Switching Methods for Semi-Fixed Rate Control in IEEE 802.11n Wireless Mesh Networks

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***Abstract*—In wireless mesh networks using IEEE 802.11 wireless LAN, it is desirable to select and use an optimum transmission rate for each link. Semi-fixed rate control (SFRC) is a technique that determines an optimum transmission rate during the auto-rate period, and then uses it during the fixed-rate period. However, evaluation of the link quality and determination of the best timing to switch from the fixed-rate period to the auto-rate period are the existing challenges. In addition, IEEE 802.11n, whose throughput performance can be enhanced by employing multiple antennas, is very sensitive to the link quality, and the optimum transmission rate is therefore also sensitive. Thus, the time required to switch from the fixed-rate period to the auto-rate period is more important for IEEE 802.11n. In this paper, we investigate the relationship between the received signal strength indicator (RSSI) of each antenna and the optimum transmission rate, and propose methods for switching from the fixed-rate period to the auto-rate period for SFRC. The experimental results indicate the effectiveness of the proposed methods.**

***Index Terms*—wireless mesh network, transmission rate control, IEEE 802.11n, RSSI**

I. Introduction

Wireless mesh networks (WMNs) are constructed in an autonomously distributed manner, and can be extended only by adding mesh nodes. WMNs attract much attention for their easy and low-cost network construction [1]–[4].

WMNs consist of mesh nodes equipped with wireless LAN interfaces based on IEEE 802.11 [5]. IEEE 802.11 wireless LAN supports multiple transmission rates decided by modulation and coding schemes (MCSs), and can achieve high throughput performance by appropriately controlling the transmission rate according to the link quality. There are two approaches for transmission rate control schemes: auto-rate control (ARC) and fixed-rate control (FRC). ARC adjusts transmission rates to achieve higher throughput performance. For example, auto-rate fallback (ARF) [6] controls the transmission rate according to the previous transmission results. If a certain number of transmissions succeed, the transmission rate is increased. On the other hand, the transmission rate is decreased when some transmissions fail. ARC provides the benefit of automatic adjustment of the transmission rate, but the transmission rate is changed frequently owing to the continuous search for a better one. In addition, ARC cannot always select a suitable transmission rate because of collisions caused by a hidden node problem [7]. On the other hand, FRC use a constant predefined transmission rate. In WMNs, mesh nodes are stationary, and the fluctuation in the link quality is low. By finding the optimum transmission rate to obtain the highest throughput in advance and using it, FRC normally achieves higher throughput than ARC [8]. ARC, however, requires prior measurement of the optimum rate. In addition, the throughput may be degraded if the link quality changes.

To solve these issues, semi-fixed rate control (SFRC) was proposed [9]. SFRC consists of auto-rate and fixed-rate periods. In the auto-rate period, ARC is used to search for the optimum rate without prior measurement. After that, the selected optimum rate is used in the fixed-rate period. In [9], the duration of the auto-rate period is investigated for selecting the optimum transmission rate, but a constant duration of the fixed-rate period is employed. Any change in the link quality is unpredictable. Thus, it is important to evaluate the link quality and determine the best time to switch from the fixed-rate period to the auto-rate period to readjust the transmission rate.

In [9], SFRC was evaluated by IEEE 802.11a/b/g wireless LAN standards alone. Alternately, IEEE 802.11n enhances the throughput performance by employing multiple-input multiple-output (MIMO) technology. MIMO technology enables multi-stream transmission by multiple antennas. The throughput performance of IEEE 802.11n considering multiple transmission rates has been evaluated by simulation [10]. The throughput performance is, however, very sensitive to location, direction, and angle of a wireless LAN interface, so that the optimum transmission rate is also sensitive. Thus, it is be more important for IEEE 802.11n WMNs to determine when to switch from the fixed-rate period to the auto-rate period.

In this paper, we propose three switching methods from the fixed-rate period to the auto-rate period for SFRC in IEEE 802.11n WMNs. The proposed methods use a received signal strength indicator (RSSI). First, we investigate the relationship between RSSI and the optimum transmission rate, and then we develop the switching methods using RSSI. MIMO technology employs multiple antennas, so this paper considers RSSIs of

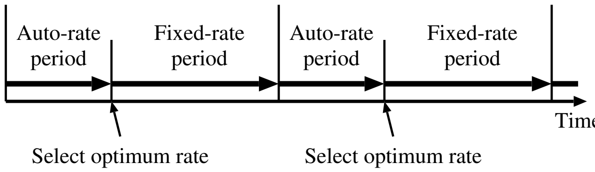


Fig. 1. Semi-fixed rate control.

individual antennas. We then evaluate the proposed methods and evaluate their effectiveness.

The rest of this paper paper is organized as follows. SFRC is briefly explained in II. Throughput and RSSI are experimentally measured, and the relationship between the optimum transmission rate and RSSI is investigated in III. The switching methods from the fixed-rate period to the auto-rate period are proposed, and their performance is evaluated in IV. Finally, this paper is concluded in V.

II. Semi-Fixed Rate Control (SFRC) [9]

This section introduces SFRC briefly. SFRC combines ARC and FRC, and can achieve high throughput performance without prior measurement.

Fig. 1 shows the concept of SFRC. SFRC consists of an auto-rate period and a fixed-rate period. Initially, a node is in the auto-rate period and uses ARC to search for the optimum transmission rate. When the auto-rate period finishes, SFRC determines the optimum transmission rate from the time ratio of each transmission rate that was adjusted by ARC. The most used transmission rate in the auto-rate period is selected as the optimum transmission rate. After determining the optimum transmission rate, the node switches to the fixed-rate period. In the fixed-rate period, the node uses the optimum rate decided in the auto-rate period. In [9], the duration of the fixed-rate period is constant. As mentioned in I, the change in the link quality is unpredictable. If the duration of the fixed-rate period is set too long, the node may miss a change in the link quality and will not use the actual optimum transmission rate. When the duration is set too short, unnecessary auto-rate periods cause throughput degradation because of the overhead caused by ARC. Thus, it is important to provide adequate timing to switch from the fixed-rate period to the auto-rate period.

III. Experimental Measurements of Throughput and RSSI

In this section, the throughput and RSSI are measured experimentally, in order to investigate the relationship between the optimum rate and RSSI. This experiment measures the throughput of all available transmission rates in IEEE 802.11n and the RSSI of each antenna between two nodes. From the measurement results of throughput, the optimum transmission rate is obtained by finding the transmission rate that maximizes the throughput. Since IEEE 802.11n uses multiple antennas, the RSSI of each antenna is individually measured.

TABLE I
Node specifics.

PC	Dell Latitude E5410 Core i5 (2.67 GHz)
wireless LAN interface	NEC Aterm WL300NC (IEEE 802.11n)
distribution	Debian 6.0.6
kernel	2.6.34
wireless LAN driver	modified math9k [11]
measurement tool	iperf 2.04 [12]

(a) Server. (b) Client.

Fig. 2. Server and client.

A. Experiment Setup

Table I shows node specifics used in this experiment. This experiment uses two laptop personal computers (PCs) as nodes, and these nodes are treated as a server and a client for measurements, as shown in Fig. 2. These PCs are equipped with wireless LAN CardBus interfaces, which employ the Atheros chipset based on IEEE 802.11n. These interfaces support both 2.4 and 5 GHz bands and 2×3 MIMO transmission using three built-in antennas; that is, at most two streams can be transmitted. Note that these interfaces do not support a three-stream transmission. A Linux-based operating system is installed in the PCs. The driver for wireless LAN interfaces is modified math9k [11], where an ad-hoc mode for IEEE 802.11n, fixed-rate function, and RSSI measuring of each antenna are added to ath9k [13]. This experiment uses iperf [12] to measure the throughput.

Fig. 3 shows node locations for the experiment, and Table II shows parameters for the experiment. In this experiment, the server and client pair measures the throughput and RSSI by transmitting a probe flow from the client to the server. The server is located on the 10th floor of a building. Although mesh nodes are usually stationary in actuality, the location of the client changes along the dashed line shown in Fig. 3 from the 9th floor to the 10th floor; hence, the link quality is purposely changed. At each location, a sample of the throughput and RSSI is measured. During the measurement of a sample, the client does not move. After the measurement, the client's location is changed to the next measurement sample. The experiment is repeated at four times, and the measurement

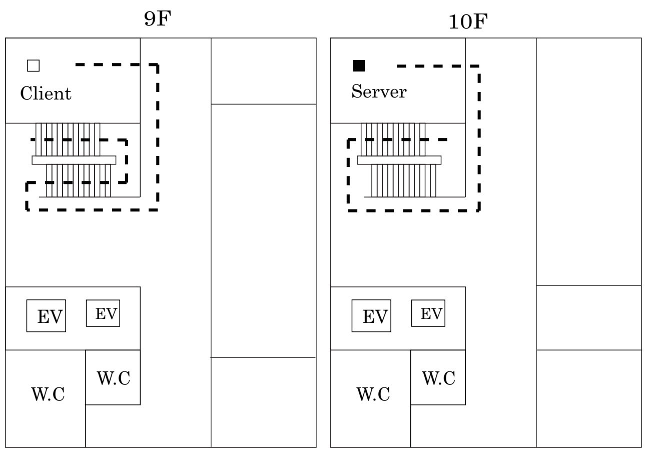


Fig. 3. Node locations for the experiment.

TABLE II
PARAMETERS FOR EXPERIMENT.

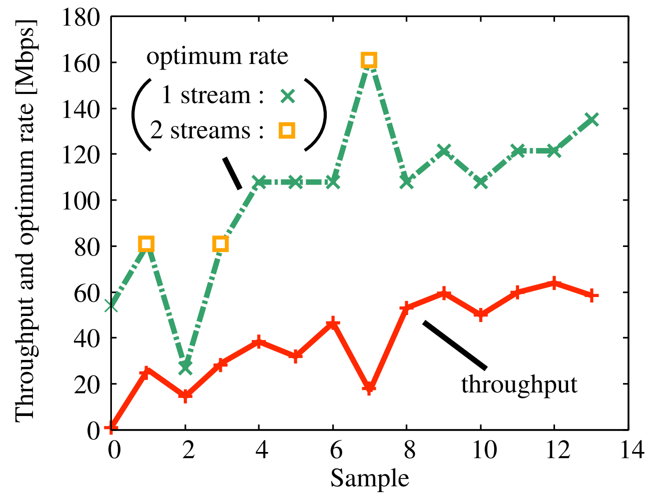
number of experiments	4 (total 70 samples)
measurement duration	5 s
packet size	1,472 bytes
transport protocol	UDP
channel	1 (2.4 GHz band) 36 (5 GHz band)
transmission rate	MCS0 – MCS15 (HT40+ Long GI) MCS7, MCS15 (HT40+ Short GI)

is achieved with a total of 70 samples taken at 70 locations.

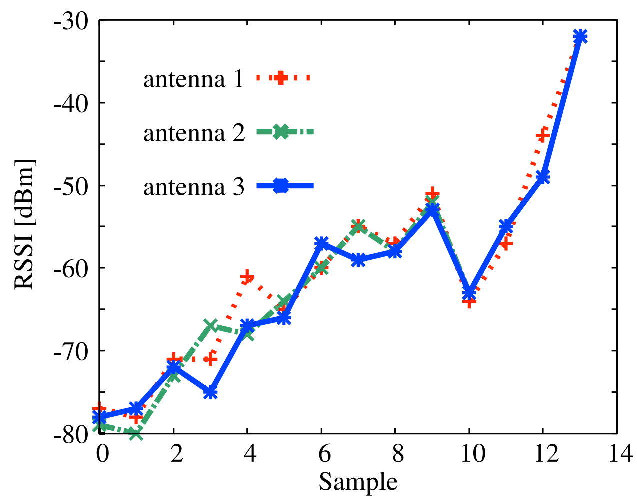
The transport protocol of the probe flow is the user datagram protocol (UDP). Packet size of the probe flow is 1,472 bytes. The channel is 1 for the 2.4 GHz band and 36 for the 5 GHz band. The transmission rates are MCSs 0 to 15 with 40 MHz bandwidth and a long guard interval (GI), and MCSs 7 and 15 with 40 MHz bandwidth and a short GI. MCSs 0 to 7 are one-stream transmissions, and MCSs 8 to 15 are two-stream transmissions. The UDP throughput is measured for 5 s at each channel, each transmission rate, and each sample.

B. Measurement Results

Figs. 4 and 5 show the measurement results of the throughput, optimum transmission rate, and RSSI for the 2.4 and 5 GHz bands, respectively, in one of 4 experiments. In both figures, the optimum transmission rate is plotted with a cross symbol for one stream and with a square for two streams. First, let us focus on the 2.4 GHz band, shown in Fig. 4. For example, RSSI decreases from -50 dBm to -65 dBm between samples 9 and 10, and the optimum transmission rate also decreases from 121.5 Mbps to 108 Mbps. Between samples 10 and 11, RSSI increases from -65 dBm to -55 dBm, and the throughput increases from 108 Mbps to 121.5 Mbps. In the 5 GHz band, relevance between the optimum rate and RSSI is similar to the 2.4 GHz band. The correlation coefficients between the optimum rate and RSSI of each antenna are shown in Table III. From this table, we can confirm a high positive



(a) Throughput and optimum rate.



(b) RSSI.

Fig. 4. Example of measurement result at each sample (2.4 GHz band).

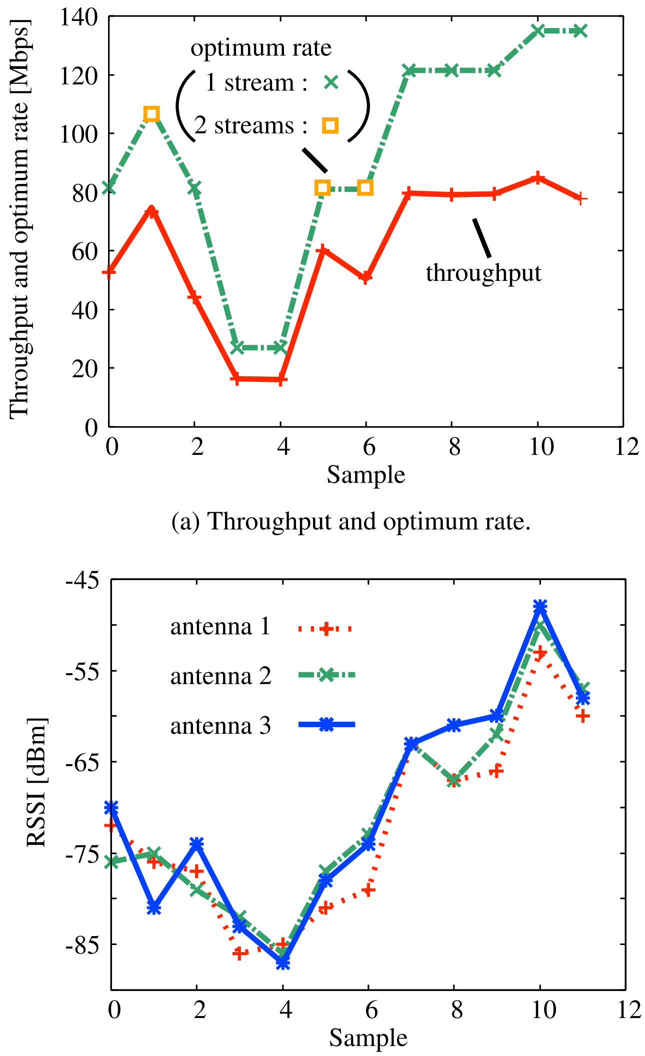
correlation coefficient between the optimum rate and RSSI. Note that the correlation coefficient of the 2.4 GHz band is slightly lower than that of the 5 GHz band. This is because the measured results of the throughput are degraded owing to interference from other wireless devices operating at the same channel.

IV. Switching Methods from Fixed-Rate Period to Auto-Rate Period

From the experimental results in III, the optimum transmission rate has a clear correlation with RSSI. In this section, we propose methods to switch from the fixed-rate period to the auto-rate period by measuring RSSI.

A. Proposed Switching Methods

In the proposed methods, the node switches to the auto-rate period when the RSSI difference between the current sample



(a) Throughput and optimum rate.

(b) RSSI.

Fig. 5. Example of measurement result at each sample (5 GHz band).

TABLE III
CORRELATION COEFFICIENTS.

	antenna 1	antenna 2	antenna 3
2.4 GHz band	0.72	0.74	0.70
5 GHz band	0.90	0.89	0.86

and the previous sample exceeds a predefined threshold. In IEEE 802.11n, multiple antennas are used for multi-stream transmissions. Let $S_k[n]$ in dBm be the RSSI of the nth sample for the kth largest value among the RSSIs of all antennas. Considering RSSIs of multiple antennas, we propose the following three methods.

1) One antenna:
This method considers only the largest value of RSSIs for all antennas. For a one-stream transmission, the throughput will depend mainly on an antenna that has the largest RSSI. When the absolute value of the difference between the largest RSSI of the current sample and that of the previous one is larger than or equal to the predefined threshold T (dB), the node switches to the auto-rate period. This condition can be expressed by

$$|S_1[n] - S_1[n-1]| \geq T. \tag{1}$$

2) Two antennas:
This method uses the RSSIs of two antennas that have the 1st and 2nd largest values; the node transmits packets by using two antennas for a two-stream transmission. When RSSIs of the node satisfy both

$$\begin{aligned} &|S_1[n] - S_1[n-1]| \geq T \text{ and} \\ &|S_2[n] - S_2[n-1]| \geq T, \end{aligned} \tag{2}$$

the node switches to the auto-rate period.

3) Stream number:
This method considers the number of streams for the current transmission rate, and combines methods 1) and 2). When the current transmission rate is a one-stream transmission, method 1) is applied. Otherwise, method 2) is applied. Let $M[n]$ be the MCS of the nth sample. The node switches to the auto-rate period when the following condition is satisfied:

$$\begin{aligned} &\text{If } M[n-1] \in \{\text{MCSs for a one-stream transmission}\}, \\ &\quad |S_1[n] - S_1[n-1]| \geq T. \\ &\text{Otherwise,} \\ &\quad |S_1[n] - S_1[n-1]| \geq T, \text{ and} \\ &\quad |S_2[n] - S_2[n-1]| \geq T. \end{aligned} \tag{3}$$

B. Numerical Results

In this section, the proposed methods are evaluated using the experimental results in III.

First, we evaluate a miss-detection probability and a false alarm probability. The miss-detection probability indicates that the node does not switch to the auto-rate period even if the optimum transmission rate changes from the previous sample to the current sample. The false alarm probability indicates that the node switches to the auto-rate period even if the optimum transmission rate does not change. For each sample measured in III, the node decides whether it switches to the auto-rate period or not according to the proposed methods. By comparing the detection result and the change in the optimum transmission rate, the miss-detection probability and false alarm probability are derived. Since there are many interference sources in the 2.4 GHz band, which will lead to inaccurate values of these probabilities, we evaluate them in the 5 GHz band only.

Fig. 6 shows the relationship between the false alarm probability and the miss-detection probability when the threshold T changes. In this figure, the curves for the proposed three methods are depicted. When the threshold T is low, the false alarm probability is large and the miss-detection probability is small; that is, plots of these curves move to the lower right. The reason is easily understood in that the node tends to switch

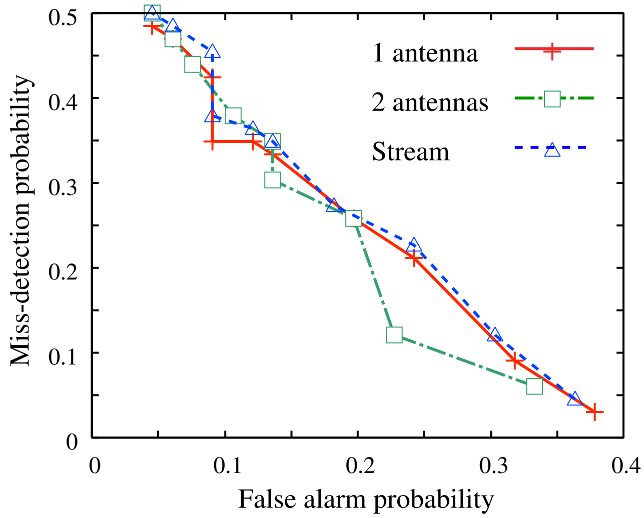


Fig. 6. False alarm probability and miss-detection probability of the proposed methods (5 GHz band).

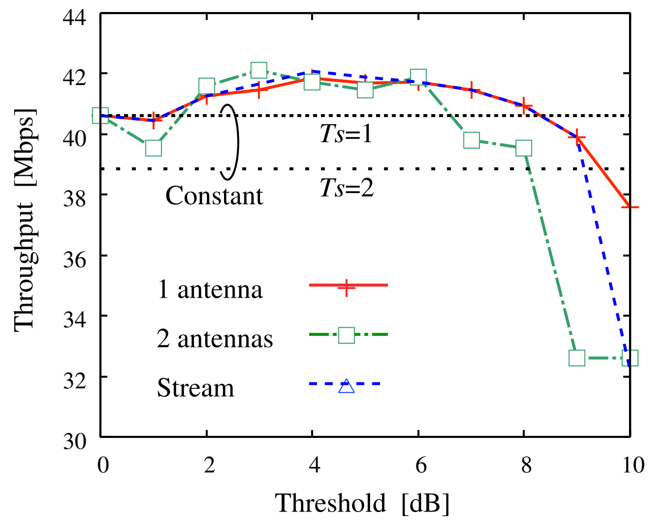


Fig. 7. Throughput as a parameter of threshold (5 GHz band).

to the auto-rate period because the threshold decreases. This figure indicates that the one antenna method and the stream number method have almost the same performance. The two antenna method performs slightly better than the others. Even if the number of streams is one, the node may use more than one antenna for diversity combining. Therefore, the two antenna method may be superior to the other methods.

In the following discussion, we evaluate the throughput performance of the proposed methods. The throughput is also derived from the measured results in III. For each sample, if the node switches to the auto-rate period, it is assumed that the node will select the optimum transmission rate in the auto-rate period. In [8], the overhead of ARC reduces the throughput of the auto-rate period by about 20%. Considering this overhead, the throughput for the optimum transmission rate measured in III is assumed to be reduced by 20%. On the other hand, if the node does not switch to the auto-rate period, the node continues to use the previous transmission rate and the throughput is derived by the measurement result of this transmission rate. The throughput of the conventional method for the constant fixed-rate period is also derived. Let T_S be a multiplier factor for the constant duration of the fixed-rate period. If $T_S = 1$, the node always changes to the auto-rate period for each sample; that is, the duration of the constant fixed-rate period is the same as the sample interval. When $T_S = 2$, the node switches to the auto-rate period every two samples, and so on.

Fig. 7 shows the throughput performance of the proposed methods. The throughput curves for the constant fixed-rate period with $T_S = 1$, and 2 are also depicted in this figure. This figure indicates that there are optimum values for the threshold in the proposed method. These optimum values are between 2 and 3 dB for all proposed methods. For lower thresholds, the false alarm probability increases and causes unnecessary switching to the auto-rate period. For higher thresholds, the miss-detection probability increases and the node tends to use a nonoptimum transmission rate. The highest throughput is almost the same among the three proposed methods. We also note that the highest throughput of the proposed methods is greater than that of the constant fixed-rate periods within a certain range of threshold values. Therefore, the proposed methods should improve throughput performance by detecting the timing of switching from the fixed-rate period to the auto-rate period for SFRC based on RSSI analysis.

V. Conclusions

In this study, we have measured fluctuations in RSSI and their relevance to the optimum transmission rate in IEEE 802.11n WMNs. As a result, it has been determined that the optimum transmission rate and RSSI have a high positive correlation coefficient. On the basis of this high correlation, we have proposed three methods to determine when to switch from the fixed-rate period to the auto-rate period by measuring the RSSI for each antenna. We have also evaluated the performance of the proposed methods through experimental results. For the relationship between the false alarm probability and the miss-detection probability, the one antenna method and the stream number method exhibit almost the same performance, while the two antenna method performs slightly better than the other two methods. By comparing the throughput of the conventional method with constant fixed-rate period, the proposed methods should improve throughput performance when an appropriate threshold is employed.

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