Mitigating Performance Anomaly of TFRC in Multi-Rate IEEE 802.11 Wireless LANs

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***Abstract*—In IEEE 802.11 Distributed Coordination Function (DCF), the multi-rate Basic Service Set (BSS) suffers from the performance anomaly issue, which brings unfairness in terms of channel occupancy time. To solve the issue, this paper presents a rate control scheme for TCP Friendly Rate Control (TFRC) in IEEE 802.11 DCF mode. The proposed scheme controls the sending rate so that each station can use the wireless channel for equal duration. This is based on the channel occupancy period used by each station in BSS, which is monitored at the Media Access Control (MAC) layer. The performance of the proposed scheme over multi-rate IEEE 802.11 DCF is evaluated and compared with that of normal TFRC through several simulations. The simulation results show that the proposed scheme exhibits fairness in terms of channel occupancy time among the competing stations, which accordingly mitigates the performance anomaly. The proposed scheme improves the aggregated throughput in BSS.**

I. Introduction

Nowadays, we can access to the Internet through Wireless Local Area Networks (WLANs) from home, office, and many public places. Most commonly used WLANs are based on IEEE 802.11 standard. In IEEE 802.11, physical (PHY) layer supports multiple data rates. For example, IEEE 802.11a PHY provides eight data rates from 6 Mb/s to 54 Mb/s. IEEE 802.11 Media Access Control (MAC) layer defines two different coordination functions: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The mandatory DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and the optional PCF is based on a centralized polling protocol. Currently, most of the 802.11-compliant products implement only DCF.

In multi-rate IEEE 802.11 WLANs, DCF causes an unfairness issue called performance anomaly [1]. This is because DCF gives approximately equal transmission opportunities to each contending station. When stations with different data rates exist in a Basic Service Set (BSS), stations transmitting at lower data rates occupy the wireless channel for a longer period than those transmitting at higher data rates. This decreases the throughput of all the higher rate stations. Especially in fee-based WLANs such as hotspots, the performance anomaly issue would degrade users' satisfaction. Against the performance anomaly, the authors proposed a new rate control scheme [2] for Transmission Control Protocol (TCP), which is the most dominant transport protocol in today's Internet traffic. However, the performance anomaly issue occurs with regardless of used transport protocols. In this paper, as a solution to the performance anomaly with User Datagram Protocol (UDP)-based applications, we apply the concepts shown in [2] to the rate control in TCP Friendly Rate Control (TFRC) [3]. TFRC is a rate-based congestion control algorithm designed for streaming multimedia contents and provides smooth rate adjustment while keeping fairness with competing TCP flows. In this paper, we also consider the situation where stations have rate-uncontrollable flows such as Constant Bit Rate (CBR) traffic.

This research work proposes a scheme that improves the transmission efficiency of TFRC in multi-rate WLANs based on IEEE 802.11 DCF mode. In the proposed scheme, each station periodically estimates how long it can use the wireless medium, while taking into account the fairness among active stations. This estimation is based on the channel occupancy time used by each station, which is monitored at the MAC layer, with the assistance of information from Access Point (AP). Using this estimation, each station calculates the maximum throughput at the transport layer based on the situation of the lower layers. Finally, TFRC sender accordingly controls the sending rate.

The remainder of the paper is organized as follows. Section II surveys research work related to the performance anomaly problem in IEEE 802.11 DCF and provides a brief introduction to the rate control algorithm in TFRC. Section III introduces the proposed rate control mechanism for TFRC against the performance anomaly issue. In Section IV, we evaluate the performance of the proposed mechanism in a multi-rate WLAN. Finally, Section V concludes the paper by summarizing the achievements of the proposed algorithm.

II. Background

A. *Performance Anomaly*

In IEEE 802.11 WLANs, we can use multiple data transmission rates. The underlying rate adaptation algorithm, such as Automatic Rate Fallback (ARF) [4], selects one of the data transmission rates according to the varying channel conditions. Alternatively, users can manually select the data transmission rates.

When multiple stations transmit frames using different data rates in a multi-rate WLAN, the BSS suffers the performance anomaly issue. The lower data transmission rate requires longer duration to transmit the same amount of data than the higher one. Since the DCF gives approximately equal transmission opportunities to each competing station, lower rate stations occupy the medium longer than higher one. The

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throughput of a station in the case of sharing the channel with lower rate stations becomes lower than that in the case of sharing with the same rate stations. The aggregated throughput in BSS is thus degraded.

To restore fairness, we need to decrease the transmission of frames transmitted from/to lower rate stations. The majority of the solutions in the recent literature manipulate one or more of the parameters defined in the Enhanced Distributed Channel Access (EDCA) function of IEEE 802.11e, which provides a Quality of Service (QoS) extension of DCF. Note that 802.11e itself cannot solve this unfairness issue. The approaches proposed in [5]–[9] set the minimum (initial) contention window ($CW_{\min}$) to values larger for lower rate stations than those set for higher rate stations, which decreases the channel access probability. The schemes shown in [9] and [10] utilize the transmission opportunity (TXOP) limit. In these schemes, higher rate stations can consecutively transmit multiple frames at intervals of short interframe space (SIFS), while lower rate stations may be required to fragment frames. All approaches discussed above create the same concern that lower rate stations suffer longer end-to-end delays. Additionally, EDCA parameters should not be used against the performance anomaly issue. These parameters are arranged for QoS differentiation, especially for delay-sensitive traffic such as voice/video applications.

The approaches presented in [6] and [11] adjust the frame length or the Maximum Transmission Unit (MTU) to equalize the channel occupancy time of each station. However, in these approaches, lower rate stations are required to transmit frames with short length. This increases the number of frames to transmit the same amount of data and thus decreases the effective throughput at the application layer due to the overhead of protocol headers. They could also intensify the contention among stations. Additionally, they cannot handle the cases where a higher rate station uses short frames, which may contain Voice over Internet Protocol (VoIP) packets. Some other schemes [12]–[14] schedule the frame transmission so that each station equally occupies the medium. These schedulers could cause longer delay and packet drops in traffic of lower rate stations.

B. TFRC

TFRC is a congestion control mechanism for unicast streaming. It achieves reasonable fairness in terms of throughput with competing TCP flows. In TFRC, data receivers periodically send a feedback packet, which contains the estimated information such as the data receiving rate (X_{recv}) and the loss event rate (p). Upon receiving a feedback packet, TFRC sender updates the allowed sending rate (X) based on the information contained in the feedback report as follows.

$$X = \begin{cases} \min(2 \cdot X,\, 2 \cdot X_{\text{recv}}), & p = 0 \\ \min(X_{\text{Bps}},\, 2 \cdot X_{\text{recv}}), & p > 0 \end{cases} \tag{1}$$

where X_{Bps} denotes the estimated average transmission rate of TCP. This estimation is currently based on the throughput equation of TCP Reno. Note that the above equation (1) is simplified from [3] for convenience of explanation.

The work shown in [15] describes poor performance of TFRC in wireless links and proposes an enhancement of TFRC based on TCP Veno. Mobile TFRC [16] decreases packet losses by limiting the sending rate to the estimated available throughput in WLANs. However, these papers do not touch on the performance anomaly issue.

III. Proposed Rate Control for TFRC in IEEE 802.11 DCF

If each competing station uses the wireless channel for equal duration, the performance anomaly issue can be solved. In this section, we propose a channel occupancy time based rate control for TFRC. The proposed scheme controls the sending rate on the basis of the throughput estimated at the transport layer so that each station can equally use the medium. Information about the channel occupancy duration monitored at MAC layer is used to adjust the sending rate in TFRC, which forms a cross-layer design.

A. Information used in the proposed scheme

Prior to transmitting a beacon, AP obtains the following information on the recent T [s]. T is the interval required to transmit n beacon frames. We describe this period as an observation slot.

- S: Set of active stations in the BSS.
- p_i: Ratio of channel occupancy time of station STA$_i$ to T ($i \in S$).
- p_{beacon}: Ratio of channel occupancy time of AP for transmitting beacon frames to T.
- $\bar{t}_{\text{BO}_{\text{AP}}}$: Average backoff time when AP transmits frames [s].
- $S_{\text{unsatisfied}}$: Set of unsatisfied stations (to be described).

The active station refers to a station actually transmitting or receiving frames, not only associating with AP. The set of active stations can be estimated by monitoring which station transmits Request To Send (RTS), Clear To Send (CTS), DATA, or acknowledgment (ACK) frames during the observation period. The channel occupancy time of a station is the duration required to transmit or receive DATA frames. It also includes the interframe spaces, the backoff periods, and the duration for control frames. Fig. 1 describes the channel occupancy time of a station (STA) transmitting or receiving a DATA frame with the RTS/CTS option. In this figure and throughout this paper, t_{DIFS} and t_{SIFS} denote the lengths of DCF interframe space (DIFS) and SIFS, respectively. t_{RTS}, t_{CTS}, t_{DATA}, and t_{ACK} are the duration for transmitting or receiving a RTS frame, a CTS frame, a DATA frame, and an ACK frame, respectively. When stations upload DATA frames, since AP does not know the average backoff time of STA ($\bar{t}_{\text{BO}_{\text{STA}}}$), AP uses $\bar{t}_{\text{BO}_{\text{AP}}}$ instead of $\bar{t}_{\text{BO}_{\text{STA}}}$ to calculate the channel occupancy time. This assumption is based on the fact that AP and upload stations contend to transmit frames.

Upon receiving a beacon frame, stations periodically obtain the following information on the recent T [s]. T is the interval

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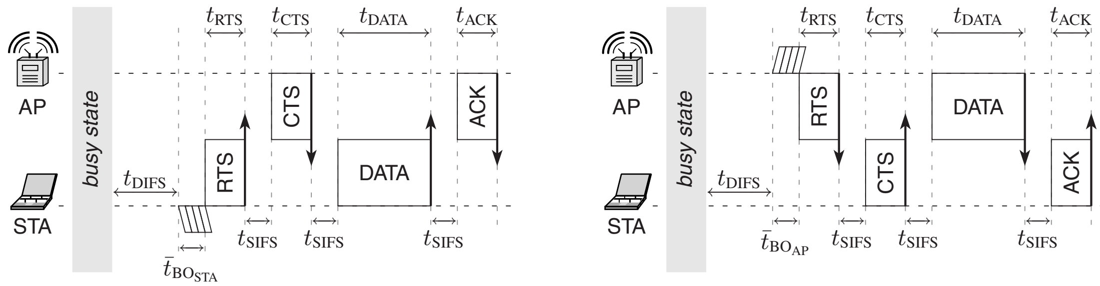

(a) STA transmits a DATA frame.

(b) STA receives a DATA frame.

Fig. 1. Calculation of the channel occupancy time of a station STA transmitting or receiving a DATA frame with the RTS/CTS option.

required to receive n beacon frames. In the remainder of this section, we describe the procedures performed by a station STA_x ($x \in S$).

R_x:	Set of rate-controllable flows [e.g., TCP or TFRC traffic] of STA_x.
U_x:	Set of rate-uncontrollable flows [e.g., CBR traffic] of STA_x.
C_{TX_x}:	Data transmission rate of STA_x [b/s].
C_{RX_x}:	Data reception rate of STA_x [b/s].
$\pi_{x,j}$:	Ratio of channel occupancy time used by flow_j of STA_x to T ($j \in R_x$).
$v_{x,j}$:	Sending or receiving rate of flow_j of STA_x [packet/s] ($j \in U_x$).
$\bar{t}_{\mathrm{BO_{STA_x}}}$:	Average backoff time when STA_x transmits frames [s].
$\bar{\lambda}_{\mathrm{data}_{x,j}}$:	Average payload size of data packets transmitted or received by flow_j of STA_x [B] ($j \in R_x \cup U_x$).
$\bar{\lambda}_{\mathrm{FB}_{x,j}}$:	Average payload size of feedback packets transmitted or received by flow_j of STA_x [B] ($j \in R_x$).
$\mathit{RTT}_{x,j}$:	Round Trip Time (RTT) of flow_j of STA_x [s] ($j \in R_x$).
$R_{\mathrm{unsatisfied}_x}$:	Set of unsatisfied flows (to be described).

B. Estimation of the available channel occupancy time

When transmitting a beacon frame, by using the information obtained in the recent observation slot, AP calculates the ratio of the available duration in BSS to the length of the observation slot (T).

$$p_{\text{available}} = 1 - p_{\text{beacon}} \tag{2}$$

The proposed algorithm attempts to evenly allocate this available duration among the active stations. Therefore, the ratio of the allocated duration for each station to T is temporarily given by the following equation.

$$p_{\text{even}} = p_{\text{available}}/|S| \tag{3}$$

where $|S|$ denotes the number of the active stations. On the other hand, BSS may have an unoccupied duration. The ratio of the unused duration to T is equal to:

$$p_{\text{remain}} = p_{\text{available}} - \sum_{i \in S} p_i. \tag{4}$$

The proposed algorithm allocates this remaining duration evenly among the unsatisfied stations. Here, an "unsatisfied station" is the station that meets the following criterion.

$$p_i \geq r \cdot p_{\text{even}}, \quad (0 < r < 1) \tag{5}$$

where r is a threshold that defines the satisfaction level of a station. AP finds a set of unsatisfied stations as $S_{\text{unsatisfied}}$ based on (5). The ratio of the additional duration for each unsatisfied station to T is calculated as:

$$p_{\text{additional}} = p_{\text{remain}}/|S_{\text{unsatisfied}}|. \tag{6}$$

AP broadcasts these fractions (i.e., p_{even} and $p_{\text{additional}}$) and the average backoff time ($\bar{t}_{\mathrm{BO_{AP}}}$) to stations using beacon frames. They are respectively expressed in 16 bits and thus increase the length of beacon frame by six bytes. For p_{even} and $p_{\text{additional}}$, we take the integer part after multiplexing the fractions by 65 535. $\bar{t}_{\mathrm{BO_{AP}}}$ is described in microseconds.

Upon receiving a beacon frame, each station estimates how long it can use the wireless channel for its flows based on (7)–(15). Basically, each station sets the ratio of the available duration to T to p_{even}. If STA_x is unsatisfied with its channel occupancy time, $p_{\text{additional}}$ is added to the ratio of the usable duration to T. This decision is based on (5) as in AP. The ratio of the available duration for STA_x to T is thus given as follows.

$$p_{\text{available}_x} = \begin{cases} p_{\text{even}} & \{x \mid x \notin S_{\text{unsatisfied}}\} \\ p_{\text{even}} + p_{\text{additional}} & \{x \mid x \in S_{\text{unsatisfied}}\} \end{cases} \tag{7}$$

Each station allocates this available duration among its flows depending on the situation or user's demand. In this paper, we assume that STA_x evenly allocates $p_{\text{available}_x}$ among its flows. If the station cannot control the sending rate of some flows, it saves durations for these flows. The duration required for each rate-uncontrollable flow in an observation slot is given by the following equation.

$$T_{\mathrm{UC}_{x,j}} = v_{x,j} \cdot T \cdot T_{\text{data}}\big(C_{\text{data}_x}, \bar{t}_{\mathrm{BO_{data_x}}}, \bar{\lambda}_{\text{data}_{x,j}}\big) \tag{8}$$

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where $T_{\text{data}}(C, t_{\text{BO}}, \lambda)$ denotes the time required for transmitting or receiving a packet with payload size λ at data rate C. With the RTS / CTS option, $T_{\text{data}}(\cdot)$ is expressed as follows.

$$T_{\text{data}}(C, t_{\text{BO}}, \lambda) = t_{\text{DIFS}} + t_{\text{BO}} + t_{\text{RTS}} + t_{\text{SIFS}} + t_{\text{CTS}} + t_{\text{SIFS}} + t_{\text{DATA}}(C, \lambda) + t_{\text{SIFS}} + t_{\text{ACK}}(C) \quad (9)$$

When STA_x is the receiver, $C_{\text{data}_x} = C_{\text{RX}_x}$ and $\bar{t}_{\text{BO}_{\text{data}_x}} = \bar{t}_{\text{BO}_{\text{AP}}}$. Otherwise, $C_{\text{data}_x} = C_{\text{TX}_x}$ and $\bar{t}_{\text{BO}_{\text{data}_x}} = \bar{t}_{\text{BO}_{\text{STA}_x}}$. The ratio of the duration required for each rate-uncontrollable flow to T is accordingly given by:

$$\hat{\pi}_{x,j} = T_{\text{UC}_{x,j}}/T = v_{x,j} \cdot T_{\text{data}}\left(C_{\text{data}_x}, \bar{t}_{\text{BO}_{\text{data}_x}}, \bar{\lambda}_{\text{data}_{x,j}}\right). \quad (10)$$

The ratio of unused duration in STA_x to T is estimated as:

$$p_{\text{remain}_x} = p_{\text{available}_x} - \sum_{j \in R_x} \pi_{x,j} - \sum_{j \in U_x} \hat{\pi}_{x,j}. \quad (11)$$

STA_x allocates this unused duration among the unsatisfied flows ($R_{\text{unsatisfied}_x}$), which meet the following criterion.

$$\pi_{x,j} \geq r \cdot \pi_{\text{even}_x} \quad \{j \mid j \in R_x\} \quad (12)$$

where,

$$\pi_{\text{even}_x} = \left(p_{\text{available}_x} - \sum_{j \in U_x} \hat{\pi}_{x,j}\right) / |R_x|. \quad (13)$$

Finally, the ratio of the available duration for each rate-controllable flow of STA_x to T is calculated as follows:

$$\pi_{\text{available}_{x,j}} = \begin{cases} \pi_{\text{even}_x} & \{j \mid j \notin R_{\text{unsatisfied}_x}\} \\ \pi_{\text{even}_x} + \pi_{\text{additional}_x} & \{j \mid j \in R_{\text{unsatisfied}_x}\} \end{cases} \quad (14)$$

where,

$$\pi_{\text{additional}_x} = p_{\text{remain}_x} / |R_{\text{unsatisfied}_x}|. \quad (15)$$

The stations then estimate the maximum throughput at the transport layer for each rate-controllable flow, as it will be described in the next section.

C. Estimation of the maximum throughput

Upon recalculating the available duration ratio ($\pi_{\text{available}_{x,j}}$) or detecting change in one's data rate (C_{TX_x} or C_{RX_x}) at the MAC layer according to the rate adaptation algorithm (e.g., ARF algorithm), a station STA_x estimates the maximum throughput of each flow. It should be noted that when switching the data rate, STA_x calculates the maximum throughput using the ratio of the available duration computed in the previous observation slot, as a new observation slot is not determined yet.

Since TFRC feedback packets are normally sent once per RTT, the duration required for feedback packets in an observation slot is calculated as follows.

$$T_{\text{FB}_{x,j}} = \frac{T}{RTT_{x,j}} \cdot T_{\text{data}}\left(C_{\text{FB}_x}, \bar{t}_{\text{BO}_{\text{FB}_x}}, \bar{\lambda}_{\text{FB}_{x,j}}\right) \quad (16)$$

When STA_x is the receiver, $C_{\text{FB}_x} = C_{\text{TX}_x}$ and $\bar{t}_{\text{BO}_{\text{FB}_x}} = \bar{t}_{\text{BO}_{\text{STA}_x}}$. Otherwise, $C_{\text{FB}_x} = C_{\text{RX}_x}$ and $\bar{t}_{\text{BO}_{\text{FB}_x}} = \bar{t}_{\text{BO}_{\text{AP}}}$. The ratio of the available duration for data packets in each TFRC flow of STA_x is thus given by the following equation.

$$\pi_{\text{data}_{x,j}} = \pi_{\text{available}_{x,j}} - \frac{T_{\text{data}}\left(C_{\text{FB}_x}, \bar{t}_{\text{BO}_{\text{FB}_x}}, \bar{\lambda}_{\text{FB}_{x,j}}\right)}{RTT_{x,j}} \quad (17)$$

The maximum throughput that can be achieved by each flow of STA_x is estimated as follows.

$$\theta_{x,j} = \frac{\bar{\lambda}_{\text{data}_{x,j}}}{T_{\text{data}}\left(C_{\text{data}_x}, \bar{t}_{\text{BO}_{\text{data}_x}}, \bar{\lambda}_{\text{data}_{x,j}}\right)} \cdot \pi_{\text{data}_{x,j}} \quad (18)$$

D. Adjustment of the sending rate

The proposed scheme limits the sending rate to the estimated maximum throughput. When STA_x is the receiver, it notifies the estimated throughput to the corresponding sender. In the proposed scheme, it writes the half of the calculated throughput ($\theta_{x,j}/2$) into the X_{recv} field in the TFRC feedback packets, which originally indicates the actual receiving rate. As described in Section II-B, since TFRC sender typically sets its sending rate to the minimum of X_{Bps} and $2 \cdot X_{\text{recv}}$ or the minimum of $2 \cdot X$ and $2 \cdot X_{\text{recv}}$, the sending rate is bounded by $\theta_{x,j}$. Otherwise, when STA_x is the sender, STA_x simply limits the sending rate in flow_j to the calculated $\theta_{x,j}$.

For TCP connections, each station controls the sending rate as shown in [2].

IV. PERFORMANCE EVALUATION

We carried out several simulations using QualNet 4.5 [17] and compared the performance of the proposed scheme against that of normal TFRC. In this work, we implemented TFRC over Real-time Transport Protocol (RTP) and UDP (i.e., TFRC/RTP/UDP/IP) based on the IETF draft [18]. Actually, it has already expired but is informative to define the format of TFRC packets. It should be noted that the idea of the proposed scheme can be applied for Datagram Congestion Control Protocol (DCCP) [19] with Congestion Control Identifier (CCID) 3 [20].

Fig. 2 depicts the configuration of the considered network. In our simulations, we model an IEEE 802.11a (5.2 GHz) BSS. We use the two-ray propagation model and the constant shadowing model without fading. The distance from AP to

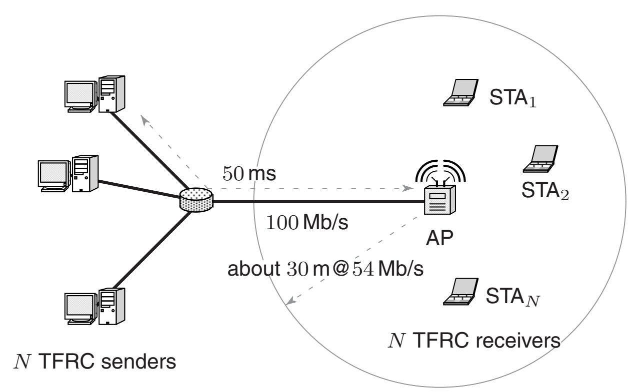

Fig. 2. Simulated network topology.

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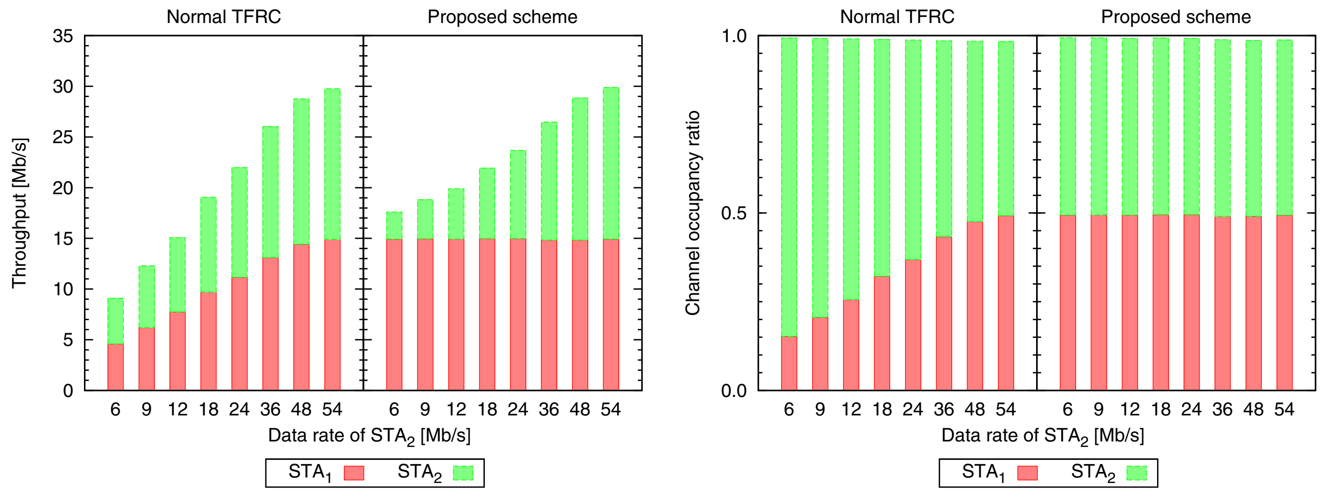

(a) Throughput.

(b) Channel occupancy ratio.

Fig. 3. STA_1 and STA_2 respectively download a file. While the data rate of STA_1 is fixed at $54\,\text{Mb/s}$, that of STA_2 is varied from $6\,\text{Mb/s}$ to $54\,\text{Mb/s}$.

each station is fixed to $10\,\text{m}$, where they can transmit/receive frames at the data rate of $54\,\text{Mb/s}$. The data rate varies with scenarios. The RTS/CTS option is always disabled (i.e., RTS threshold is fixed to 2346).

In our scenarios, each station has only a single TFRC flow. N stations download a file from different servers. IP packet size is set to $1500\,\text{B}$. The link delays from the TFRC senders to AP are $50\,\text{ms}$. Since all wired links have more bandwidth ($100\,\text{Mb/s}$) than the wireless ones, congestion does not occur in the wired links. IP router buffer sizes are set to $150\,\text{kB}$. In the proposed scheme, n and r are empirically set to 3 and 0.8, respectively. Since the beacon interval is set to $100\,\text{ms}$, the length of an observation slot (T) is $300\,\text{ms}$. The total simulation time is set to $600\,\text{s}$. The other parameters are set to the default values as specified in QualNet. All results are an average of multiple simulation runs.

As the first step, to demonstrate how the proposed scheme copes with the performance anomaly issue, we examine the performance in some characteristic situation. In this scenario, there are only two competing stations, STA_1 and STA_2, in BSS ($N = 2$). While the data rate of STA_1 is fixed to $54\,\text{Mb/s}$, that of STA_2 is varied from $6\,\text{Mb/s}$ to $54\,\text{Mb/s}$. This configuration simulates the case where users manually choose their own data rates. Fig. 3 depicts the throughput and the channel occupancy ratio of each flow when both stations download a file. Here, the channel occupancy ratio of a flow denotes the ratio of its channel occupancy time to the simulation time. In normal TFRC, both stations obtain almost the same throughput regardless of their data rates. However, as described in Section II-A, the throughput of STA_1 decreases if STA_2 uses a lower data rate. This also decreases fairness among stations in terms of channel occupancy time. On the other hand, the proposed scheme allows stations to occupy almost the same duration regardless of their data rates. Therefore, even if STA_2 uses a lower data rate, the throughput of STA_1 is not affected. Accordingly, the aggregated throughput in the proposed scheme is higher than that in normal TFRC. Even when both stations use the same data rate ($54\,\text{Mb/s}$), the proposed scheme gives a little higher throughput than normal TFRC due to reduction in packet drops.

Secondly, we evaluate the performance in scenario where the BSS has more stations. N is varied from one to 20. Each station randomly chooses the data transmission rate from 6, 9, 12, 18, 24, 36, 48, $54\,\text{Mb/s}$ in each simulation. Fig. 4(a) shows the aggregated throughput of all stations in BSS. Fig. 4(b) depicts the fairness in terms of channel occupancy during the entire simulation time. Based on Jain's fairness index [21], we use the following metric as the fairness in terms of channel occupancy time.

$$f = \frac{\left(\sum_{i=1}^{N} t_i\right)^2}{N \sum_{i=1}^{N} t_i^2} \tag{19}$$

where t_i denotes the channel occupancy time used by STA_i. The closer the index is to one, the more fairness the system exhibits in terms of channel occupancy. Fig. 4(c) represents the average packet drop ratio per station. Each one is calculated as the ratio of dropped TFRC data packets to transmitted TFRC data packets.

As shown in Fig. 4, the proposed scheme exhibits better performance than the normal TFRC also in these situations. The proposed scheme remedies the performance anomaly and exhibits good fairness in terms of channel occupancy. Additionally, the proposed scheme decreases the packet drops. The better performance of the proposed scheme is due to the fact that a TFRC sender controls its sending rate based on the number of competing stations and its own data rate at the MAC layer. It accordingly achieves higher total throughput than the normal TFRC.

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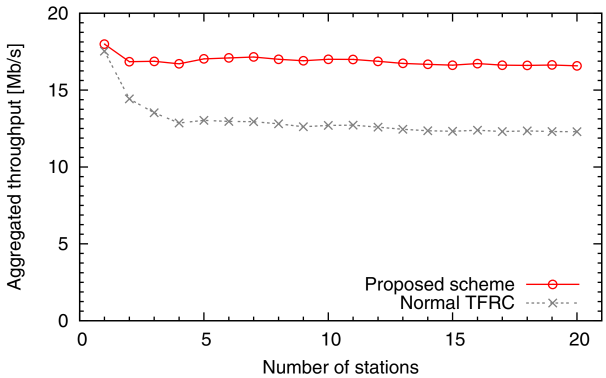
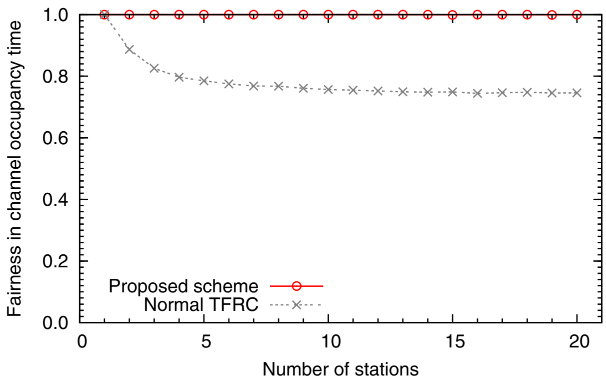
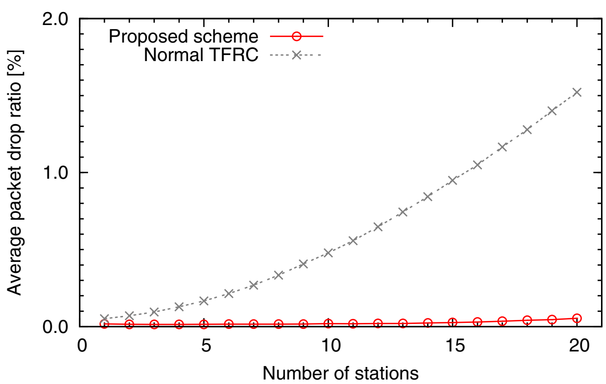


(a) Aggregated throughput in BSS.



(b) Fairness index in terms of channel occupancy time.



(c) Average packet drop ratio.

Fig. 4. A number of stations download a file. Each station randomly chooses its own data rate in the beginning of each simulation run.

V. Conclusion

This paper proposed a new rate adjustment algorithm for TFRC to mitigate the performance anomaly issue in multi-rate IEEE 802.11 DCF. The proposed scheme utilizes the channel occupancy of stations monitored at the MAC layer. In the proposed scheme, each station periodically estimates the maximum throughput available for each flow. TFRC sender then controls the sending rate based on the estimated throughput.

Performance of the proposed scheme was evaluated through several simulations using a simple IEEE 802.11a BSS and was compared with that of the normal TFRC. Simulation results have demonstrated that the proposed scheme could remedy the performance anomaly problem. The proposed scheme improves the aggregated throughput in BSS and the fairness in terms of channel occupancy among the competing stations.

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References

[1] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, “Performance anomaly of 802.11b,” in *Proc. IEEE INFOCOM*, vol. 2, San Francisco, CA, Mar./Apr. 2003, pp. 836–843.

[2] K. Kashibuchi, T. Taleb, Y. Nemoto, and N. Kato, “Channel occupancy time based TCP rate control for IEEE 802.11 DCF,” in *Proc. IWCMC*, Crete Island, Greece, Aug. 2008, pp. 932–937.

[3] S. Floyd, M. Handley, J. Padhye, and J. Widmer, “TCP friendly rate control (TFRC): Protocol specification,” RFC 5348, Sep. 2008.

[4] A. Kamerman and L. Monteban, “WaveLAN®-II: A high-performance wireless LAN for the unlicensed band,” *Bell Labs Tech. J.*, vol. 2, no. 3, pp. 118–133, summer 1997.

[5] H. Kim, S. Yun, I. Kang, and S. Bahk, “Resolving 802.11 performance anomalies through QoS differentiation,” *IEEE Commun. Lett.*, vol. 9, no. 7, pp. 655–657, Jul. 2005.

[6] D. Yang, T. Lee, K. Jang, J. Chang, and S. Choi, “Performance enhancement of multirate IEEE 802.11 WLANs with geographically scattered stations,” *IEEE Trans. Mobile Comput.*, vol. 5, no. 7, pp. 906–919, Sep. 2006.

[7] A. Babu and L. Jacob, “Fairness analysis of IEEE 802.11 multirate wireless LANs,” *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 3073–3088, Sep. 2007.

[8] T. Joshi, A. Mukherjee, Y. Yoo, and D. Agrawal, “Airtime fairness for IEEE 802.11 multirate networks,” *IEEE Trans. Mobile Comput.*, vol. 7, no. 4, pp. 513–527, Apr. 2008.

[9] A. Banchs, P. Serrano, and H. Oliver, “Proportional fair throughput allocation in multirate IEEE 802.11e wireless LANs,” *Wireless Netw.*, vol. 13, no. 5, pp. 649–662, Oct. 2007.

[10] I. Tinnirello and S. Choi, “Temporal fairness provisioning in multi-rate contention-based 802.11e WLANs,” in *Proc. IEEE WoWMoM*, Taormina, Italy, Jun. 2005, pp. 220–230.

[11] J. Dunn, M. Neufeld, A. Sheth, D. Grunwald, and J. Bennett, “A practical cross-layer mechanism for fairness in 802.11 networks,” *Mobile Netw. and Appl.*, vol. 11, no. 1, pp. 37–45, Feb. 2006.

[12] G. Tan and J. Guttag, “Time-based fairness improves performance in multi-rate WLANs,” in *Proc. USENIX*, Boston, MA, Jun. 2004, pp. 269–282.

[13] R. G. Garroppo, S. Giordano, S. Lucetti, and L. Tavanti, “Providing air-time usage fairness in IEEE 802.11 networks with the deficit transmission time (DTT) scheduler,” *Wireless Netw.*, vol. 13, no. 4, pp. 481–495, Aug. 2007.

[14] Y. Seok, T. Kwon, Y. Choi, and J. Bonnin, “Temporal fairness guarantee in multi-rate wireless LANs for per-flow protection,” *Wireless Netw.*, vol. 13, no. 2, pp. 237–258, Apr. 2007.

[15] B. Zhou, C. P. Fu, C. T. Lau, and C. H. Foh, “An enhancement of TFRC over wireless networks,” in *Proc. IEEE WCNC*, Hong Kong, China, Mar. 2007, pp. 3019–3024.

[16] L. Zhang, P. Senac, E. Lochin, and M. Diaz, “Mobile TFRC: a congestion control for WLANs,” in *Proc. WoWMoM*, Newport Beach, CA, Jun. 2008, pp. 1–4.

[17] Scalable Network Technologies, Inc. Qualnet. [Online]. Available: http://www.scalable-networks.com/

[18] L. Gharai, “RTP with TCP friendly rate control (TFRC),” IETF Internet draft, draft-ietf-avt-tfrc-profile-10.txt, Jul. 2007.

[19] E. Kohler, M. Handley, and S. Floyd, “Datagram congestion control protocol (DCCP),” RFC 4340, Mar. 2006.

[20] S. Floyd, E. Kohler, and J. Padhye, “Profile for datagram congestion control protocol (DCCP) congestion control ID 3: TCP-friendly rate control (TFRC),” RFC 4342, Mar. 2006.

[21] R. Jain, A. Durresi, and G. Babic, “Throughput fairness index: An explanation,” ATM_Forum/99-0045, Feb. 1999.