in E \ and \ (\ell_1,\ell_2) \in I_G \tag{4}$$

Constraint (4) ensures that both of the interfering links cannot be activated simultaneously. In this paper, we assume the set of interference link pairs I_G is computed from the given network topology

F. Hop Count Constraint

In order to ensure that each link is not overloaded and achieve collision-free end-to-end transmission, each of the traffic demands from s to d can be arbitrarily split and assigned long routing paths. For each source and destination pair (s, d), let $\delta_{s\to d}$ indicate the minimum hop count to reach d from s, i.e., the shortest-path from s to d in G. To prevent the path length from largely increasing, we have the following constraint,

$$\sum\nolimits_{\ell\in E} f_\ell^{(s,d)} \le D(s,d)(\delta_{s\to d}+k) \quad for\,each\,(s,d)\in V\times V \tag{5}$$

In (5), $k \ge 0$ is a control factor. In general, the length of the routing path can be controlled by adjusting it. Thus, this scheme could easily turn into the shortest-path routing scheme when $k = 0$.

G. Objective Function

Given the network topology, the expected traffic demand matrix and the parameters, the constraints in $(1) - (5)$ form the feasible region that can support the expected traffic demands and collision-free transmission. We have the objective function,

$$minimize \quad \sum\nolimits_{\ell\in E} Z_\ell \tag{6}$$

In (6), the objective is to minimize the number of active links. Using the minimum number of links to meet the traffic demand would effectively reduce the competition of link resource and improve the capacity of networks under real traffic.

H. Optimization Problem Formulation

Now, we summarize our problem formulation. Given the network topology G, traffic demand matrix D, slots number N, the set of interference pairs I_G, link capacity C, parameters k, the following optimization problem is formulated,

$$min \quad \sum\nolimits_{\ell\in E} Z_\ell,$$

$$Subjiect \quad to$$

$$\sum\nolimits_{i:(i,j)\in E} f_{(i,j)}^{(s,d)} - \sum\nolimits_{z:(j,z)\in E} f_{(j,z)}^{(s,d)} = \begin{cases} -D(s,d), \text{if } j = s, \\ D(s,d), \text{if } j = d, \\ 0, \text{otherwise}, \end{cases} \quad i,j,s,t,z\in V,$$

$$\sum\nolimits_{(s,d)\in V\times V} f_\ell^{(s,d)} \le Z_\ell C \qquad \ell\in E,$$

$$\sum\nolimits_{(s,d)\in V\times V} \sum\nolimits_{\ell\in F_a} f_\ell^{(s,d)} \le C,$$

$$Z_{\ell_1} + Z_{\ell_2} \le 1 \quad \ell_1, \ell_2 \in E\,and\,(\ell_1,\ell_2)\in I_G,$$

$$\sum\nolimits_{\ell\in E} f_\ell^{(s,d)} \le D(s,d)(\delta_{s\to d}+k) \quad for\,each\,(s,d)\in V\times V,$$

$$where$$

$$f_\ell^{(s,d)} \ge 0 \quad \ell\in E,$$

$$Z_\ell \in \{0,1\} \quad \ell\in E. \tag{7}$$

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed scheduling algorithm DA-CATBS. We used MATLAB R2018b [19] with the optimization toolbox to solve MILP and executed it on a standard PC with Core (TM) i5-3470 CPU (3.20 GHz), 10 GB memory. The structure of network which we used is grid topology.

In experimenting, we suppose planned WMNs whose topology and node locations are carefully designed to cover a certain geometrical area. We apply our scheduling algorithm to 5×5 grid topology and the capacity of links are set as $C = 54\,Mbps$.

Here, we show an example case. We select a result with $N = 5, k = 2, M = 5$, and a traffic pattern shown in Table I, where the demand values and node pairs are randomly selected. The results schedule is shown in Fig.3, in which the directed links between neighbor nodes indicate active links in the computed schedule. The color of each link represents the different slot being assigned, e.g., from node 5 to 0, the slot number is 3. Links which interfere with each other are assigned with different slots, e.g., interfering links $(11, 16)$ and $(21, 16)$ are assigned with slot 1 and slot 3, respectively. To illustrate different traffic flow from s to d which across the same link, we use the expression such as $a+b$, e.g., $15+10+4$ on link $(12, 7)$ indicates there are three different traffic flows over the link and the total load value is $29\,Mbps$. Obviously, traffic load over each link must be less or equal to $54\,Mbps$. The total load of the links that share capacity is also limited, e.g., within the sensing range of node 12, the total load of sharing capacity links must be less than $54\,Mbps$. Each flow can be arbitrarily split between source and destination node, e.g., the flow between source node 17 and destination node 4 is split into two paths where total path length is limited as described before.

TABLE I
TRAFFIC PATTERN(M=5)

NO.	Source Node	Destination Node	Traffic Demand(Mbps)
1	1	23	7
2	20	3	10
3	17	4	60
4	18	0	20
5	14	15	9

Because this work is an extended study of CATBS, we compare our proposed scheduling algorithm DA-CATBS with CATBS.

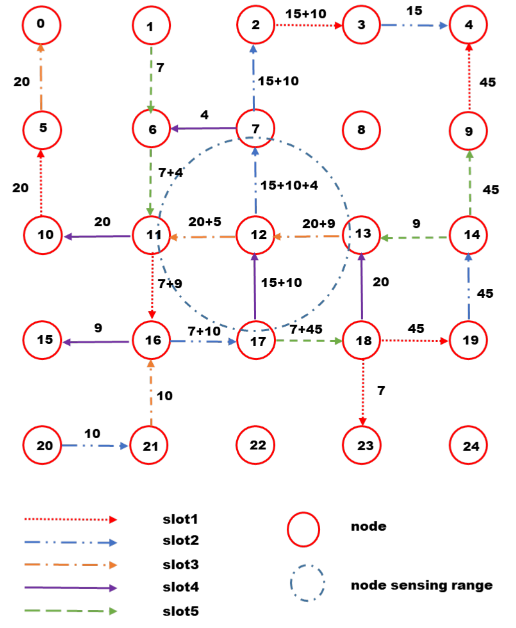

Fig. 3. $G = 5 \times 5, N = 5, k = 2, M = 5, C = 54\,Mbps$

We show Figs.4, 5 and 6 for the results of the maximum allowable transmission rate per flow can achieve without exceeding any link capacity in random traffic pattern. In this testing, we generated 10 flows that have the same transmission rate and whose source-destination nodes are selected randomly. We set $N = 4, 5, 6$, and tried several values of k. We gradually increased the transmission rate of the flows and recorded the maximum transmission rate such that capacity of any link is exceeded. It should be noted that when there is no calculation result in the experiment for more than 1 hours, we force the program to stop and regard that the transmission rate reaches the maximum value(i.e., no feasible solution was obtained). In Fig.4, it is clear that DA-CATBS has better performance than CATBS, e.g., when $N = 6, k = 0$ DA-CATBS can supports the maximum transmission rate $29\,Mbps$, whereas CATBS only supports $14\,Mbps$. The reason is that CATBS does not been consider traffic demands while achieving collision-free end-to-end transmissions, which makes CATBS use the same schedule even for the different demand matrix. Furthermore, the link-state routing scheme with short-path computation incorporated with CATBS causes to generate bottleneck links, in which traffic load easily exceeds their capacity even under relatively low traffic demand. In Figs.4, 5 and 6, we also see that, in DA-CATBS, the value of N or k raises as the transmission rate of the flows increases. However, in CATBS, due to bottleneck links, the transmission rate shows a downward trend. This means that, in DA-CATBS scheme, larger number of slots or longer routing paths can improve network throughput. Network managers can adjust the value of N or k to provide reasonable service.

We tested different traffic demands, and the results is shown in Table II, in which the values of our objective function, i.e., the number of active links in the schedule, are shown for each case. We see that when the value of $N = 2$ or 3, the network cannot support the given traffic demand matrix whatever the value of k. However, when the value of $N = 4, 5\,or\,6$ our scheduling algorithm can give different schedules to support the traffic demand matrix. In [10], CATBS has been proved that $4 - 6$ slots are sufficient to compute zero-interference schedules in this same topology. It requires $4, 5$ and 6 with $k = 4, 2$ and 0, respectively. Shown as Table III, in which ”$\circ$” denotes the zero-interference schedule can be computed. This means, when $N = 4, k = 0\,or\,2$ and $N = 5, k = 0$ CATBS is insufficient to support this given traffic demand matrix, i.e., it cannot cope with this traffic demands without collision of transmissions. Therefore, DA-CATBS is more flexible than CATBS.

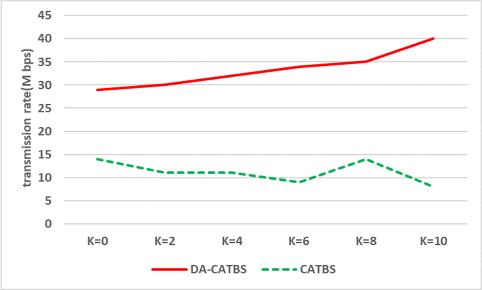

Fig. 4. Comparison of DA-CATBS and CATBS, N=6

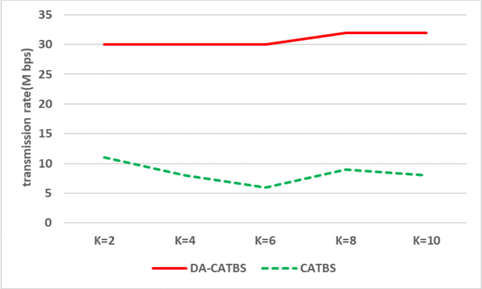

Fig. 5. Comparison of DA-CATBS and CATBS, N=5

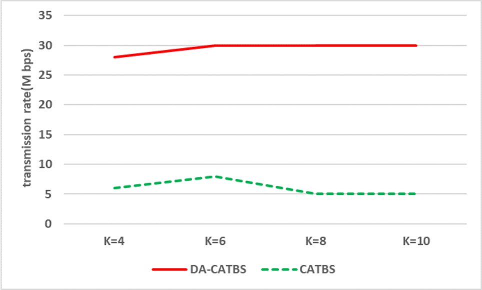

Fig. 6. Comparison of DA-CATBS and CATBS, N=4

V. CONCLUSION

As extended study of CATBS, in this paper, we proposed a new scheduling algorithm called DA-CATBS. Different

TABLE II
CALCULATED VALUE OF DA-CATBS OBJECTIVE FUNCTION

	N=2	N=3	N=4	N=5	N=6
k=0	-	-	59	38	31
k=2	-	-	35	37	35
k=4	-	-	35	32	31
k=6	-	-	34	39	32
k=8	-	-	39	33	28
k=10	-	-	40	37	30

"-" indicates the current traffic pattern cannot be supported.

TABLE III
CATBS CALCULATION RESULTS

	N=2	N=3	N=4	N=5	N=6
k=0	-	-	-	-	○
k=2	-	-	-	○	○
k=4	-	-	○	○	○
k=6	-	-	○	○	○
k=8	-	-	○	○	○
k=10	-	-	○	○	○

"-" indicates CATBS insufficient to compute zero-interference schedule.

from CATBS focuses on the topology of the network, use a controllable factor to achieve zero interference transmission. DA-CATBS takes into account the traffic demands and network topology. We choose a slotted CSMA as MAC model which the same as CATBS. Experimental results show this scheme can cope with various traffic patterns without collision transmission. Compared with CATBS, it has larger flexibility against variation of traffic patterns and improves the capacity of networks under real traffic. By adjusting the number of slots and routing path length, it can improve the network performance. Thus, this scheme could provide important reference in planning and managing of wireless mesh networks. The disadvantage is that long routing paths may lead to end-to-end transmission delay and use multi-path may cause packets to arrive out of order.

The next task is to proceed in-depth evaluation in both algorithm and communication performance. We will re-considering the optimization function and use single-path routing. Also, the real-implementation and evaluation is expected for the future.

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