PAPER

Cross-Layer Scheme to Control Contention Window for Per-Flow in Asymmetric Multi-Hop Networks

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SUMMARY The IEEE 802.11 MAC standard for wireless ad hoc networks adopts *Binary Exponential Back-off* (BEB) mechanism to resolve bandwidth contention between stations. BEB mechanism controls the bandwidth allocation for each station by choosing a back-off value from one to CW according to the uniform random distribution, where CW is the contention window size. However, in asymmetric multi-hop networks, some stations are disadvantaged in opportunity of access to the shared channel and may suffer severe throughput degradation when the traffic load is large. Then, the network performance is degraded in terms of throughput and fairness. In this paper, we propose a new cross-layer scheme aiming to solve the per-flow unfairness problem and achieve good throughput performance in IEEE 802.11 multi-hop ad hoc networks. Our cross-layer scheme collects useful information from the physical, MAC and link layers of own station. This information is used to determine the optimal Contention Window (CW) size for per-station fairness. We also use this information to adjust CW size for each flow in the station in order to achieve per-flow fairness. Performance of our cross-layer scheme is examined on various asymmetric multi-hop network topologies by using Network Simulator (NS-2).
key words: *cross-layer, per-flow/per-station fairness, bandwidth utilization, multi-hop wireless, IEEE 802.11, back-off algorithm, asymmetric topology*

1. Introduction

Multi-hop wireless networks have become increasingly popular. They provide a fast and easy way to establish a new network in areas where the infrastructure cannot be established because it is expensive or inconvenient. However, in asymmetric multi-hop networks, the network performance in terms of throughput and fairness is not necessarily satisfactory. Here, asymmetric means that the stations have different conditions in channel access or different number of flows or different hop distances to destination. To solve this problem, we need to consider both MAC and link layer contentions. Due to the MAC layer contention, the bandwidth allocation for each station cannot ensure per-station fairness [1], [2]. Each station transmits both direct flow, which is generated by the station, and forwarding flows, which are generated by the neighboring stations. Thus, there is a contention between the direct flow and forwarding flows at the buffer space of the link layer, and then forwarding flows often lose in competition against the direct flow [3], [4].

The *Distributed Coordination Function* (DCF) [5] is a fundamental MAC technique of the IEEE 802.11 [6], which is designed to provide fair opportunity for every station to transmit its frame in a distributed manner. The DCF employs the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) protocol with access mechanism based on *Binary Exponential Back-off* (BEB) mechanism [7]. BEB mechanism controls the channel access frequency of each station by choosing randomly a back-off value from one to CW according to the uniform random distribution, where CW is the contention window size. So, it seems that all the contending stations will have the same opportunity of access to the shared channel, however, in asymmetry multi-hop topologies, BEB mechanism suffers from the unfairness problem and low throughput, especially in case of large traffic offered load [8]–[10].

BEB mechanism determines the Contention Window (CW) size for corresponding to the congestion condition. BEB mechanism doubles the CW size upon each collision until reaching CW_{max} and reset the CW size to CW_{min} upon each successful transmission. However, BEB mechanism does not consider other conditions about neighboring stations or higher layer, e.g., the number of flows in the channel or the number of users in the system. Thus, the CW size after some congestion may not be the optimal value for fairness, especially in asymmetric multi-hop networks [11], [12]. Moreover, because the CW size is the same for all flows generated from one station, all flows will access channel with the same priorities. There is an unfairness problem between flows in the buffer space, so the different CW size should be given for each flow to reduce the contention between them.

If the optimal CW size is determined and set for each individual station, BEB mechanism can give fair bandwidth allocation between stations. Further, if a different CW size is given to each flow, the contention between flows is controllable. However, determining the optimal CW size requires global information of the network, which is nearly impossible to obtain in multi-hop ad hoc networks because each station works distributive. In our cross-layer scheme, we control CW size in order to achieve good per-flow fairness without global information. We collect information from the physical, MAC and link layers, which is used to determine a better CW size.

The purpose of this paper is to achieve per-flow fairness by helping disadvantaged flows get more chance to access channel. See Appendix for our detail definition about per-flow fairness in case there are both *small* and *large* offered

Manuscript received March 29, 2010.
Manuscript revised May 31, 2010.
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DOI: 10.1587/transcom.E93.B.2326

load flows. We propose five modules, which work at the physical, MAC and link layers. *CS Flow Estimation* module is put at the physical layer to sense whether some flows are being transmitted in the carrier sensing range but out of the transmission range of the station. *TX Flow Estimation* module is put at the MAC layer to classify the flows which are being transmitted in the transmission range of the station. *Utilization Estimation* module is put at the MAC layer to measure the current link utilization. *Queue Estimation* module is put at the link layer to evaluate the contention between flows in the buffer space. The last *CW Monitor* module is put at the MAC layer to decide a good CW size for achieving fair bandwidth allocation between stations and also between flows in the station based on the information collected from above four modules.

In general, there is trade-off between fairness and throughput performance [13]. In our cross-layer scheme, the per-flow fairness performance is much improved and we also achieve good throughput performance. We use the Network Simulator (NS-2) [14] to evaluate our cross-layer scheme in many asymmetric multi-hop topologies.

The rest of the paper is organized as follows: Section 2 reviews related work. Section 3 describes our cross-layer scheme. Section 4 evaluates our cross-layer scheme by comparing with original FIFO scheduling in IEEE 802.11 standard [6], and PCRQ scheduling [15]. Finally, Sect. 5 concludes the paper and suggest further research.

2. Related Work

According to studies in the past several years [1], [10], the weaknesses of IEEE802.11 give poor fairness for flows in multi-hop ad hoc networks. The fairness performance at the MAC layer is considered in the protocols MACA [1] and its extension MACAW [16], in which the four-way handshake signals RTS/CTS/Data/ACK are used to reduce collisions caused by hidden terminals in the networks. However, the RTS/CTS scheme in DCF does not solve all unfairness problems in case of asymmetric topology [8], [10]. Li et al. [10] investigated *Extended Inter-Frame Spacing* (EIFS) problem, i.e., the fixed EIFS value leads to unfair bandwidth allocation for each station. They proposed flexible EIFS values based on a measurement of the length of *Sensing Range* (SR) frame. However, the length of SR frame cannot be always recognized because of the spatial reuse of the bandwidth. The paper [8] investigated other asymmetric topology, that is the *three-pair* problem. The analysis of the *three-pair* problem in [8] is based on Markov chain and gives some accurate results. Because they studied the impact of asymmetric multi-hop networks only by the *three-pair* scenario, their methodology cannot be applied to arbitrary topology. Moreover, those studies mainly consider the per-station unfairness problem and they do not consider the per-flow unfairness problem, which is caused at the link layer.

Some papers proposed scheduling methods to solve the per-flow unfairness problem in multi-hop networks. Jangeun et al. [3] pointed out the weak point of FIFO scheduling in multi-hop networks. They proposed various queuing schemes to achieve some level of per-flow fairness. Shagdar et al. [4] proposed scheduling algorithms which use Round Robin (RR) queue to solve the link layer contention, and modify the MAC layer by dequeuing all packets at the head of RR queues with one time back-off algorithm to solve the MAC layer contention. Those papers [3], [4] assume that the MAC layer gives the ideal per-station fairness, however such assumption cannot be satisfied in general. The paper [15] proved that the RR scheduling cannot help per-flow fairness due to unfairness at the MAC layer. The *Probabilistic Control on Round robin Queue* (PCRQ) scheduling [15] improves fair bandwidth allocation at the MAC layer and achieves good per-flow fairness. The PCRQ scheduling uses RR queues with three algorithms to control input/output packets and the turn of RR queues. Some delays are given to the direct flow in order to give more chance of channel access to forwarding flows. As a result, the fairness of bandwidth allocation is improved and good per-flow fairness is achieved.

Many other studies also tried to solve the unfairness problem by modifying BEB mechanism. The CW size in BEB mechanism is doubled when a station experiences a packet collision and the CW size is reset to CW_{min} when a station transmits a packet successfully. To prevent a large oscillation of CW size, some studies tried to adjust BEB mechanism as Multiplicative Increase and Linear Decrease (MILD) [16], Exponential Increase Exponential Decrease (EIED) [17] and Linear/Multiplicative Increase and Linear Decrease (LMILD) [18]. Because BEB mechanisms in their methods still work only based on collision information, the CW size is not necessarily the optimal value for fairness. Fang et al. [19] reviewed the unfairness problem in BEB mechanism. Each station estimates the channel utilization of its own and that of neighboring stations then adjusts the back-off algorithm to give each station some value of bandwidth, called the *statistical fair access*. The statistical fair access must be predefined, but it is difficult in general because the value depends on topologies. There are some other studies on the control of CW size to achieve per-flow fairness [20], [21], but almost all of them consider only single-hop networks. Unlike those studies, our solution tries to evaluate fair bandwidth allocation by examining the number flows which are being transmitted in the carrier sensing range of the station, then CW size is adjusted to achieve fair bandwidth allocation even in case of asymmetric topologies. Moreover, we determine a good CW size for each flow to achieve per-flow fairness.

3. Proposed Cross-Layer Scheme

In multi-hop ad hoc networks, some flows are in difficulties of accessing the channel due to both MAC and link layer contentions. The CW size is related to the probability of channel access. We will propose a new cross-layer scheme to collect useful information from the physical, MAC and

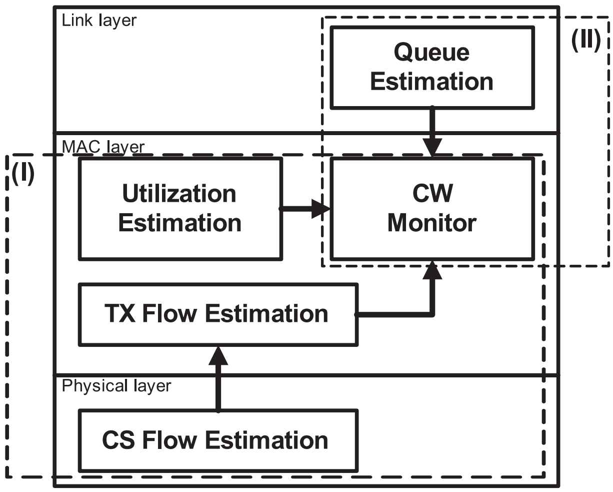

Fig. 1 The proposed five modules. (I) and (II) are Module Set I and II, respectively.

link layers, and then adjust a good CW size based on this information. By using a flexible CW size in back-off state, we help disadvantaged flows get more chance to access channel.

Our cross-layer scheme in Fig. 1 consists of five modules. CS Flow Estimation module is put at the physical layer to sense the existence of a flow in the carrier sensing range but out of the transmission range. TX Flow Estimation module is put at the MAC layer to count the number of flows in the transmission range. Utilization Estimation module is put at the MAC layer to measure the current link utilization. Queue Estimation module is put at the link layer to evaluate the contention between flows in the buffer space. The main module of our cross-layer scheme is CW Monitor module which is put at the MAC layer.

The five modules are categorized into two sets of modules, i.e., *Module Set I* and *Module Set II* as shown in Fig. 1. Module Set I consists of CS Flow Estimation module, TX Flow Estimation module, Utilization Estimation module and CW Monitor module. Module Set II consists of Queue Estimation module and CW Monitor module. Module Set I decides a good CW size for solving the MAC layer contention. While, Module Set II decides a good CW size for solving the link layer contention.

3.1 CS Flow Estimation Module

CS Flow Estimation module works on the physical layer. It senses by the physical power the existence of a flow which is in the carrier sensing range but out of the transmission range of the station. We call such a flow as CS flow. The power of packets from a CS flow is larger than the carrier sensing threshold and smaller than the reception threshold. The station can sense the existence of CS flows but cannot distinguish each flow. Hence, in this case, even if there are many such flows, we consider all CS flows as one flow. We define n_{CS} by

$$n_{CS} = \begin{cases} 0, & \text{if there is no CS flow ,} \\ 1, & \text{if there are one or more CS flows.} \end{cases} \quad (1)$$

3.2 TX Flow Estimation Module

TX Flow Estimation module works on the MAC layer to count the number of flows in the transmission range. We call these flows as TX flows. A TX flow is identified by MAC and IP addresses of both source and destination by decoding the header of packets. We denote the number of TX flows by n_{TX}.

TX Flow Estimation module receives n_{CS} from CS Flow Estimation module then we have the total number of flows n_{total} in the TX Flow Estimation module as

$$n_{total} = n_{TX} + n_{CS}. \quad (2)$$

Among TX flows, the flows transmitted from the station are denoted as SEND flows. The SEND flows include the direct flow which is generated by the station and forwarding flows which are generated by the neighboring stations. We define the number of SEND flows as n_{SEND}.

We define the fair share ratio of the bandwidth for the station as the ratio of the number of transmitting flows n_{SEND} to the total number of flows n_{total};

$$Fair\_Share\_Ratio = \frac{n_{SEND}}{n_{total}}. \quad (3)$$

The total number of flows n_{total} in (2) includes both TX flows and CS flows because the wireless channel is used not only by the TX flows but also by some of CS flows. However, a CS flow may not share the channel with the station if the sender station of that CS flow is of the carrier sensing range. Moreover, we cannot distinguish the CS flows by the local information of the station. By these two reasons, we consider all the CS flows as one flow even if there are two or more flows.

The end of CS and TX flows are estimated as follows. We set *timeout* period. If no packet from CS flow is detected during the *timeout* period, we decide the end of CS flow. Similarly for TX flows.

3.3 Utilization Estimation Module

Utilization Estimation module evaluates the real link utilization of the station. The link utilization is measured by examining the $Active\_Time$ of the station in a predefined estimation period EP. The $Active\_Time$ of the station is defined as the time used for transmitting packets of its SEND flows. Algorithm 1 shows how to estimate the $Active\_Time$ by sensing packets.

The $Real\_Share\_Ratio$ is defined as the ratio of the $Active\_Time$ to the estimation period EP as;

$$Real\_Share\_Ratio = \frac{Active\_time}{EP}. \quad (4)$$

3.4 Queue Estimation Module

The contention at the link layer causes the problem that the

Algorithm 1 Active time estimation

Initialization:
  $Active\_Time = 0$
  $T_{Active} = 0$
Begin
  for each interval time EP **do**
    $Active\_Time = 0.8 * Active\_Time + 0.2 * T_{Active}$
    $T_{Active} = 0$
    for each packet p **do**
      if $p \rightarrow destID == localID$ **then**
        if $p \rightarrow Type == CTS$ **then**
          $T_{Active} = T_{Active} + T_{RTS} + T_{CTS}$
        else if $p \rightarrow Type == ACK$ **then**
          $T_{Active} = T_{Active} + T_{DATA} + T_{ACK}$
        end if
      end if
    end for
  end for
End

direct flow occupies the buffer completely when the offered load is large. Only by using RR queues, these unfairness problem cannot be solved [15]. In our cross-layer scheme, RR queue is used at the link layer and Queue Estimation module examines the queue length of each flow. The load of a flow is measured by comparing its queue length to the average queue length of all flows. Then the packet at the head of the queue for $flow\ i$ is marked at the following probability;

$$P_{i\_marked} = \begin{cases} \dfrac{qlen_i - ave}{(n-1)ave}, & \text{if } qlen_i > ave, \\ 0, & \text{if } qlen_i \leq ave, \end{cases} \tag{5}$$

where $qlen_i$ is the queue length of $flow\ i$, ave is the average of the queue lengths for all flows in the station, and $n = n_{SEND}$ is the number of SEND flows of the station.

3.5 CW Monitor Module

In the original IEEE 802.11, the CW size is based only on the congestion condition, so it is not a good value for fair bandwidth allocation. CW size is related to the channel access probability of the station. By reducing the CW size in the back-off state, the channel access probability of the station increases, and then the station can take more bandwidth allocation. Conversely, by increasing the CW size in the back-off state, the neighboring stations have more chance in accessing channel. Based on the CW value in the back-off algorithm of the IEEE 802.11 and the network condition, we will determine a better CW size in the back-off state in order to achieve per-flow fairness.

We will show in the next section the functions of Module Set I and II.

3.6 Module Set I

Module Set I consists of CS Flow Estimation module, TX Flow Estimation module, Utilization Estimation module and CW Monitor module. Module Set I adjusts CW size based on the relation between *Fair_Share_Ratio* (3) and *Real_Share_Ratio* (4) in order to achieve per-station fair bandwidth allocation. *Fair_Share_Ratio* and *Real_Share_Ratio* are estimated by TX Flow Estimation module and Utilization Estimation module, respectively. Both values are sent to CW Monitor module by using cross-layer signal.

When there is a packet ready to be sent, CW Monitor module adjusts CW size as follows;

$$CW' = \frac{Real\_Share\_Ratio}{Fair\_Share\_Ratio} CW. \tag{6}$$

In (6), the $Fair\_Share\_Ratio$ value is used as a threshold of channel access priority. If the station recognizes that its $Real\_Share\_Ratio$ is smaller than its $Fair\_Share\_Ratio$, it will use a smaller CW size in the back-off state. Then, the station can increase its chance to access channel and its bandwidth allocation. On the other hand, if the station recognizes that its $Real\_Share\_Ratio$ is lager than its $Fair\_Share\_Ratio$, it will use a larger CW size in the back-off state. Thus, the station decreases its chance to access channel, so other disadvantaged stations will get more chance to access the channel. In case some stations have only small offered load flows, they will access channel easily, and the remaining bandwidth is shared by other stations. Therefore, Module Set I use the channel bandwidth more effectively and ensure fair bandwidth allocation between stations.

3.7 Module Set II

Module Set II consists of Queue Estimation module and CW Monitor module. Module Set II adjusts CW size for each flow to achieve per-flow fairness. Queue Estimation module marks a packet at the probability in (5). When the marked packet is ready to be sent, CW Monitor module will assign larger back-off time for this packet as follows;

$$CW'' = \begin{cases} \kappa * CW', & \text{for a marked packet,} \\ CW', & \text{for a non-marked packet,} \end{cases} \tag{7}$$

where $\kappa > 1$ is a constant, which we call a delay weight constant and CW' is the value defined in (6). Note that the value of CW is determined by the original IEEE 802.11 back-off mechanism and we do not touch the mechanism itself. CW' and CW'' are only used when a packet comes to back-off state.

Thus, Module Set II can help disadvantaged flows have more chance to access channel based on its queue length. Moreover, when a large back-off time is set to packets of large offered load flows, those packets will be delayed longer before sending than by the conventional method. Then, during this delay time, packets from the neighboring stations have more chance to reach the station. Thus, the fairness between the direct flow and forwarding flows is also improved.

Let us consider the throughput performance of our method. Module Set II gives longer delay to marked packets than the conventional method, but the extra delay time is very small. Moreover, the flows of neighboring stations can increase their throughput. Therefore, the difference of total throughput is negligible.

4. Performance Evaluation

We now evaluate the performance of our cross-layer scheme by comparing with the original FIFO scheduling in IEEE 802.11 standard [6], PCRQ scheduling [15] on various asymmetric topologies of multi-hop wireless ad hoc networks. We also compare with the method where only Module Set I is used, because we can expect that the per-flow fairness performance may be improved based on the improvement of per-station fairness by Module Set I. We use Network Simulator (NS-2) [14] for evaluation. The simulation parameters are shown in Table 1. In PCRQ scheduling, we use the same parameters as in [15], i.e., the input weight constant $\alpha = 2.0$, the hold weight constant $\beta = 0.3$, the output weight constant $\gamma = 0.3$ and delay time $\delta = 1$ [ms]. In our cross-layer scheme, we set the delay weight constant $\kappa = 2$, *timeout* = 2 [s] and *EP* = 2 [s].

The fairness and throughput performance metrics are evaluated.

- Fairness Index: We use Fairness Index, which is defined by R. Jain [22] as follows;

$$\text{Fairness Index} = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} x_i^2}, \quad (8)$$

  where n is the number of flows, x_i is the end-to-end throughput of $flow\ i$. The value of Fairness Index ranges from $1/n$ to 1. In the best case, i.e., the throughput of all flows are equal, Fairness Index achieves 1. In the worst case, the network is totally unfair, i.e., one flow gets all the capacity while other flows get nothing, then Fairness Index is $1/n$. In this paper, Fairness Index is evaluated based on the goodput at the destination station.
- Total Throughput: We define the Total Throughput as the sum of throughputs of all flows in the simulation.

4.1 Scenario-1: The Large-EIFS Topology

Scenario-1 includes a chain of three stations with two flows. See Fig. 2. (0, 0) means the x-y coordinate of station R, and so on. This topology is also known as *large-EIFS* problem [10], which is described in Fig. 3. In this scenario, stations S1 and S2 are in one transmission range, and stations S1 and R are in other transmission range. Stations S2 and R are out of the transmission range but in the carrier sensing range. At the last state of the four-way handshaking process from sender S1 to receiver R, R sends an ACK frame in reply to a data frame from S1, then S2 detects the ACK frame, but cannot decode it. Thus, S2 must wait an EIFS before accessing the channel, while S1 waits a DIFS, which is much smaller than the EIFS. Li et al. [10] has proved that bandwidth allocation for S1 is four times greater than S2 because of the *large-EIFS* problem.

We examine the network performance in this scenario by letting the stations S1 and S2 generate traffic at the same offered load G to R. The performance metrics Fairness Index and Total Throughput are evaluated versus offered load G.

In Figs. 4 and 5, "Module Set I" means the result by using only Module Set I and "Proposed Method" means both Module Set I and II. Fairness Indices are shown in Fig. 4. When the offered load G is small, all scheduling methods get Fairness Index 1. When the offered load G becomes large, in FIFO scheduling, the direct flow gradually occupies completely the buffer space, then Fairness Index becomes very

Table 1 Parameters in the simulation.

Channel data rate	2 [Mbps]
Antenna type	Omni direction
Radio Propagation	Two-ray ground
Transmission range	250 [m]
Carrier Sensing range	550 [m]
MAC protocol	IEEE 802.11b (RTS/CTS is enable)
Contention Window	CW_{min} = 32, $CWmax$ = 1024
Connection type	UDP/CBR
Buffer size	100 [packet]
Packet size	1 [KB]
Simulation time	300 [s]

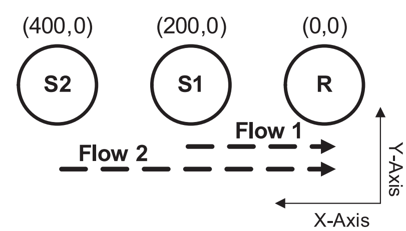

Fig. 2 Scenario-1: The *large-EIFS* problem.

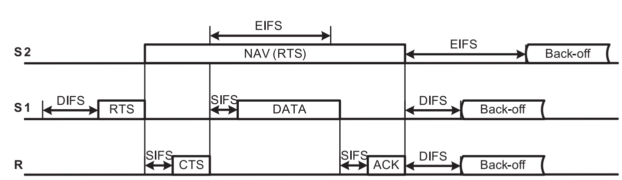

Fig. 3 Unfairness in bandwidth due to *large-EIFS* problem.

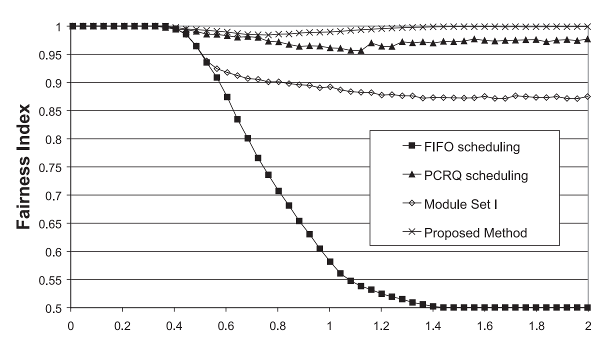

Fig. 4 Fairness index in scenario-1.

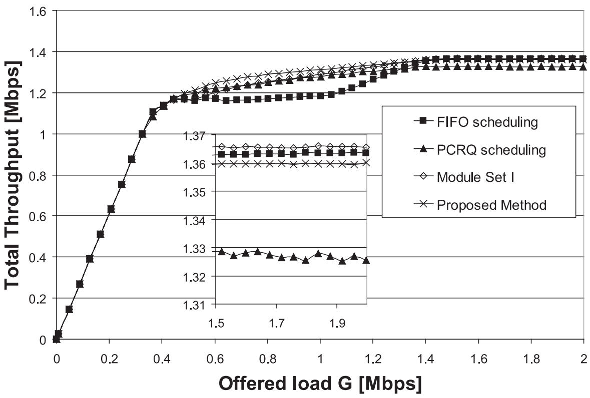

Fig. 5 Total throughput in scenario-1.

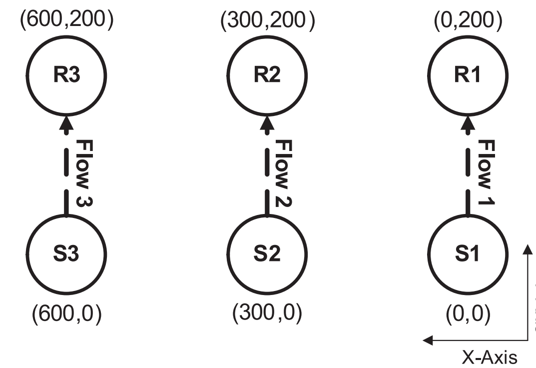

Fig. 6 Scenario-2: *Three-pair* problem.

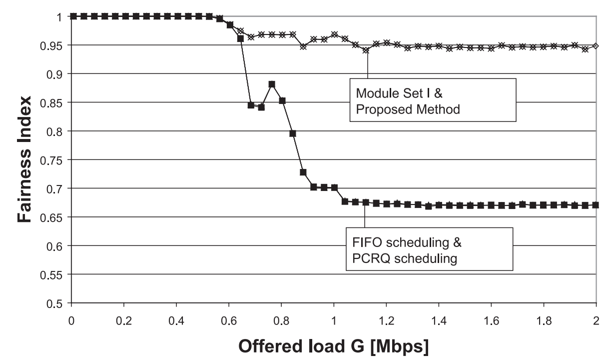

Fig. 7 Fairness index in scenario-2.

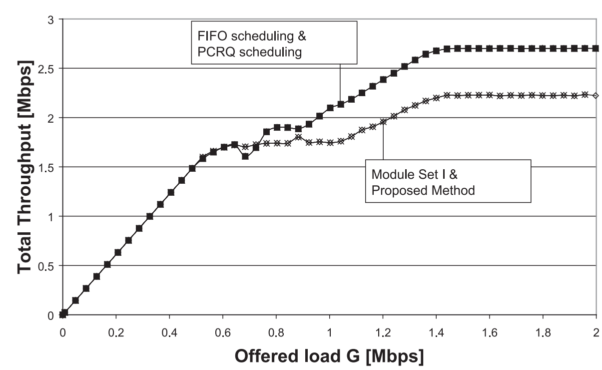

Fig. 8 Total throughput in scenario-2.

bad. In PCRQ scheduling [15], input and output packets to RR queues are controlled, then the throughput of each flow becomes fairer and also the bandwidth allocation at the MAC layer is improved. Thus, PCRQ scheduling achieves good Fairness Index. In Proposed Method, the fairness performance in both MAC and link layers are improved, so we achieve very good Fairness Index. When only Module Set I is applied, Fairness Index is much improved compared to FIFO scheduling.

Total Throughput of all flows are shown in Fig. 5. When the offered load is small, Total Throughput of all methods are similar. When the offered load becomes large, in PCRQ scheduling, bandwidth utilization is less efficient than the others because PCRQ scheduling gives some delays to packets of advantaged flows. In Module Set I, S2 increases its chance to access channel by reducing back-off time, and then the network utilization is also improved. Module Set I achieves the best Total Throughput in all methods. Because Module Set II gives large back-off time to some packets of advantaged flows, Proposed Method achieves Total Throughput slightly smaller than Module Set I and FIFO scheduling.

4.2 Scenario-2: The *Three-Pair* Topology

Figure 6 shows the topology of Scenario-2. The problem in this scenario is also known as *three-pair* problem which was first investigated in [8]. In this scenario, stations S1-S2 and S2-S3 are out of the transmission range but in the carrier sensing range. Stations S1 and S3 are out of the carrier sensing range, hence the two external pairs S1-R1 and S3-R3 are completely independent, i.e., they can send packets simultaneously without interference with each other. Thus, two external pairs contend bandwidth only with the central pair S2-R2, while the central pair contends with both external pairs. In this topology, the central pair cannot access the medium in the saturated state in the original IEEE 802.11 [8].

We examine the unfairness problem in this topology by letting the stations S1, S2 and S3 generate traffic at the same offered load G to R1, R2 and R3, respectively. The performance metrics are evaluated versus offered load G.

Fairness Indices are shown in Fig. 7. When the offered load becomes large, FIFO scheduling and PCRQ scheduling cannot help the central pair access the medium, because PCRQ scheduling only works at the link layer, so it does not have information of flows out of the transmission range. Therefore, it cannot improve the MAC layer fairness. In Proposed Method, the central pair finds out that its bandwidth is less than the fair bandwidth allocation. Then Proposed Method tries to improve its chance to access channel by reducing the back-off time of station S2. Thus, Proposed Method can achieve a good MAC layer fairness and per-flow fairness. Module Set I shows exactly the same results as Proposed Method, because there is no link layer contention

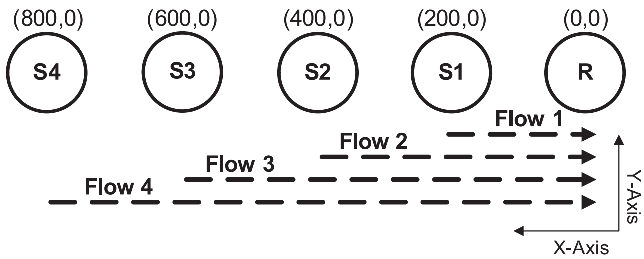

Fig. 9 Scenario-3: a five-station chain with four flows.

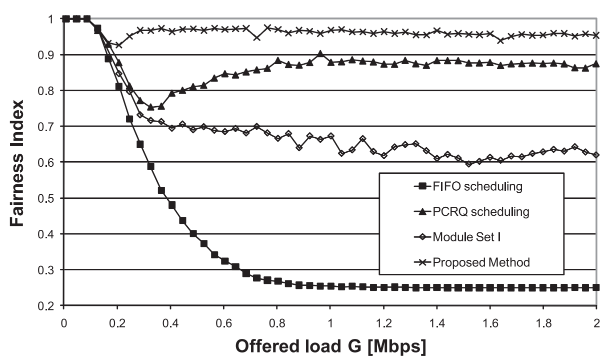

Fig. 10 Fairness index in scenario-3.

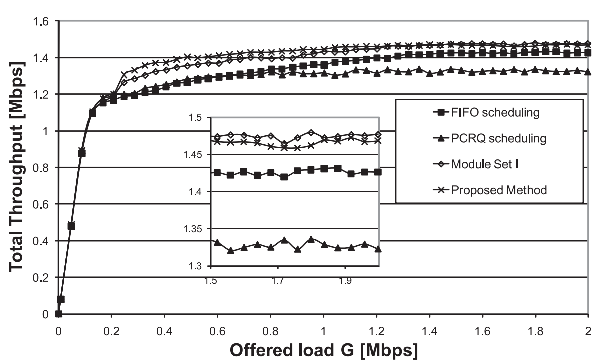

Fig. 11 Total throughput in scenario-3.

in this topology.

Total Throughput of all flows are shown in Fig. 8. When the offered load G becomes large, Module Set I and Proposed Method achieve smaller Total Throughput than the other methods. This phenomenon is explained as follows. In FIFO scheduling and PCRQ scheduling, the central pair cannot access the channel bandwidth and two external pairs can use the whole channel bandwidth. Thus, Total Throughput can be twice of the channel bandwidth. While in Module Set I and Proposed Method, the MAC layer fairness is ensured, so the central pair can achieve a half of the channel bandwidth, then the two external pairs have only a half of the channel bandwidth. Thus, Total Throughput is one and a half of channel bandwidth.

4.3 Scenario-3: The Long Station Chain Topology

Scenario-3 includes a chain of five stations with four flows

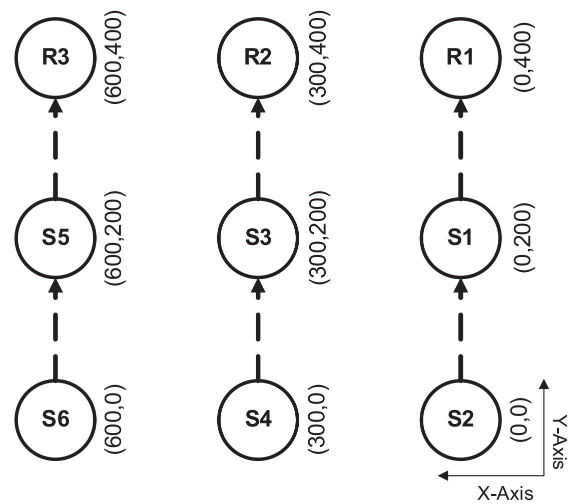

Fig. 12 Scenario-4: Grid scenario.

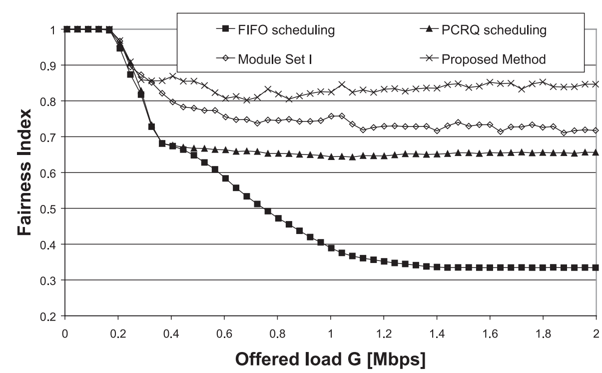

Fig. 13 Fairness index in scenario-4.

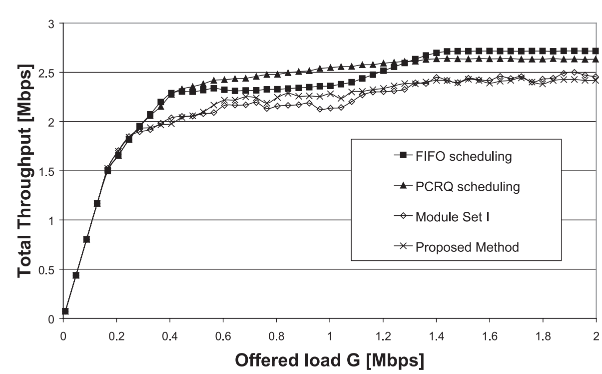

Fig. 14 Total throughput in scenario-4.

as shown in Fig. 9. The stations S1, S2, S3, and S4 generate traffic at the same offered load G to R. This scenario faces with much harder MAC and link layer contentions than Scenario-1.

The performance results are shown in Figs. 10 and 11. The results show that both PCRQ scheduling and Proposed Method get better fairness performance than the others. Proposed Method also has advantage in throughput performance because of the good operation of Module Set I.

4.4 Scenario-4: The Grid Topology

Scenario-4 is a grid topology with high station density and large traffic density as in Fig. 12. In this scenario, the columns are separated by a distance greater than the transmission range but smaller than the carrier sensing range. The stations in a column generate traffic at the same offered load G to the receiver in the same column. This topology faces both *large-EIFS* and *three-pair* unfairness problems.

Fairness Index between six flows are shown in Fig. 13. When the offered load G becomes large, each method gives different Fairness Index due to contention between the direct flow and forwarding flows at the link layer, and due to both *large-EIFS* and *three-pair* problems at the MAC layer. Fairness Index of FIFO scheduling is the worst because of the unfairness problems in both MAC and link layers. By the same reason explained in Scenario-2, PCRQ scheduling cannot solve the unfairness in *three-pair* problem. Thus, Fairness Index of PCRQ scheduling is not good. Fairness Index of Module Set I is better than PCRQ scheduling, but Module Set I still cannot solve the contention at the link layer. Proposed Method achieves the best per-flow fairness among all methods because we improved the fairness at both MAC and link layers.

Total Throughput performance are shown in Fig. 14. At the large offered load, Total Throughput of Proposed Method is smaller than the other methods by the same reason with Scenario-2.

4.5 Scenario-5: The Random Topology

Scenario-5 is a random topology. We make topologies with 50 stations at random position in 1000 [m] × 1000 [m] area. Among those 50 stations, n stations are chosen randomly and these n stations generate UDP traffic to one destination station. Total offered load of source stations is set equal to the channel data rate 2 [Mbps]. The average of Fairness Index and total end-to-end throughput are used as the metrics to compare the throughput and fairness performances, respectively. These terms of the network performance are examined versus the number of flows. Each data point is the average over 20 simulations. The simulation results are shown in Figs. 15 and 16.

The simulation results also prove that Proposed Method achieves good fairness performance as in Fig. 15. Our throughput performance is slightly reduced by the trade-off with fairness performance as described in Fig. 16.

4.6 Scenario-6: The Dynamic Number of Flows and the Dynamic Offered Loads

Scenario-6 is used to examine bandwidth utilization of Proposed Method in case that the number of flows and offered load change by time. We use the same topology as Scenario-1. The simulation time is 450 [s]. The offered loads of flow 1 and 2 change by time as (0, G, G), (50, G, G/2),

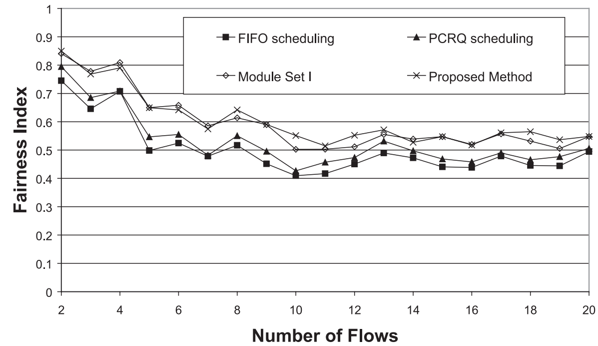

Fig. 15 Fairness index in scenario-5.

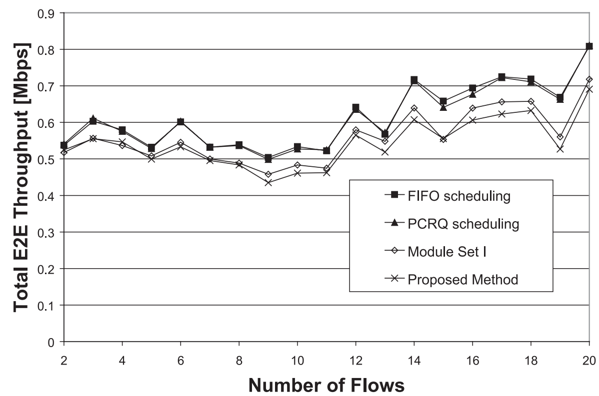

Fig. 16 Total throughput in scenario-5.

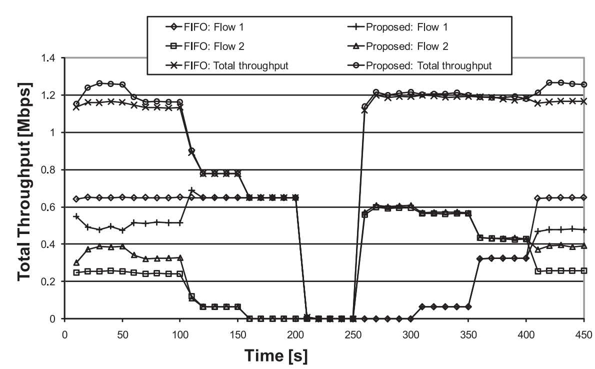

Fig. 17 Throughput in scenario-6.

(100, G, G/10), (150, G, 0), (200, 0, 0), (250, 0, G), (300, G/10, G), (350, G/2, G), (400, G, G), where (t, G1, G2) denotes the changing time, offered load of flow 1 and offered load of flow 2, respectively. We set G equal to 0.65 [Mbps]. Proposed Method is compared only with the original IEEE 802.11. The simulation results are shown in Fig. 17.

When the total offered load is small, e.g., from 100 [s] to 200 [s], every flow can get the throughput equal to its offered load in both Proposed Method and the original IEEE 802.11, regardless of the difference of each flow's offered load. When the total offered load is greater than the channel capacity, e.g., from 50 [s] to 100 [s] and 300 [s] to 400 [s], in Proposed Method, the throughput of the small offered load flow is equal to its offered load and the large offered load flow gets the remaining bandwidth. Total Throughput in Proposed Method is always better than in the original IEEE 802.11 even if the offered loads and the number of flows change by time.

5. Conclusion and Future Work

We proposed a new cross-layer scheme to achieve good fairness of throughputs between flows. Our cross-layer scheme consists of two module sets. Module Set I controls the MAC layer contention. We used information from the physical and MAC layers and modify the CW size in back-off state to achieve the fair bandwidth allocation for each station. Module Set II controls the link layer contention. We controlled RR queue in order to help each flow use bandwidth fairly. The cross-layer signal is sent from the link layer to the MAC layer, and then the MAC layer gives a long back-off time to packets from large offered load flows.

By NS-2 simulation, we compared our cross-layer scheme with FIFO scheduling, PCRQ scheduling and the method using only Module Set I. The results showed that our cross-layer scheme achieved good performance in *large-EIFS* problem, *three-pair* problem scenarios and also complex asymmetric topologies as *long-station chain*, *grid*, random and dynamic topologies. In these topologies, FIFO scheduling cannot solve the link layer contention. PCRQ scheduling can achieve good per-flow fairness, however, it works only at the link layer so it cannot solve per-flow fairness between stations. Module Set I tries to achieve fair bandwidth allocation between stations, the per-flow fairness performance also is improved. Proposed Method uses cross-layer information to improve both MAC and link layer fairness. Therefore, we had good results in per-flow fairness even in asymmetric topologies.

This paper is our first challenge to apply the proposed method for per-flow fairness in the multi-hop ad hoc networks, and we evaluated only for UDP traffic. A good performance for TCP traffic also is obtained by some simulations in our laboratory. This is because TCP data packets can be considered to be similar with UDP packets, and the feedback ACK packets can be treated as a small offered load flow in our cross-layer scheme. They have more priority to access channel and more chance for successful transmission. However, we found that the fairness performance issue of TCP is a tough issue, because, for example, TCP cannot distinguish packet losses caused by network congestion from those caused by wireless link errors. In future work, a cross-layer method to exchange information between TCP layer and MAC layer will be investigated to improve network performance in the mixture of UDP and TCP traffics.

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Appendix: Definition of Per-Flow Fairness

Here, we consider the definition of per-flow fairness as follows. Let n be the number of flows sharing the channel bandwidth B. The offered load of $flow\ i$ is denoted by G_i and the resulting throughput is denoted by Th_i, $i = 1, 2, ..., n$. We assume $G_1 \leq G_2 \leq ... \leq G_n$. We define per-flow fairness by

$$Th_i = \begin{cases} G_i, & \text{for } i = 1, ..., m, \\ \dfrac{B - \sum_{j=1}^{m} Th_j}{n - m}, & \text{for } i = m+1, ..., n, \end{cases} \qquad \text{(A· 1)}$$

where m is the index in $0, ..., n$ which satisfies $G_m \leq \frac{B-\sum_{j=1}^{m} Th_j}{n-m}$ and $G_{m+1} > \frac{B-\sum_{j=1}^{m} Th_j}{n-m}$. We call $flow\ i$, $i = 1, 2, ..., m$, “small” offered load flow and $flow\ i$, $i = m + 1, m + 2, ..., n$, “large” offered load flow. In case that all flows are large offered load flows ($m = 0$), the ideal per-flow fairness is achieved when every flow gets the same throughput. In case there are some small offered load flows ($m \geq 1$), the ideal per-flow fairness is such that the throughput of every small offered load flow is equal to its offered load, and the remaining bandwidth is shared equally by large offered load flows. For example, if there are four flows with offered loads 0.2 [Mbps], 0.5 [Mbps], 0.7 [Mbps], 0.8 [Mbps], and the channel bandwidth is 2 [Mbps]. Then, flows with offered load 0.2 [Mbps] and 0.5 [Mps] are small offered load flows while flows with offered load 0.7 [Mbps] and 0.8 [Mbps] are large offered load flows. The ideal per-flow fairness is such that the throughputs are 0.2 [Mpbs], 0.5 [Mbps], 0.65 [Mbps], 0.65 [Mbps], respectively.

We can consider the case that the offered loads are not constant and change by time. The definition of per-flow fairness is based on the average offered loads for a specific interval time.

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