Leader-based Rate Adaptive Multicasting for Wireless LANs

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***Abstract*—Multicasting is useful for various applications such as multimedia broadcasting. In current 802.11, multicast frames are sent as broadcast frames at a low transmission rate without any acknowledgement or binary exponential backoff. This naive multicasting mechanism degrades the performance of not only multicast flows but also unicast flows. In this paper, we propose a new multicasting mechanism based on the leader-based approach to improve the legacy multicast transmissions, maintaining coexistence with legacy 802.11 devices. Simulations show that our protocol achieves well-balanced performance in terms of reliability, latency, goodput, and transmission fairness in comprehensive environments.**

I. INTRODUCTION

Multicasting is efficient for transmitting identical data to multiple users. When the same data are transmitted to multiple receivers, multicasting saves network resources as opposed to unicasting to individual users. From this economic point of view, applications such as video conferencing, news broadcasting, and information sharing among wireless devices had better use multicast communications for distributing identical data.

The IEEE 802.11 standard [1] is a very popular protocol today as it provides a cost effective solution to relatively high bandwidth capacity. However, the IEEE 802.11 standard does not address multicast communications yet. It supports multicast transmissions by leveraging broadcast without any feedback, which leads to three problems.

The first one is the *reliability problem*. Legacy multicast of 802.11 has no error recovery mechanism such as retransmission. Although multimedia applications can tolerate a little loss, in error-prone wireless channels, their performance might be quite degraded. Also for applications with no error tolerance such as file sharing, the overhead of application layer error recovery lays a burden on the network load, if there is no lower layer support.

The second one is the *performance anomaly problem*. The IEEE 802.11a/b/g standards provide a multi-rate capability (e.g., 12 different transmission rates in the 802.11g PHY), which can be dynamically adapted to achieve high throughput under varying channel conditions. Recently, a number of algorithms for rate adaptation [10][11][12][13] have been proposed, but they are focused on unicast. For multicast, commercial APs still use a low fixed transmission rate. The low transmission rate exhibits longer channel occupation of the shared medium, and then this results in a performance anomaly. In [5], Heusse *et al.* indicate that the performance of all mobile stations is considerably degraded when some mobile stations use a transmission rate lower than others.

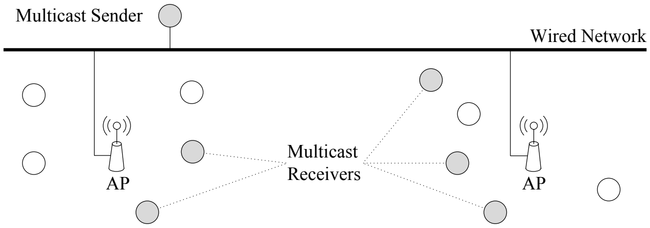

Fig. 1. A simple illustration of multicast networks

The last one to be considered is the *fairness problem*. Basically, 802.11 DCF achieves long term fairness of transmission opportunity by adjusting the contention window size. Legacy multicasting in 802.11 does not include a feedback mechanism, so there is no way to adjust its contention window. In a congestion situation, while unicast flows increase their contention windows to avoid collisions, the contention windows of multicast flows are fixed to the minimum size. Consequently, greedy multicast flows keep overwhelming the shared channel, and unicast flows suffer from starvation.

In this paper, we introduce a novel feedback mechanism and a rate adaptation technique to solve the above problems. Also we seek to maintain coexistence with legacy 802.11 devices, and try not to increase implementation complexity.

The rest of this paper is organized as follows. Section II and Section III present the background and related work on multicasting and rate adaptation. Section IV describes our Leader-based Multicast with Auto Rate Fallback protocol (LM-ARF), and Section V then examines its performance. Finally, we conclude the paper with future work in Section VI.

II. BACKGROUND

To achieve reliable multicast transmissions, corrupted frames should be retransmitted. As shown in Fig. 1, multicast

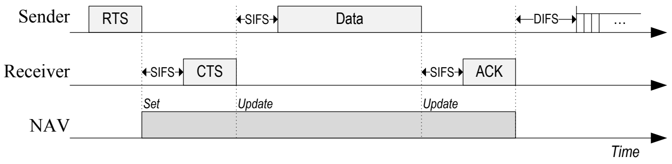

Fig. 2. The 802.11 DCF provides fair access to the shared medium for unicast flows, adjusting contention window size. Also the closed-loop unicast ensures reliable transmission.

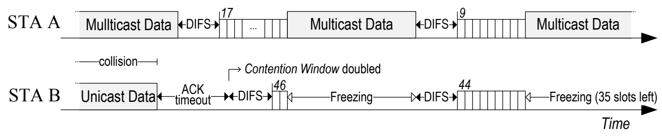

Fig. 3. Multicast flows without binary exponential backoff incur the unfairness problem due to the minimum contention window. There are no RTS/CTS exchanges in legacy multicast transmissions.

data are transmitted over wired and wireless media. If the end-to-end applications deal with retransmissions even though most of errors occur in the wireless transmission links, it will be highly inefficient. Instead, if errors on wireless links are recovered at the link level, it will reduce latency, and save bandwidth capacity in wired medium. For these reasons, we propose to augment link level multicasting in this paper. Hereafter, *multicasting* means layer-2 (L2) multicasting at the MAC layer and a multicast sender means an AP of an infrastructure-based wireless LAN.

For unicasting, the IEEE 802.11 DCF provides reliable transmissions and fair access to the shared medium, using acknowledge feedback and contention window control. The wireless channel is reserved by RTS/CTS exchange, as shown in Fig. 2, and the receiver transmits an ACK frame after it receives a correct data frame. When the sender did not receive a CTS (or ACK) frame due to collision or channel error, it doubles its contention window and waits chance to retransmit an RTS (or data) frame by binary exponential backoff. On the other hand, in multicast transmissions, 802.11 only sends a multicast data frame at a low transmission rate, and does not utilize an ACK frame ever, and hence its contention window size is fixed to the minimum value. Fig. 3 illustrates a multicast transmission.

III. RELATED WORK

Many studies are proposed about this topic, but most of studies are focused on only one or two problems. In [6], Kuri *et al.* have proposed a novel mechanism called a leader-based protocol (LBP) for multicasting in a wireless LAN in order to improve the reliability of multicast frames. LBP selects one of multicast receivers, so that it will send an acknowledgement frame back to a multicast sender. It only addresses the reliability problem, so there is still the performance anomaly problem.

In [7], Choi *et al.* have proposed a novel scheme termed unicast-friendly multicast that dynamically adapts the contention window for multicasting depending on the number of competing stations in a wireless LAN in order to solve the fairness problem. However, multicast flows still have the reliability problem and the performance anomaly problem.

In [8], Villalon *et al.* have proposed an auto-rate selection mechanism for multicasting (ARSM). ARSM dynamically selects a multicast rate based on the feedback information pertaining to channel conditions perceived by mobile stations. ARSM also solves the fairness and the packet loss problems by utilizing LBP. However, ARSM requires the introduction of new MAC control frame formats and the modification of the PHY (PLCP) header as well. This makes it incompatible with the 802.11 standard.

IV. LEADER-BASED MULTICAST WITH AUTO RATE FALLBACK

We now propose the leader-based multicast protocol that solves reliability, performance anomaly, and fairness issues. Our Leader-based Multicast with Auto Rate Fallback (LM-ARF) protocol describes the behaviors of an AP and multicast group member stations within its cell.

A. Leader-based Feedback

In this section, we introduce a leader-based feedback mechanism to address reliable multicasting. The basic idea is to emulate unicast transmission using a leader-based approach. In a nutshell, one of the receiving stations, which is the leader[1], is responsible for sending ACKs on behalf of the participating multicast stations. If any multicast receiver, which is not the leader, fails to receive a multicast frame, it will send a negative acknowledgement (NAK) to request retransmissions. In this case, the AP will adapt the contention window, and even adjust the PHY data rate according to ARF [10].

First, the AP contends with other stations for channel access to send its multicast frame. When the AP wins channel access, it starts transmitting a *CTS-to-Self* frame at a basic rate (1Mbps or 2Mbps)[2]. The frame's destination is the multicast group address [3], which is assumed to be supplied by an upper layer protocol. The CTS-to-Self frame is devised for two purposes: guaranteeing the channel access and announcing the transmission of a multicast frame. Updating Network Allocation Vector (NAV), the CTS-to-Self frame will reserve the channel until the multicast is finished. Also the CTS-to-Self frame informs the multicast receivers of a pending multicast data frame, so the multicast receivers figure out their multicast data frame will be transmitted after the SIFS. Because the CTS-to-Self frame is short and is transmitted in the low basic rate, this frame is likely to be delivered to most of stations in a cell without error. After transmitting the CTS-to-self frame, the AP waits for the SIFS and then transmits the

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[1] The leader can be elected within the framework of standards, using such as multicast diagnostic functionality in 802.11v [2]. The detailed leader election process is beyond the scope of this paper.

[2] In this paper, we use 1Mbps as the basic rate.

multicast frame. Then each multicast receiver acts differently depending on whether it is a leader or not.

- For the leader, if the data frame is successfully received, it transmits an ACK frame after the SIFS. If not, it does nothing.
- For a non-leader, if the data frame is successfully received, it does nothing. If not, it transmits a NAK frame after the SIFS. Sending the NAK frame will prevent the AP from receiving a positive acknowledgement from the leader by causing a collision. Fig. 4 illustrates this case.

In case of the leader receiving an erroneous frame, it does not need to send a NAK frame.

After the AP receives an ACK frame, a NAK frame, collided frames, or nothing, it waits for the DIFS and contends again with other stations for retransmission. The contention window size will be doubled if a retransmission is needed. But the number of retransmissions is limited like a unicast transmission. Note that the contention window size will be adjusted the same as that of a unicast transmission, so that LM-ARF keeps fairness between unicast flows and multicast flows. By retransmitting and backing off exponentially, the reliability and fairness problems can be solved in LM-ARF.

B. Rate Adaptation

We address the reliable multicast transmission mechanism in the previous section, but there remains the performance anomaly problem. In legacy multicasting, an AP always transmits a multicast frame at the low fixed rate. But LM-ARF also adopts the rate adaptation mechanism to overcome inefficient transmission of multicast frames. Recently, many rate adaptation algorithms are proposed and most of them can be applied to our protocol. We first introduce ARF [10], the most widely-deployed rate adaptation scheme in the commercial 802.11 wireless LAN devices, and adopt it to our protocol.

ARF keeps a timer and a tuple that consists of a current data rate, a number of successful consecutive transmissions and a number of consecutive transmission failures for each destination. In our protocol, we need to maintain a tuple for each multicast group. ARF checks the current status after every transmission whether the multicast data rate can be increased or decreased.

- If the AP succeeds in 10 consecutive transmissions or the timer expires, the multicast data rate is increased to the next higher rate and the timer is reset.
- If the AP fails in 2 consecutive transmissions, the multicast data rate is decreased to the next lower rate and the timer is restarted.

In case that the transmission fails right after increasing data rate, the multicast data rate is decreased immediately even though the failure occurs only once. This transmission is referred to as the probing transmission. Besides the above cases, the multicast data rate will not be changed.

C. Implementation Issues

In legacy multicasting, an upper layer protocol of 802.11 may receive duplicated multicast frames, because legacy 802.11 does not check the duplication of multicast frames when the AP retransmits them. If the duplication is a critical problem, as a possible solution, we can use a *virtual BSSID* on retransmission. On infrastructure networks, the transmitter address field of the multicast frame is the address of the AP, which is the BSSID. Whenever mobile stations receive the multicast frame, they check the BSSID to find out whether the frame is from the AP they belong to. If we choose another BSSID that can be inferred by LM-ARF for the retransmitted multicast frame, the duplication problem is solved.

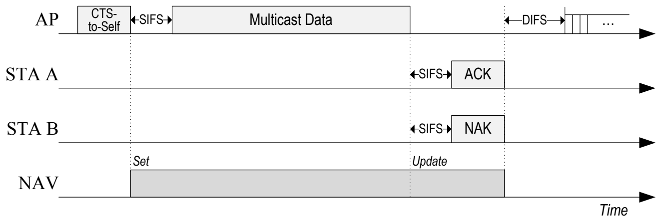

Fig. 4. Station A, the leader, transmits the ACK frame for its correctly received data frame. Station B, one of the multicast group member and not the leader, received the CTS-to-self frame but received the erroneous data frame. Therefore it transmits the NAK frame to notify the AP of the failure.

Another issue is how to embody a NAK frame. One way to implement a NAK frame without adding a new control frame is that using a legacy ACK frame replacing its receiver address field with the virtual BSSID as well. Then the AP can determine whether the received acknowledge frame is the ACK or NAK, by checking the receiver address field.

V. PERFORMANCE EVALUATION

In this section, we conduct a performance study to evaluate the proposed algorithm, using *ns-2* simulator. LM-ARF is implemented on top of the 802.11 DCF module.

A. Simulation Setup

PHY values are based on the ORiNOCO 802.11b card data sheet. Each station transmits with 15dBm power. Four PHY rates of 1Mbps, 2Mbps, 5.5Mbps, and 11Mbps are used. To simulate a wireless transmission error of an 802.11b channel, we use the bit error rate (BER) vs. signal-to-noise ratio (SNR) curves provided by [9]. We apply different BERs to preamble, PLCP header, and MAC protocol data unit (MPDU) separately since they use different modulation schemes according to 802.11, we finally calculate the frame error rate (FER) from the BER.[3]

For the simulation, we set up an infrastructure wireless LAN with one fixed AP and a varying number of mobile stations. The stations that receive multicast frames are arranged for each simulation scenario. The stations other than multicast

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[3] The error rate for l-bytes long frame is given by

$$\mathrm{FER} = 1 - (1-\mathrm{BER}_{bpsk})^{bitPreamble} \cdot (1-\mathrm{BER}_{bpsk})^{bitHeader} \cdot (1-\mathrm{BER}_{data})^{8\cdot(l+28)},$$

where BER_{bpsk} is a bit error rate of BPSK scheme and BER_{data} is a bit error rate of a modulation scheme for MPDU transmission. Each BER is taken from pre-calculated table by current SNR and modulation scheme. 28 bytes are added due to MAC header and FCS in MPDU.

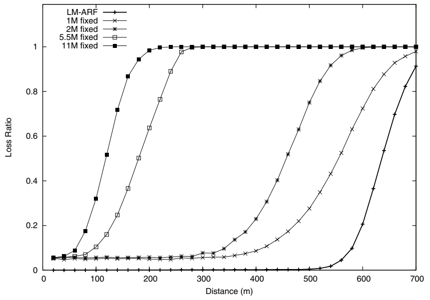

Fig. 5. Loss ratio of 10 multicast receivers with 5 contending unicast flows

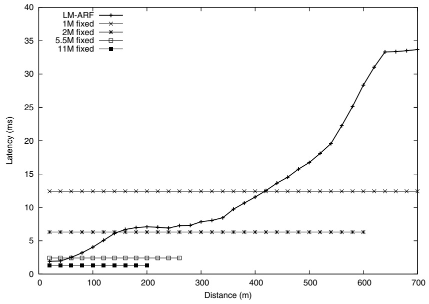

Fig. 6. Latency of 10 multicast receivers with 5 contending unicast flows

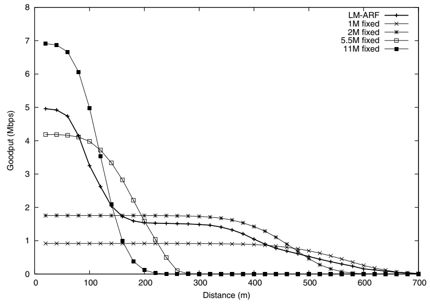

Fig. 7. Goodput of 10 multicast receivers with 5 contending unicast flows in case of saturated multicast traffic

group members are distributed nearby the AP, which generate uploading TCP unicast traffic so as to contend for the shared channel and potentially make collisions with multicast transmissions. Also we assume the wireless channel with random noise and small scale fading, and incorporate *Ricean fading* as a radio propagation model.

Every sender (multicast or unicast) generates a single flow of 1500 byte long data frames, and the data frames are transmitted without fragmentation. The RTS, CTS, and ACK frames are always transmitted at the basic rate of 1Mbps.

B. Constant Bit Rate Traffic

We first check out the overall performance in terms of loss ratio, latency, and goodput by generating constant bit rate (CBR) traffic of 512Kbps for multicast. The CBR traffic is used to simulate that the AP multicasts the frames from multimedia applications. Up to 700m distance[4], we measure each metric of LM-ARF, legacy multicasting (1Mbps), 2Mbps, 5.5Mbps, and 11Mbps fixed data rate multicasting. 10 multicast receivers are circularly centered at the AP, with the varying distance from the AP, and 5 stations other than the multicast group members generate uploading TCP traffic nearby the AP.

Fig. 5 shows the loss ratio of multicast frames over distance. In measurements, we count the number of the lost frames when any receiver did not receive a multicast frame correctly. The loss ratio of 11Mbps fixed multicasting increases rapidly as the distance from the AP is over 50m, and the reliability of legacy multicasting also gradually gets worse from 300m distance. None of them achieve reliable transmissions. LM-ARF, owing to retransmissions, shows much less loss ratio until 500m distance, which confirms that LM-ARF achieves better reliability than legacy multicasting.

Fig. 6 plots the average latency from the point the AP starts sending a multicast frame to the point all of the multicast receivers correctly receive the frame. Before 400m distance, the latency of LM-ARF is smaller than that of legacy multicasting. This smaller latency also means that LM-ARF occupies the sharing medium for shorter time and gives other stations more chance to transmit. LM-ARF use less airtime up to 18% of that of the legacy multicasting.[5] The latency of LM-ARF is worse from 400m distance because even the lowest rate cannot deal poor channel condition, so this causes retransmissions. This retransmission continues until the retry count reaches the upper limit.

We also conduct the goodput evaluation of saturated multicast traffic, which makes the AP's data queue never empty. Fig. 7 illustrates the rate adaptation of LM-ARF achieves a fairly good performance. Because of the overhead by CTS-to-Self frames and ACK frames, in some ranges, fixed rate multicasting shows better goodput.

C. Fairness

The 802.11 DCF is designed to offer equal transmission opportunities to all contending stations. However, legacy multicasting does not offer ACK feedback and does not backoff exponentially, so the size of contention window is fixed to the minimum size. Hence, unicast flows suffer from unfair transmission opportunity in case of poor channel conditions or intense collisions by many contending stations. In particular, the fixed contention window of legacy multicasting results in more frequent collisions in case of many multicast flows.

To show that LM-ARF has a good fairness property, we evaluate a scenario that one multicast flow and 10 unicast flows are contending. All of 802.11 senders always contend for the wireless medium whenever the channel is available, and their data queues are never empty. During the first 200 seconds, the multicast sender transmits frames according to the 802.11 standard, and then switches into the LM-ARF mechanism. We plot the average number of transmissions per second of each station (the AP and the unicasting stations), counting transmissions that do not make collisions. Fig. 8 shows the

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[4] Range of 1Mbps in open environment is 550m, according to ORiNOCO 802.11b card data sheet.

[5] We obtain this timing analysis by

$$\frac{T_{cts} + T_{data(\mathrm{11M})} + T_{ack} + 2 \cdot \mathrm{aSIFSTime} + \mathrm{aDIFSTime} + \overline{T}_{backoff}}{T_{data(\mathrm{1M})} + \mathrm{aDIFSTime} + \overline{T}_{backoff}},$$

where

$$\begin{aligned} T_{cts} &= T_{ack} = \mathrm{tPCLPreamble} + \mathrm{tPLCPHeader} + 8 \cdot 14/1\mathrm{M}, \\ T_{data(R)} &= \mathrm{tPCLPreamble} + \mathrm{tPLCPHeader} + 8 \cdot (l + 28)/R, \\ \overline{T}_{backoff} &= \mathrm{aCWmin}/2 \cdot \mathrm{aSlotTime}, \end{aligned}$$

using the IEEE 802.11b PHY layer values for the roman font variables.

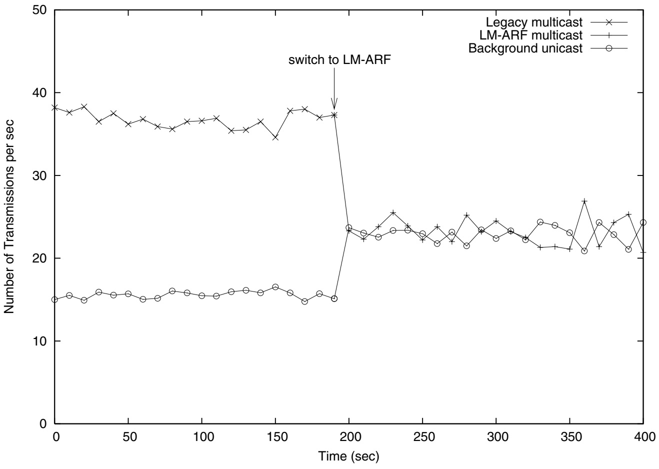

Fig. 8. Number of transmissions between one multicast flow and 10 unicast flows

fairness is almost perfect after we switch the multicast protocol to LM-ARF.

D. Mobility

In presence of mobility, a receiver's data rate for successful receptions changes every moment by its propagation distance, and rich channel variation incurs the unreliability. We now evaluate two simulation scenarios to check out how the mobility would affect multicasting performance.

First, we placed 10 mobile stations which receive multicast frames around the AP at the same distance at the beginning. Making mobile stations follow a pre-defined trajectory that moves away from the AP for the first 50 seconds and comes back to the AP for the last 50 seconds at a fixed speed, we observe how the rate adaptation mechanism in LM-ARF works. Fig. 9 plots the date rate of the AP sampled in every second, which shows LM-ARF adapts the rate to yield better goodput without affecting the reliability.

In the other scenario, we randomly arrange the mobile stations, and then make them wander about at a person-walking speed (4m/s). The AP multicasts 512Kbps CBR traffic at a fixed place. To compare with legacy multicasting, we limit the roaming region to 1Mbps transmission range and run the scenario for one hour simulation time. Fig. 10 exhibits LM-ARF outperforms legacy multicasting by about 22% in goodput. Note that LM-ARF also achieves almost reliable transmissions.

VI. CONCLUSION

Legacy 802.11 multicasting transmits at a low bit rate, pessimistically assuming the worst channel condition among receivers. This assumption degrades the performance of not only multicast flows but also unicast flows. In this paper, we propose a novel multicasting protocol, called LM-ARF, for IEEE 802.11 wireless LANs. By receiving ACKs from a leader in successes and NAKs from other stations in failures, a multicast sender can retransmit erroneous data, adapt transmission rate, and adjust contention window size. Evaluated via comprehensive simulation over various scenarios, LM-ARF shows that it outperforms legacy multicasting in terms of reliability, latency, goodput, and transmission fairness. As a future work, we will consider other rate adaptation algorithms such as [11][12][13], which outperform ARF.

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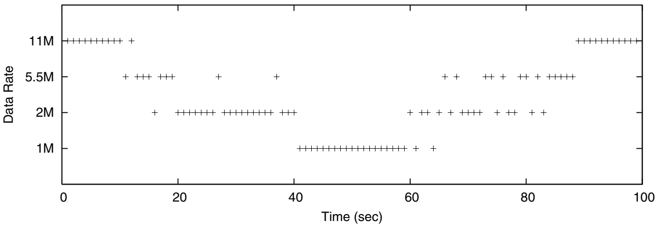

Fig. 9. Multicast data rate of the AP, whose receivers move away from the AP for the first 50 seconds and come back to the AP for the last 50 seconds at a fixed speed

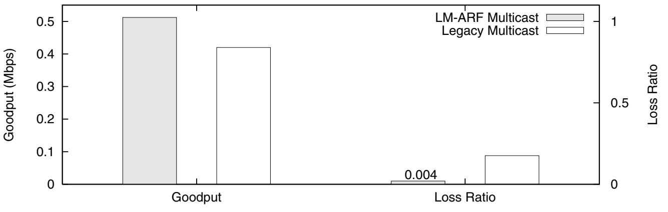

Fig. 10. Average goodput and loss ratio for random moving receivers during one hour simulation time