A Packet Scheduling Algorithm for Max-Min Fairness in Multihop Wireless LANs

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Abstract

In this paper, we propose a probabilistic packet scheduling scheme achieving max-min fairness without changing the existing IEEE 802.11 medium access control (MAC) protocol. In the proposed scheme, packets at each wireless node are managed on a per-flow basis. When a wireless node is ready to send a packet, the packet scheduler of the node is likely to select the queue whose number of packets sent in a certain time is the smallest. If the selected queue has no packet, the node defers the transmission by a fixed duration. In order to verify the improvement in per-flow fairness, we evaluate the performance of the proposed scheme by ns-2. The numerical examples show that our proposed scheme achieves better per-flow fairness than the existing schemes in networks of not only chain topologies but also random topologies.

Key words: IEEE 802.11 DCF, multihop communication, packet scheduling, throughput performance, max-min fairness

1 Introduction

Recently, multihop wireless local area networks (LANs) have attracted considerable attention for next-generation networks supporting a large number of end users. Currently, the most prevalent wireless LAN standard is IEEE 802.11. The distributed coordination function (DCF) is a fundamental mechanism of

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the medium access control (MAC) protocol for IEEE 802.11, employing Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The IEEE 802.11 DCF specifies random backoff algorithm, with which each wireless node transmits data in an autonomous-decentralized manner.

When the number of nodes increases, the overall throughput significantly degrades due to the hidden-node problem. To resolve this problem, the four-way handshake by using Request-To-Send/Clear-To-Send (RTS/CTS) frames is available in IEEE 802.11. Because the four-way handshake was developed for single-hop communications, however, it does not work well for multihop communications. The multihop wireless LANs have several issues to be tackled such as routing, the guarantee of quality of service (QoS), security and fairness. In this paper, we focus on throughput unfairness, in which the end-to-end throughput of a packet flow degrades significantly with the increase in the number of its transmission hops.

There is much literature for achieving per-flow fairness in multihop wireless networks. Salem and Hubaux [11] focused on Spatial Time Division Multiple Access (STDMA) [7] and proposed a MAC-level packet scheduling for wireless mesh networks (WMNs), in which transmission rights are assigned to the links such that the spatial reuse is maximized. Nandi and Gupta [6] reported the imprecise Extended Inter-Frame Space (EIFS) problem in which mismatch between the EIFS value and desired one causes unfairness and throughput degradation. They proposed an enhanced carrier sensing (ECS), which differentiates the types of erroneous frames based on their lengths and defers the transmission accordingly. Note that the above two methods require the modification of the existing IEEE 802.11 MAC layer, which is not preferable from the deployment viewpoint.

Izumikawa et al. [4] proposed a per-flow packet scheduling scheme in which packets in a wireless node are classified into the packets originating from the node and those forwarded from the other nodes. The transmission order of packets is determined in a round-robin fashion based on their source identifications. Note that this scheme is designed for achieving the same throughput among flows regardless of the number of hops. Therefore, it works well only when all sender nodes transmit packets at the same rate and the link capacities are the same.

Giang and Nakagawa [2] proposed Probabilistic Control on Round robin Queue (PCRQ) for the link layer. PCRQ is a per-flow-based packet scheduler, consisting of probabilistic packet enqueueing, round-robin-based queue selection for transmission, and probabilistic packet dequeueing. The PCRQ scheduling improves not only fairness but also the buffer resource utilization and packet delay. In order to achieve high performance with PCRQ, however, several control parameters should be determined appropriately, and this parameter setting is an open issue.

Note that all the above schemes considered the improvement of fairness when the offered load is the same among all wireless nodes, which never holds in heterogeneous networks. In this paper, we consider max-min fairness for heterogeneous networks. A packet scheduler is said to achieve max-min fairness when the minimum data transmission rate is maximized firstly, and the second smallest rate is maximized secondly, and so on. Max-min fairness was firstly proposed in [9], and extensively studied in the literature [3,5].

In this paper, focusing on the Logical Link Control (LLC) layer that is the upper layer of the IEEE 802.11 MAC layer, we propose a packet scheduling scheme to achieve max-min fairness without modification of the IEEE 802.11 MAC layer. In the proposed scheme, each wireless node manages packets on a per-flow basis. That is, packets in a flow are stored at a queue dedicated to the flow. When a wireless node is ready to send a packet, the packet scheduler of the node is likely to select the queue which has sent a small number of packets in a certain time. If the selected queue has no packet to transmit, the node defers the transmission by a fixed duration. This gives the other nodes more chances to transmit their packets, some of which might be directed to the selected one. In other words, the node is likely to receive packets to forward while deferring its own transmission. Therefore, a significant improvement in per-flow fairness is expected to be achieved. To verify the effectiveness of the proposed scheme, we evaluate its performance by the network simulator ns-2 [1].

The rest of the paper is organized as follows. In Section 2, we show some problems related to IEEE 802.11 DCF. We describe our packet scheduling algorithm in Section 3, and numerical examples are presented in Section 4. Finally, conclusions and future work are presented in Section 5.

2 Buffer Management Issue for Multihop Wireless LANs

The throughput degradation of IEEE 802.11 DCF-based multihop wireless LANs are caused by several reasons such as network allocation vector (NAV) blocking [10,14], the imprecise EIFS problem [6], and the buffer management issue. In this section, we focus on how the buffer management mechanism affects the throughput degradation.

Figure 1 shows an example that two wireless nodes (WN1 and WN2) transmit data to a BS at rate G. Here, we assume that WN1 is located within the transmission range (TR), and that WN2 is located outside TR but within the carrier sensing range (SR). Therefore, WN1 can transmit data frames directly

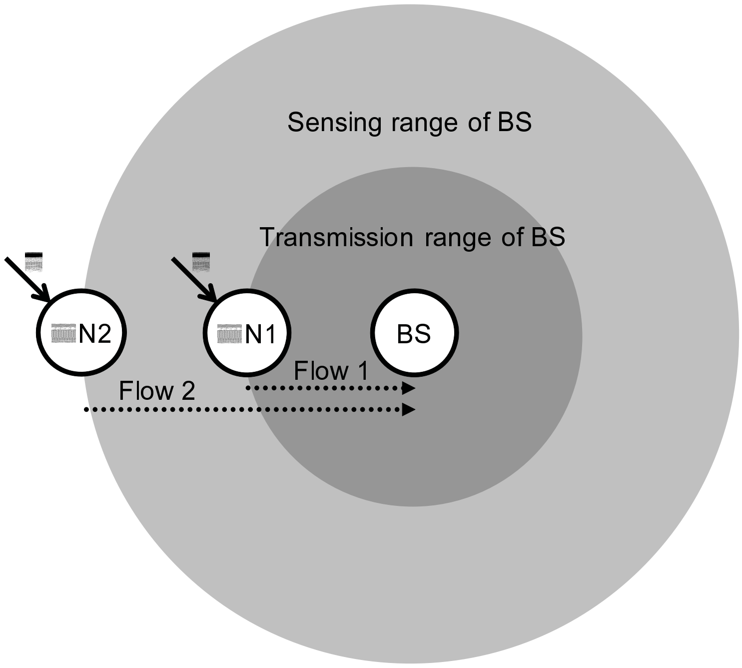


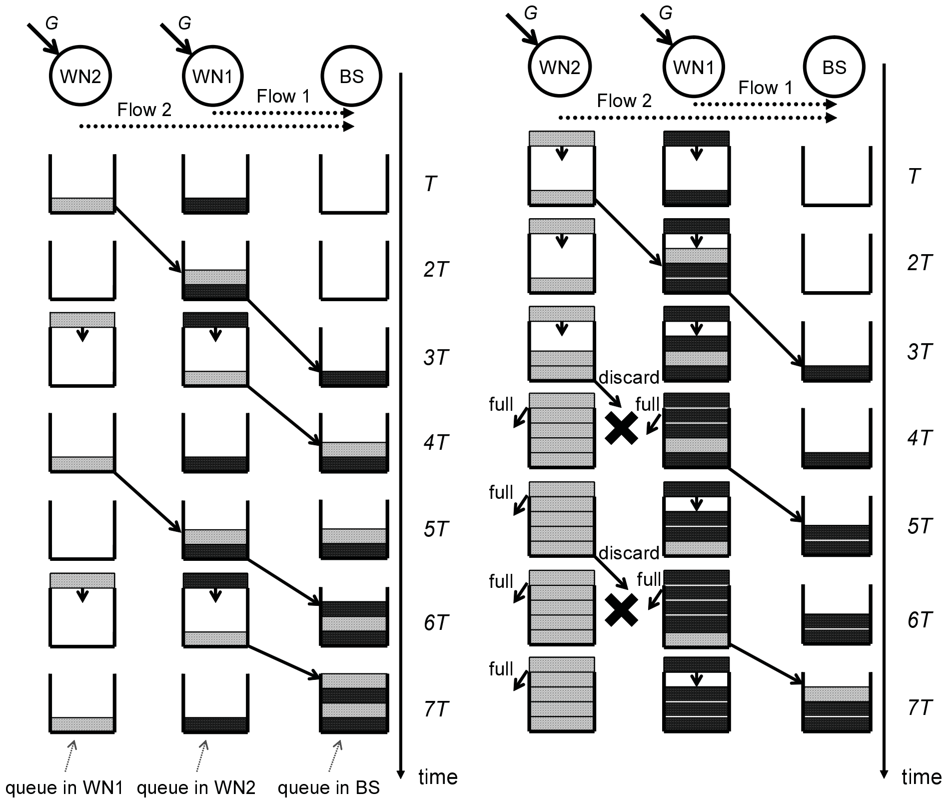
Fig. 1. The basic chain topology.

to the BS (a single-hop transmission), however, WN2 cannot communicate with the BS directly. The frames transmitted from WN2 are received at WN1 first and then forwarded to the BS (a two-hop transmission).

In the following, we call a frame a packet for convenience. In general, a wireless node has a single FIFO queue for packet scheduling. In multihop environment, each node may transmit new packets originating from the node and those forwarded from the other nodes through the single queue. This causes unfairness in per-flow end-to-end throughput. Consider the case where wireless nodes WN1 and WN2 send data to a BS at a fixed rate G, as shown in Fig. 1. WN1 needs G receiving bandwidth and $2G$ transmission bandwidth in order to ensure that both the nodes transmit data to the BS at rate G. That is, WN1 needs the total available bandwidth of $3G$. In what follows, we will focus on the buffer management mechanism of the link layer.

For simplicity, we assume that each node generates a new packet every $3T$ period and that the transmission right alternates between WN1 and WN2 in $2T$ period, as shown in Fig. 2(a). We also assume that the buffer size is four (packets). In Fig. 2(a), the offered load G is small and hence no packet loss occurs.

Now consider the overloaded case where each node generates a new packet every T period and the transmission right alternates between the two nodes in $2T$, as shown in Fig. 2(b). Here, packets originating from WN1 are more frequently received than packets forwarded from WN2. Because the buffer size is four, WN1 discards packets from WN1 and WN2 at $4T$ and $6T$ due to buffer



(a) Small offered load case (b) Large offered load case

Fig. 2. Queueing dynamics

saturation. Note that packets originating from WN2 also suffer from packet loss at WN2's transmission buffer. Therefore, the end-to-end throughput of WN2 packets significantly degrades in comparison with that of WN1 packets.

One of methods to improve the end-to-end throughput is the round-robin scheduling in which packets are managed at a wireless node in a per-flow basis. In this case, queues are classified into two types: one is an origin queue for packets originating from the node, and the others are forwarding queues for packets sent from the other nodes. Note that the round-robin scheduling is effective only when the offered loads at wireless source nodes are small. When they are large, the round-robin scheduling does not work well due to a shortage of packets to be forwarded in the transmission buffer.

Now consider the following modification of the round-robin scheduling. When the packet scheduler selects a queue having no packet, the packet scheduler waits for a new packet's arrival. In this modification, the packet scheduler at the node is forced to transmit a packet in a cyclic order. When the offered load at a wireless node is different from those at other nodes, however, the resulting end-to-end throughput may be limited by the packet flow whose

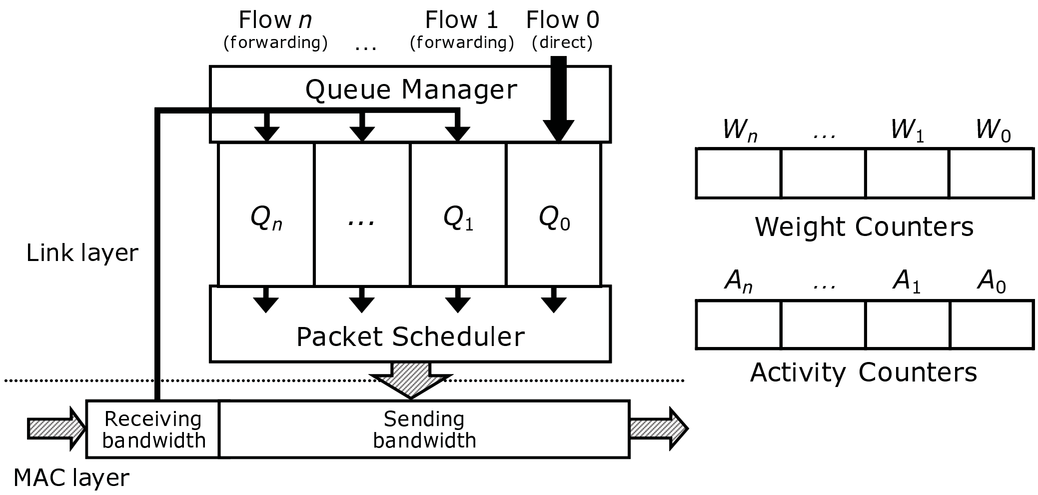


Fig. 3. The traffic control mechanism in the proposed scheme.

offered load is the smallest. In other words, this modification cannot achieve max-min fairness.

3 Proposed Scheme

In this section, we present the details of the packet scheduling scheme improving per-flow throughput fairness for multihop wireless LANs.

Figure 3 shows the traffic control mechanism in the proposed scheme. A wireless node has queues $(Q_0, Q_1, ..., Q_n)$, weight counters $(W_0, W_1, ..., W_n)$ and activity counters $(A_0, A_1, ..., A_n)$ corresponding to each flow (Flow 0, Flow 1, ..., Flow n). Let W_{max} be the maximum value of the weight counters. The proposed scheme consists of the queue manager and the packet scheduler. The MAC layer part of the figure conceptually illustrates how the wireless-link bandwidth is shared among the receiver and sender processes. In comparison with conventional packet scheduling, the packet scheduler of the proposed scheme increases the receiving bandwidth while decreasing the sending bandwidth by deferring a packet transmission for a fixed duration.

3.1 Queue Manager Process

In Fig. 4, the flowchart of the queue manager process is described. Consider the case where the wireless node receives a packet from a source node. If the queue corresponding to the source node exists, the packet is forwarded into the queue, and the corresponding activity counter is set to the default value. If the queue does not exist, a new queue and the corresponding counters are

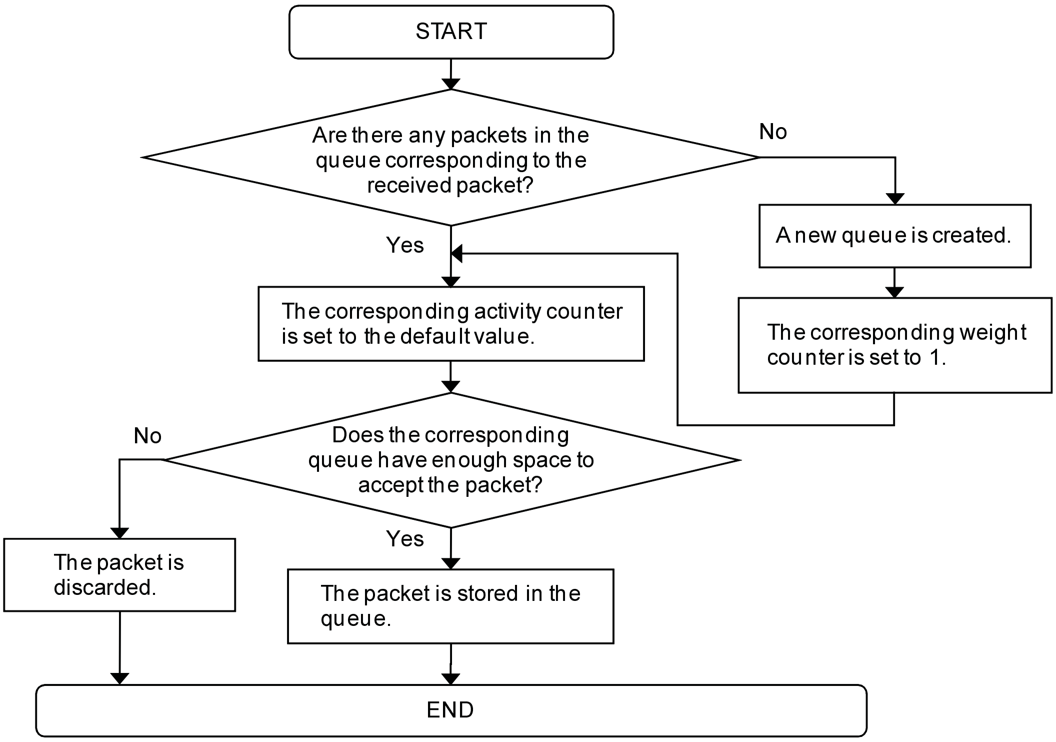


Fig. 4. The flowchart of the queue manager.

created and initialized. If the queue is not full of packets, the arriving packet is stored in the queue. Otherwise, the packet is discarded.

3.2 Packet Scheduler Process

Figure 5 describes the flowchart of the packet scheduler, which selects one of the existing queues for the next transmission according to the values of the weight and activity counters. First of all, the scheduler refers to all the queues whose weight counters are greater than zero, and checks whether each of them has packets or not. If there exists only one queue satisfying the above conditions, this queue is selected for the next transmission. If there exist several queues, the scheduler selects one of them in the following probabilistic manner.

Suppose that the scheduler manages n queues and that the weight counter value of Q_k $(1 \leq k \leq n)$, W_k, is w_k. In the proposed algorithm, queue Q_k is selected for the next transmission with probability $w_k / \sum_{i=1}^{n} w_i$. If Q_k is selected and has some packets, W_k is set to $w_k - 1$ and a packet is dequeued from Q_k. Otherwise the corresponding activity counter is decremented by one, and the node defers its transmission for a fixed duration t_{wait}, repeating the above procedure. If all the queues have no packet, all the corresponding weight counters are incremented by one. Note that the weight counters cannot exceed

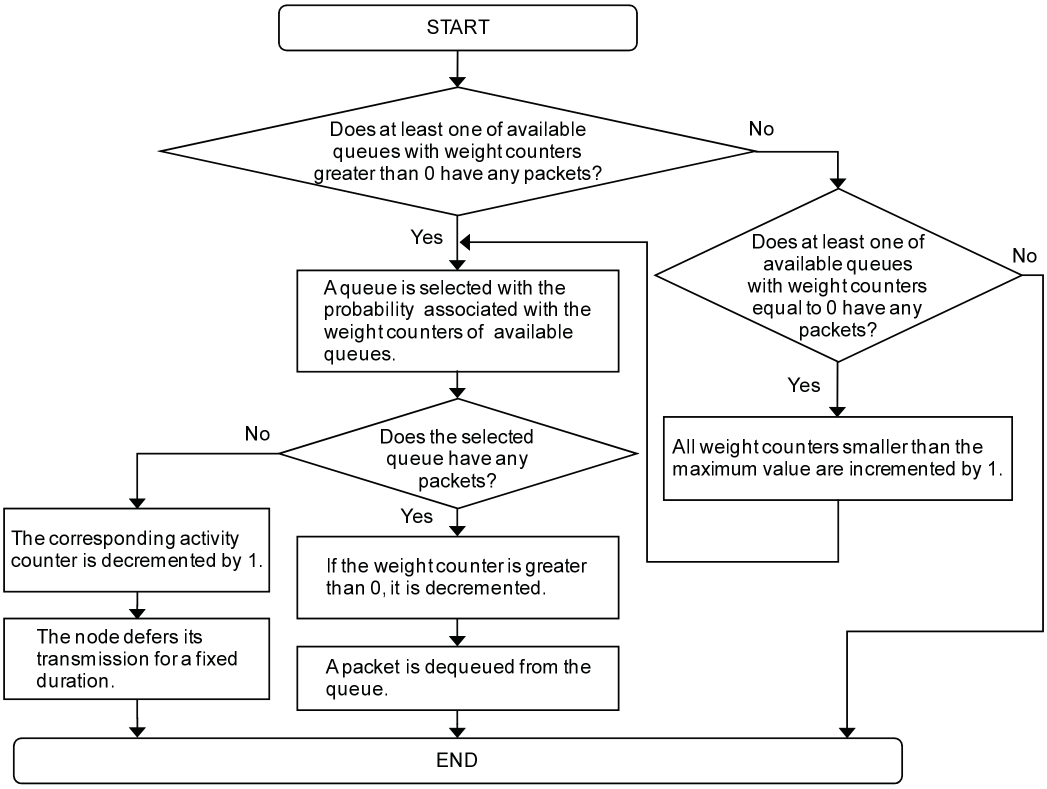


Fig. 5. The flowchart of the packet scheduler.

the given maximum value, W_{max}. When the activity counter of Q_k reaches zero, queue Q_k is removed.

When the wireless node does not receive a packet from a source node for a while, the corresponding weight counter increases and the queue for the source node is frequently selected. This yields more chance for the node to transmit and hence may increase the bandwidth for packet reception. As a result, packets from the source node are more likely to reach the wireless node.

4 Performance Evaluation

In this section, we evaluate the fairness performance of the proposed scheme in comparison with some existing schemes, using the network simulator ns-2. We consider the following three schemes:

- Scheme 1 (FIFO):
  Each node has only a FIFO queue.
- Scheme 2 (round-robin):
  Each node has per-flow queues which are serviced in a round-robin fashion.

Table 1
Basic simulation parameters.

Parameter	Value
Antenna type	Omni direction
Radio propagation	Two-ray ground
Channel data rate	11 [Mbps]
MAC protocol	IEEE 802.11 DCF
RTSThreshold	300 [byte]
Max retry times	7
Transmission range	120 [m]
Sensing range	220 [m]
Node spacing	100 [m]
Packet size	1500 [byte]
Buffer size	50 [packets]
Simulation time	120 [sec]

If the selected queue has no packet, the transmission right is immediately assigned to the next queue.

- Scheme 3 (proposed in [4]):
  Each node has a downlink queue and two uplink queues. One of the uplink queues is an origin queue which accumulates packets originating from the node itself. The other uplink queue is a forwarding queue in which packets are sent from the other nodes. Packets in both origin and forwarding queues are transmitted in a way such that during a time interval between consecutive transmissions of packets originating from the node, at most one packet per source node is transmitted. For more details, the readers are referred to [4].

Table 1 shows the basic parameters used in simulation experiments. The parameters for the MAC layer are cited in the widely used IEEE 802.11b standard. In what follows, these parameters are used unless otherwise noted.

We use the following fairness index [12] as a measure to evaluate per-flow throughput fairness for the case where the offered loads are the same.

$$FairnessIndex = 1 - \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{2(n-1)\bar{x}}, \tag{1}$$

where n is the number of flows, x_i the end-to-end throughput of Flow i ($1 \leq i \leq n$), and $\bar{x}$ the average end-to-end throughput achieved by all n flows. The

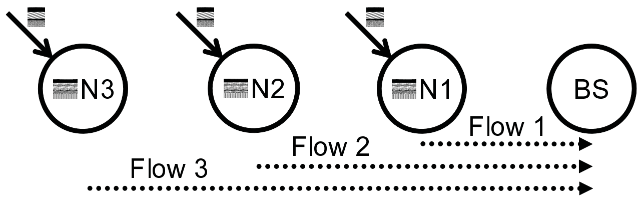


Fig. 6. Four-node chain topology.

fairness index lies in the range from 0 to 1, and the value close to 1 indicates high per-flow fairness. In accordance with [4], the series of packet interarrival times for each flow is generated by a constant interval multiplied by a random number which is uniformly distributed in $(-0.5, 0.5)$.

4.1 Chain Topology

In this subsection, we evaluate the performance of the proposed scheme for chain topologies.

4.1.1 Impact of Offered Traffic

First, we investigate how the offered load affects per-flow fairness in a simple chain topology. In this experiment, we consider the chain topology with three nodes and a BS, as shown in Fig. 6. Here, we have Flows 1 to 3, and the number of transmission hops for Flow i is i. The offered load for the three flows is G, and its range is from 100 [kbps] to 2000 [kbps].

Figure 7 shows the fairness indices for all the schemes. We observe that both the proposed scheme and Scheme 3 always keep high per-flow fairness, while Schemes 1 and 2 degrade their fairness when G is greater than 700 [kbps]. This result implies that the proposed scheme and Scheme 3 succeed in providing high per-flow fairness in comparison with the conventional Schemes 1 and 2.

Next, we consider the total throughput which is defined as the sum of end-to-end throughputs over all wireless links. For example, in Fig. 6, suppose that each flow's end-to-end throughput is x_i $(i = 1, 2, 3)$ and that no packet loss occurs at each wireless link. Let $T_{m,n}$ $(m, n \in \{\mathrm{BS}, \mathrm{WN1}, \mathrm{WN2}, \mathrm{WN3}\})$ denote the aggregate throughput between neighboring nodes m and n. In this case, the total throughput is given by

$$\begin{aligned} T_{\mathrm{WN3,WN2}} + T_{\mathrm{WN2,WN1}} + T_{\mathrm{WN1,BS}} &= x_3 + (x_2 + x_3) + (x_1 + x_2 + x_3) \\ &= x_1 + 2x_2 + 3x_3. \end{aligned}$$

Note that if the network is overloaded, the total throughput may not be the

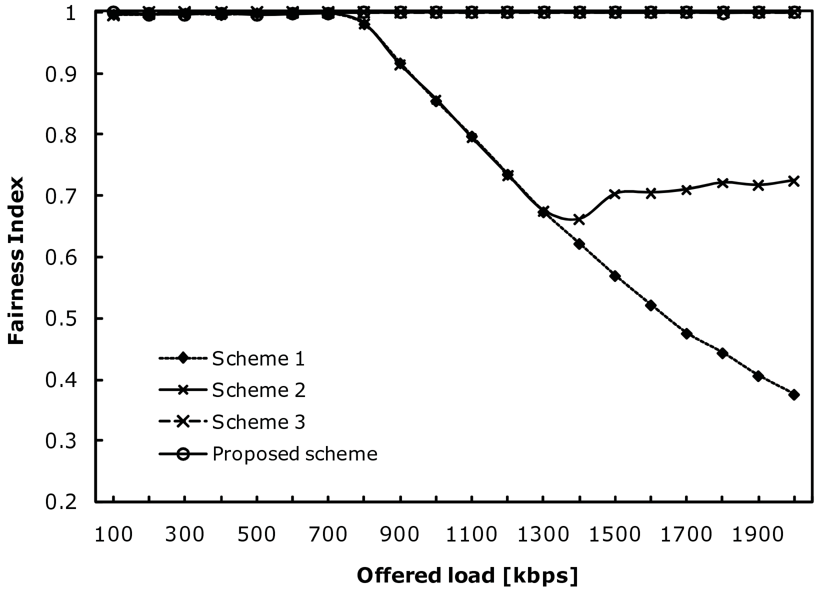


Fig. 7. Fairness index vs. offered load for each scheme.

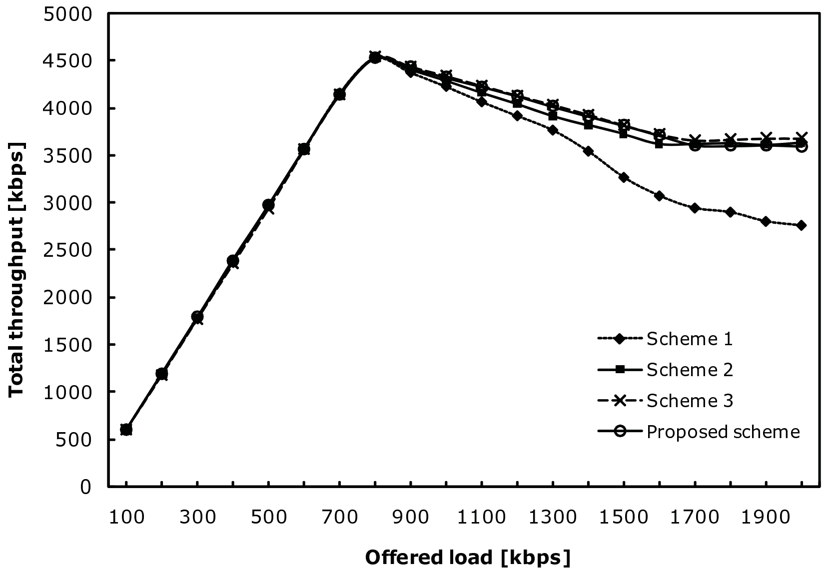


Fig. 8. Total throughput vs. offered load for each scheme.

same as the sum of multiples of end-to-end throughputs.

Figure 8 represents the total throughput against the offered load for the four schemes. In Fig. 8, the total throughput of each scheme increases linearly, and then decreases gradually due to congestion. A remarkable point here is that the total throughputs of the proposed scheme and Scheme 3 are almost the same. From Figs. 7 and 8, we can see that the proposed scheme succeeds in achieving the same performance as Scheme 3 in terms of per-flow fairness and

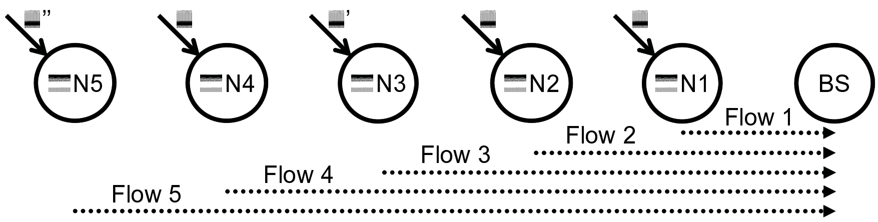


Fig. 9. Six-node chain topology.

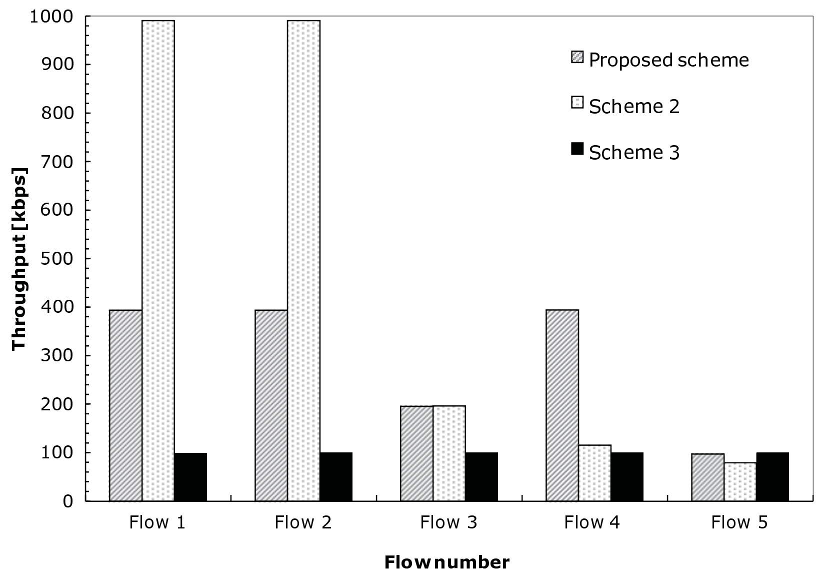


Fig. 10. End-to-end throughput for heterogeneous offered traffic (WN1, WN2, WN4: 1000 [kbps], WN3: 200 [kbps], WN5: 100 [kbps]).

the network utilization when all source nodes have the same offered load.

4.1.2 Impact of Heterogeneous Offered Traffic

In this subsection, we investigate how the proposed scheme achieves max-min fairness when the offered loads are heterogeneous. In this experiment, the proposed scheme is compared with the existing schemes for the six node chain topology shown in Fig. 9.

Figure 10 shows the end-to-end throughput of each flow. In this figure, the offered loads at WN3 and WN5 are set to 200 [kbps] and 100 [kbps], respectively, and those for the other nodes are set to 1000 [kbps]. In the proposed scheme, we set $W_{max} = 12$ and $t_{wait} = 400$ [μs]. We observe from the figure that the end-to-end throughput of a flow with a large number of hops degrades for Scheme 2. Especially, the end-to-end throughput of Flow 4 is significantly reduced with the scheme. This implies that the round-robin scheduling is not effective to improve max-min fairness.

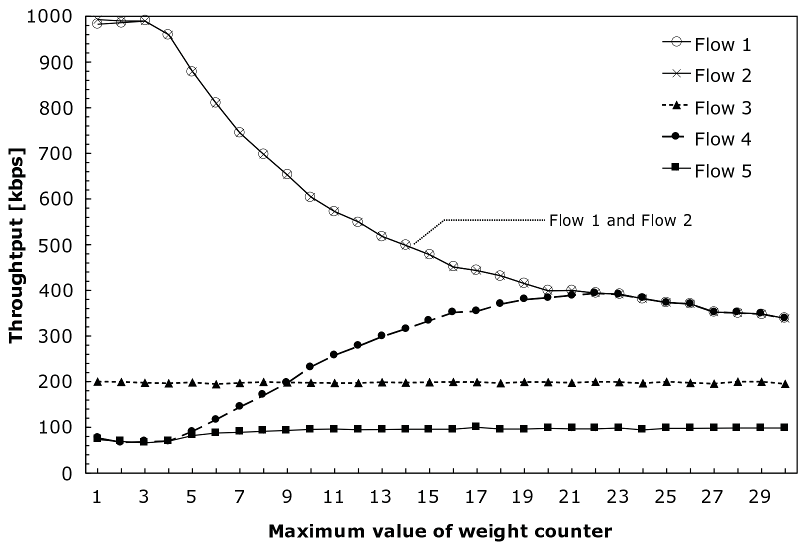


Fig. 11. End-to-end throughput vs. maximum value of weight counter ($t_{wait} = 200$ [μs]).

In terms of Scheme 3, we observe that end-to-end throughputs of all flows are the same and equal to the end-to-end throughput of Flow 5. Note that the offered load at WN5 is the smallest among all the source nodes. This result implies that Scheme 3 achieves high per-flow fairness to maximize the fairness index, however, the resulting overall throughput decreases significantly. This is because all the source nodes except WN5 defer its transmission until it receives a packet from Flow 5.

On the contrary, the end-to-end throughputs of Flows 3 and 5 for the proposed scheme are almost equal to their respective offered loads. In addition, the end-to-end throughputs of the other source nodes are almost the same and larger than those achieved by Scheme 3. This result implies that the proposed scheme significantly improves max-min fairness in comparison with the existing schemes.

4.1.3 Effect of Parameter Adjustment

In this subsection, we investigate how the parameter W_{max} affects the performance of the proposed scheme. Here, the chain topology shown in Figure 9 is considered, and the offered loads at WN3, WN5 and the others are set to 200 [kbps], 100 [kbps] and 1000 [kbps], respectively. t_{wait} is set to 200 [μs].

Figure 11 shows the end-to-end throughput against W_{max}. When W_{max} is small, the end-to-end throughputs of Flow 1 and Flow 2 are the same and reach the highest value among all the end-to-end throughputs. Note that the end-to-end throughput of Flow 4 is almost the same as that of Flow 5 even though the offered load at WN4 is greater than that at WN5. This is because

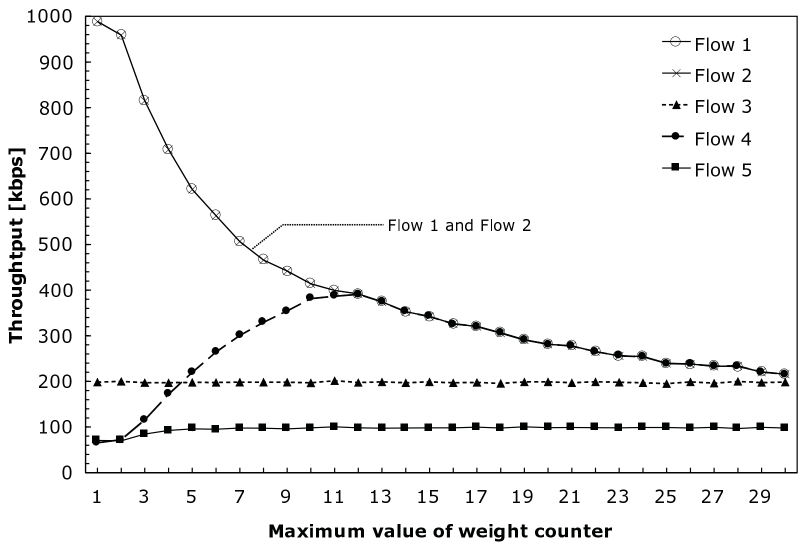


Fig. 12. End-to-end throughput vs. maximum value of weight counter ($t_{wait} = 400$ [μs]).

the proposed scheme for an overloaded network behaves like a probabilistic round-robin scheduling when W_{max} is close to one. More precisely, when the network is overloaded, packets in Flow 4 and those in Flow 5 are likely to be stored at WN4, and all the queues of WN4 are likely to be served equally due to a small W_{max}. As a result, the packet transmission rate of Flow 4 is almost equal to that of Flow 5.

When W_{max} increases, the end-to-end throughputs of Flow 1 and Flow 2 decrease, while the end-to-end throughput of Flow 4 increases and finally coincides with those of Flow 1 and Flow 2 at $W_{max} = 22$. Note that the proposed scheme with this W_{max} value achieves max-min fairness. When W_{max} is greater than 22, however, the end-to-end throughputs of Flow 1, Flow 2 and Flow 4 decrease gradually, while the other two end-to-end throughputs remain constant. This is because the packet scheduler of each node is likely to defer a packet transmission when W_{max} is large.

Next, we investigate the effect of t_{wait} on the max-min fairness. In this experiment, t_{wait} is fixed as 400 [μs]. The other parameters are the same as the previous experiment. Figure 12 represents the end-to-end throughput against W_{max}. In this figure, the optimal value of W_{max} is around 12, which is smaller than that in Fig. 11. We investigated several t_{wait}'s, and found that W_{wax} is inversely proportional to t_{wait} for the network with six-node chain topology [1].

[1] Unfortunately, we also confirmed that the optimal W_{wax} significantly depends on network topology, the number of source nodes, the offered load and the link speed. This implies that W_{max} should be carefully determined with regard to those factors. The systematic approach to determining W_{max} is an open issue and our future work.

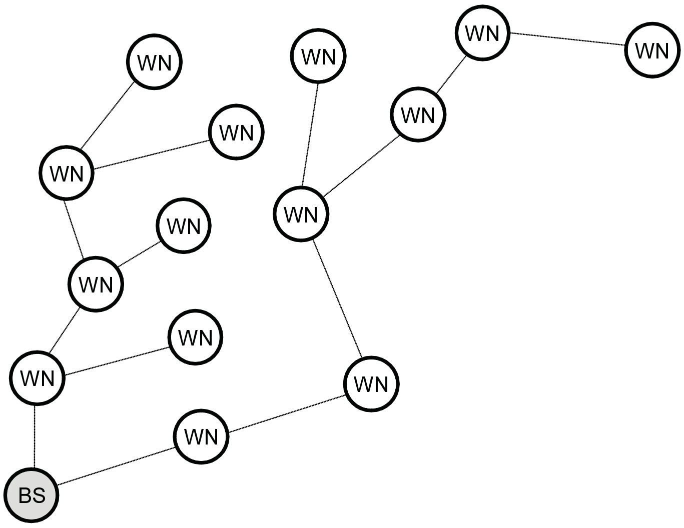


Fig. 13. Sample of generated topologies.

Table 2
Average of fairness indices for the 50 different topologies.

	Proposed scheme	Scheme 2	Scheme 3
Sample average	0.92916	0.74649	0.76627
95% CI	(0.91232, 0.94599)	(0.72865, 0.76434)	(0.74655, 0.78599)

4.2 Random Topology

In this subsection, we investigate the performance of the proposed scheme for random topology in case where the offered loads are homogeneous among nodes. We consider a 500 x 300 [m^2] simulation plane. In this plane, a BS is located at one of four corners and 14 nodes are randomly placed such that each node has no relay node within a 60-meter radius but has at least one relay node within a 110-meter radius. The number of sample planes generated for this simulation experiment is 50. For each simulation plane, the fairness index was calculated for the proposed scheme and Schemes 2 and 3. In terms of the routing protocol, we adopted Destination-Sequenced Distance Vector (DSDV) [8].

Figure 13 shows a sample of automatically generated topology and its communication pathway. Figure 14 shows the fairness indices for the three schemes. The horizontal axis represents the simulation-run number. The offered load at each node is set to 150 [kbps]. It is observed from Figure 14 that in most cases, the fairness index of the proposed scheme is the largest among the three schemes. Table 2 shows the average of the fairness indices and the 95% confidence intervals (CI's) for the simulation results in Figure 14. We observe that the proposed scheme achieves higher fairness than the existing schemes in a random topology. From these results, we can claim that the proposed scheme

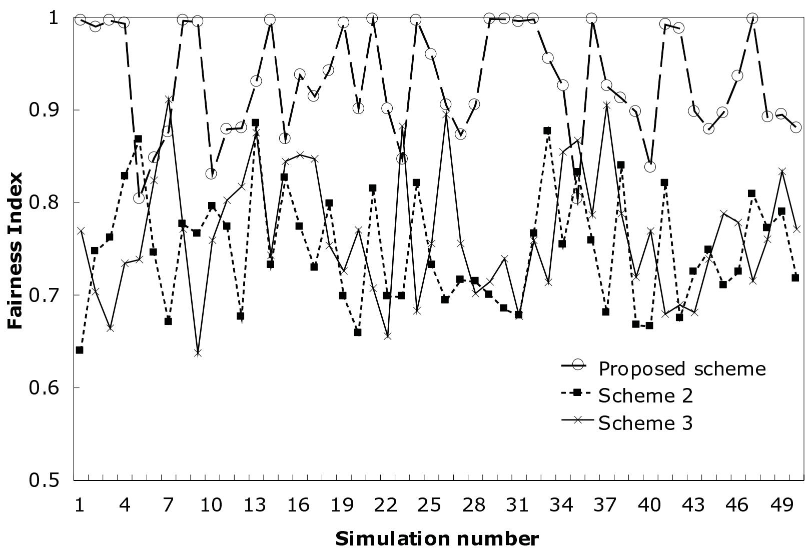


Fig. 14. Fairness indices for the 50 different topologies.

significantly improves the fairness performance for not only chain-topology networks but also random-topology networks.

5 Conclusion

In this paper, we considered the issue of unfairness for the per-flow throughput in IEEE 802.11 multihop wireless LANs. We proposed a probabilistic packet-scheduling scheme in which an autonomous traffic control mechanism is introduced without the modification of the MAC protocol. The performance of the proposed scheme was investigated by ns-2 simulation. From the simulation results, it was observed that the proposed scheme can achieve higher per-flow fairness than the existing schemes in both chain and random topologies. In addition, the proposed scheme can also improve max-min fairness. We also found that in chain-topology networks, the optimal value of the weight counter is inversely proportional to the unit time of deferring. However, finding the optimal weight counter value is currently an open problem, and this is our future work.

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