Throughput and QoS Improvement of Wireless LAN System Employing Radio over Fiber

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Abstract

There are many wireless devices in our society, and new wireless communication standards are continuously appearing. It is annoying for users and also difficult for some to keep up with technology standard changes. Applying radio-over-fiber (RoF) technologies to wireless local area network (WLAN) systems is one possible solution to this problem. However, these systems contain an optical fiber cable, which has a non-negligible propagation delay for IEEE 802.11-based WLANs. This delay caused by optical transmission degrades the throughput and quality-of-service (QoS) of a WLAN system. In this paper, we describe a novel method to resolve this problem and demonstrate its effectiveness using computer simulations. We show that the proposed method provides approximately double the total throughput and provides an uplink and downlink frame-rate ratio of one regardless of the optical fiber propagation delay or the number of stations (STAs).

1. Introduction

There are many wireless appliances in use today that are compatible with a variety of communication standards, and new standards are frequently defined. A radio-over-fiber (RoF) scheme [1] is a possible solution to keep up with these changing standards. As shown in Fig.1, a wireless local area network (WLAN) with a RoF system is created by connecting all appliances in the home area network (HAN) of a customer to a central office with an optical fiber. The existing access point (AP) is replaced by a radio-frequency (RF) unit composed of an antenna, amplifiers, analog-to-digital (AD)/digital-to-analog (DA) converters, and an interface circuit. The other physical (PHY) and media-access-control (MAC) functions of the existing AP are moved to the central office's facility.

This system reduces the operating cost of the customer's appliances by updating the functions at the central office's facility only when new WLAN-standard-based appliances are introduced. When using this system, there are some problems caused by the propagation delay of the optical fiber between the customer and the central office. We have already solved one of these problems, i.e., collision of ACK frames with other frames, by extending the network allocation vector (NAV) [2]. However, even with this approach, there remains a fairness problem between the uplink and the downlink.

This paper discusses the fairness problem caused by the propagation delay and proposes a new method to solve this issue. We confirm the effectiveness of the proposed method by using computer simulations.

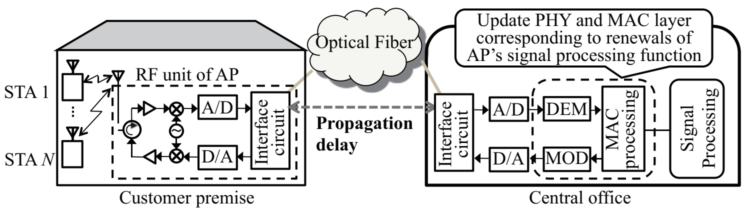


Fig. 1 WLAN system with RoF.

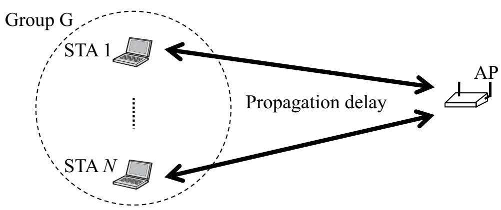


Fig. 2 Equivalent model of RoF system.

2. System Model

We consider the WLAN system with RoF in Fig.1. This system consists of wireless stations (STAs) and an RF unit at the customer premises and a modulator/demodulator (MOD/DEM) unit and a MAC processing unit at the central office. There is an optical fiber link between the customer premises and the central office. Each STA has an IEEE 802.11a interface. The RF unit is composed of a circulator, down/up-converters, AD/DA converters, and an electric-to-optic (EO)/optic-to-electric (OE) interface. The RF unit can be seen as a remote antenna of the AP placed at the central office. In this system, a data frame transmitted by a STA is first transmitted to the RF unit at the customer premises; it is then amplified, down-converted, digitized, and optically converted. Finally, the data frame is transmitted through the optical fiber and received at the central office. The received signal is demodulated and processed by the MAC and signal processing unit.

The above-mentioned WLAN system with RoF is replaced by an equivalent model of a long-distance communication system in Fig.2. Each STA belongs to the AP; therefore, there is a negligible propagation delay between STAs. In contrast, there exists a large propagation delay between the AP and the STAs owing to the optical fiber connections. In Japan, most telephone subscribers are located within 5 km of telecommunication offices. In order to cover most customers, we consider a fiber length of 10 km, which corresponds to a one-way propagation delay of 50 μs. This delay can be derived from the refractive index of the single-mode optical fiber, i.e., 1.5.

We assume that all STAs and the AP operate in accordance with the IEEE 802.11a standard and that the MAC layer uses the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. All STAs and the AP operate in the basic access mode. The system parameters are summarized in Table 1. The MAC payload size is set to 300 B for the uplink and 1500 B for the downlink, which corresponds to an up/downlink throughput ratio of 1:5 [3].

Table 1 System parameters

Transmission rate	24 Mbit/s	Traffic	Saturated
Number of STAs	9, 19	Maximum propagation delay between AP and STAs	50 μs
Uplink MAC payload	300 B/frame		
Downlink MAC payload	1500 B/frame	Maximum Fiber length	10 km

3. Problem Caused by Large Propagation Delay

In this section, we show the problem caused by the large propagation delay between the AP and the STAs that causes degradation of the frame-rate performance owing to collision events between ACK frames and other frames. We have already solved this problem by extending the NAV period [2]. Results from a computer simulation of the NAV-extended method are shown in Fig.3, which shows that the total frame rate of the NAV-extended method is improved considerably for propagation delays greater than 33.5 μs. However, the frame-rate performance of the AP, i.e., the downlink, is extremely degraded.

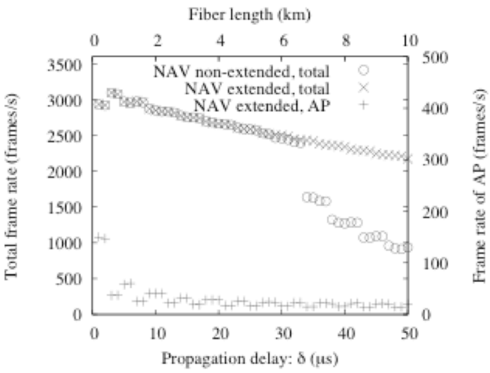


Fig. 3 Frame rate versus propagation delay.

This fairness problem between the uplink and downlink frame rates has been studied when the propagation delay is negligibly small [4]. To mitigate this fairness problem, we use the CWmin control method [4] in which CWmin of the AP (CWmin_d) is set to a lower value than those of the STAs. This makes the backoff counter of the AP tend to be lower, which allows the AP to transmit frames more frequently than the STAs. For the case with no propagation delay, the optimal value of CWmin_d is calculated by Eq. (1):

$$\mathrm{CWmin\_d} = \left\lfloor \frac{3}{2} + \frac{B}{R^*} + \sqrt{\left(1 + \frac{B}{R^*}\right)^2 + \frac{2B}{R^*}} \right\rfloor \qquad (1)$$

where $\lfloor x \rfloor$ is the floor function, i.e., the largest integer not greater than x; $B = \frac{\mathrm{CWmin\_u}(\mathrm{CWmin\_u}-2)}{2(\mathrm{CWmin\_u}+1)}$; R^* is the target value of the frame-rate ratio R; CWmin_u is the value of CWmin of the STAs; and CWmin_d is the value of CWmin of the AP.

Here, the target value R^* is set to one, referring to the traffic measurement [3], and we assume that CWmin_u = 15. This value of CWmin is the default value for IEEE 802.11a STAs. With Eq. (1), the optimal CWmin_d is calculated to be 4 for $N = 9$ and $R^* = 1$ and to be 3 for $N = 19$ and $R^* = 1$. If the propagation delay becomes large, the optimal CWmin_d should be modified because large propagation delays cause an increase in the number of frame collision events between the AP and the STAs.

Suppose that there is a large propagation delay between the AP and the STAs. After the STA begins a transmission, the AP cannot detect the transmitted frames for a period of time equal to the propagation delay. Therefore, the AP can start transmission even if the STAs have already started their own transmission. The frame transmitted by the AP may collide with the frame sent by an STA. An example of this event is shown in Fig.4.

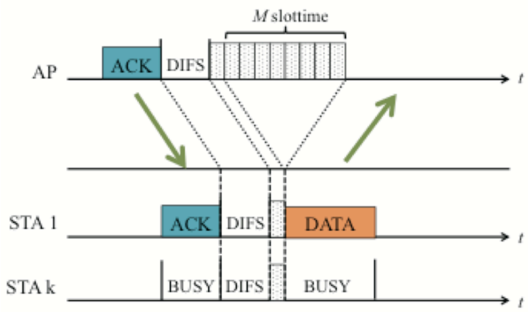


Fig. 4 Failure to detect transmission.

Fig. 4 shows the behavior of the AP and the STAs just after STA 1 successfully transmits a frame. We assume a propagation delay δ, a backoff counter value of one for STA 1, and a backoff counter of two or more for the other STAs. As shown in Fig.4, the AP starts counting down the backoff counter after a distributed interframe space (DIFS) period. Then, the STAs start counting down after a period of δ later. When the counter of STA 1 is equal to zero, STA 1 starts transmitting a data frame, and the other STAs begin reception. The transmitted data frame is transmitted through the optical fiber, and the AP cannot detect the transmission during the period of δ . Meanwhile, the AP continues counting down its backoff counter.

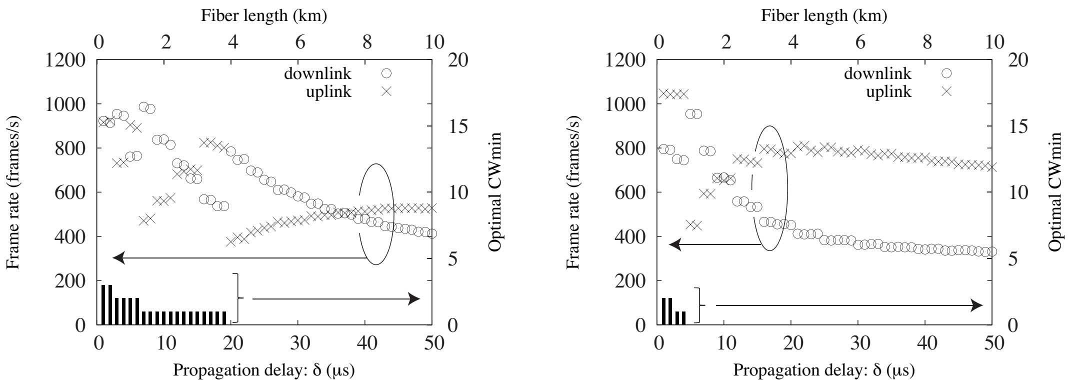
If the AP initially has a backoff counter value of $M + 1$ or less, the backoff counter value becomes zero before the data frame arrives at the AP, leading to a collision. M is expressed by Eq. (2) [5]:

$$M = \left\lfloor \frac{2\delta + \varepsilon}{\sigma} \right\rfloor$$

where σ is the slot time, ε is the sum of the clear channel assessment (CCA) time, the receive-to-transmit turnaround time, and the MAC protocol processing time.

During the period of M, the AP cannot detect a transmission by any of the STAs. In addition, an STA cannot detect a transmission from the AP during the M slot time, but it can detect all the other STAs immediately. As a result, the collision probability of the AP becomes relatively high compared to those of the STAs, which lowers the frame rate of the AP. The downlink frame rate must increase to satisfy the target ratio of the up/downlink frame rate R^*.

The optimal values of CWmin of the AP for the propagation delay and the number of STAs are obtained from computer simulations considering the calculated values derived from Eq. (1). CWmin_d is determined to be optimal if the ratio of the uplink and downlink frame rates is the closest to the target value of one. Results for $N = 9$ and $N = 19$ are shown in Figs.5 (a) and 5 (b), respectively. These figures show the frame rates of the uplink and downlink as well as the optimal values of CWmin_d.



(a) 9 STAs (b) 19 STAs

Fig. 5 Frame rates of the up/downlink and the optimal CWmin with the CWmin control method.

The downlink frame rate increases by using the CWmin control method. However, the frame-rate ratio R is not necessarily equal to the target value of one in the range with the same value of CWmin_d. The downlink frame rate is degraded as the propagation delay increases, whereas the uplink frame rate is improved. This is because CWmin_d takes discrete integer values and is not fine enough to cover the full range of propagation delays. The value of M increases as the propagation delay increases, which makes the collision probability higher.

As described above, the CWmin control method gives transmission priority to the AP, which can improve the frame rate of the downlink and can control the frame-rate ratio to some extent. However, the optimal value of CWmin for the case of no propagation delay does not necessarily result in the exact target value of R^* when there is large propagation delay.

4. Proposed Method

In this section, we propose a novel method for resolving the problem described in Sect. 3, which improves the downlink frame rate by reducing data frame collision events between the AP and the STAs. This method can control the ratio of the uplink and the downlink frame rates precisely. There still exists some "competition," even with the use of the CWmin control method in Sect. 3. The CWmin control method gives priority to the AP, but it does not improve the overall probability of collisions. The increased collision probability depends on the system parameters: the value of the propagation delay and the number of STAs. Therefore, it is important to modify the MAC protocol in order to reduce collision probability.

To reduce collision events as much as possible and to control the up/downlink frame rates, we propose a novel method that allows the AP to obtain supplementary chances to transmit data frames in addition to those opportunities obtained by the normal backoff algorithm. This method allows the AP to start transmission regardless of its own backoff counter value within a short interframe space (SIFS) period after reception of the data frame from the STAs. The AP can avoid "competition" with the STAs because the transmitted frame of the AP never collides with the frames transmitted by the STAs.

Suppose that an STA has just succeeded in its own transmission, as shown in Fig.6. If the AP starts transmitting a data frame after the SIFS period, the data frame can be received by the STAs without competition. This is because a

DIFS period has not expired at the STAs' side, and the STAs are not able to start transmission. In this way, the AP avoids "competition" with the STAs. Moreover, the AP does not reset its backoff counter or the backoff stage when transmitting frames in this manner. This prevents the AP from being given excess priority.

We performed computer simulations to confirm the effectiveness of the proposed method, and the simulated up/downlink frame rates are shown in Fig.7. Figs.7 (a) and (b) correspond to $N = 9$ and $N = 19$, respectively. These figures show that the ratio of the up/downlink frame rates is almost equal to the target value of one for each propagation delay and each number of STAs. This is because the AP seldom succeeds in transmitting owing to the normal backoff algorithm, especially with a large propagation delay, as discussed in Sect. 3. Therefore, almost all transmissions by the AP are due to the proposed method.

When an STA succeeds in transmitting one data frame, the AP can also transmit one data frame. This is why the up/downlink ratio R is nearly equal to the target value of one, regardless of the system conditions with saturated traffic. In addition, when the propagation delay is 50 μs, the total frame rate is approximately two times higher than the total frame rate obtained using the CWmin control method, as shown in Fig.5 (a). This is achieved by avoiding "competition." The CWmin control method forces the AP to transmit frequently, which leads to more frequent "competitions." Accordingly, the collision probability between the AP and the STAs increases, and the frame rate degrades significantly. With our new approach, we achieved higher total frame rates and improved fairness for the up/downlink frame rates.

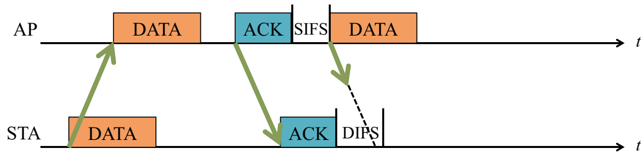
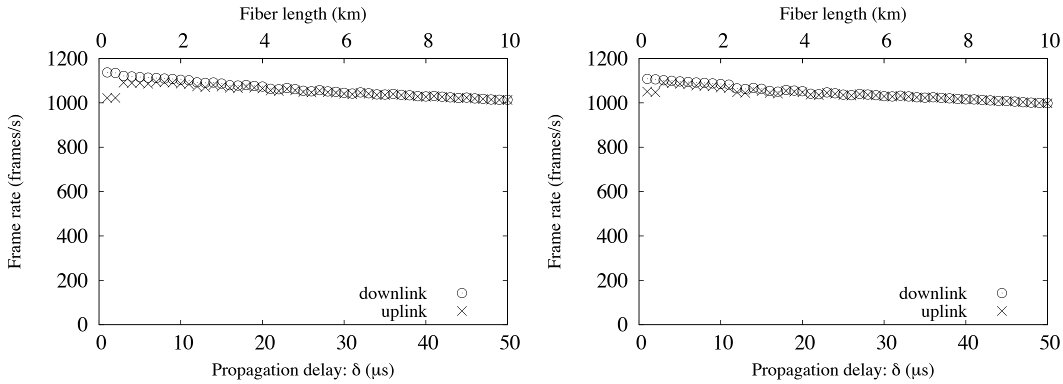


Fig. 6 Proposed method.



(a) 9 STAs (b) 19 STAs

Fig. 7 Frame rate with proposed method.

5. Conclusion

The conventional method that employs the CWmin control method exhibited poor downlink performance with a large propagation delay. In order to solve this problem, we proposed a new method that allows the AP to transmit only when the AP receives a data frame from the STAs. Computer simulations revealed that the frame-rate ratio approaches the target value of one, and the total frame rate is approximately doubled compared to the CWmin control method.

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