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# Multicasting multimedia streams in IEEE 802.11 networks: a focus on reliability and rate adaptation

**Nakjung Choi · Yongho Seok · Taekyoung Kwon · Yanghee Choi**

**Abstract** Multicasting multimedia streams in IEEE 802.11 wireless LANs has two issues: reliability and rate adaptation. We address these issues by proposing two mechanisms that augment the current multicasting standards in a backward-compatible fashion. Semi-reliable multicasting (SRM) selects a leader who sends feedback information to lessen the reliability problem of multicast frames. Probing-based auto-rate fallback (PARF) allows the multicast source to adjust the bit rate depending on the link conditions of multicast recipients. Comprehensive simulation experiments reveal that SRM + PARF achieves reliability and link efficiency close to those of an omniscient multicasting framework.

**Keywords** IEEE 802.11 · Multicasting · Reliability · Rate adaptation · Compatibility · Leader

## 1 Introduction

One of the key advantages of the IEEE 802.11 series standards [8, 9] is the multi-rate transmission capability. That is, the bit rate of data transmissions can be dynamically adjusted depending on wireless channel conditions. For example, if the signal-to-interference noise ratio (SINR) is sufficiently high, transmission rates can be higher than the basic rate.[1] Since the multi-rate capability is implemented at the PHY layer, a MAC protocol should be augmented in order to fully exploit this capability. Auto-Rate Fallback (ARF) [11] or Adaptive ARF [13] is the de facto standard that enables IEEE 802.11 MAC to make use of this multi-rate capability. As the channel condition improves, ARF provides a high performance gain over the IEEE 802.11 basic rate. There is a consensus that the IEEE 802.11 protocol can be a good candidate for wireless multimedia streaming services in a small area due to its high link bandwidth. However, when multimedia frames are multicasted, the current IEEE 802.11 MAC protocol has two serious problems.

The first one is a *reliability problem*. In the current IEEE 802.11 multicasting standard, there is no feedback from the multicast recipients and hence the sender (here, the access point) cannot figure out whether a multicast frame is successfully received by every recipient. Thus, the collided or garbled multicast frame is dropped without any retransmission. Hence, as the level of contention or interference increases, the loss rate of multicast frames will increase accordingly. To mitigate this *reliability problem*, the IEEE 802.11 MAC protocol should be modified to retransmit lost multicast frames.

The other one is a *performance anomaly problem*. Heusse et al. [6] indicate that the aggregate throughput of a WLAN cell is considerably degraded when some stations use transmission rates lower than others. Currently, most of the

N. Choi · Y. Seok · T. Kwon (✉) · Y. Choi
School of Computer Science and Engineering,
Seoul National University, Seoul, Korea
e-mail: tk@mmlab.snu.ac.kr

N. Choi
e-mail: fomula@mmlab.snu.ac.kr

Y. Seok
e-mail: yhseok@mmlab.snu.ac.kr

Y. Choi
e-mail: yhchoi@mmlab.snu.ac.kr

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[1] The IEEE 802.11 standard defines a basic rate set (BRS), which is a minimum set of bit-rates which all stations in a WLAN cell can support to receive 802.11 control frames. Currently, most commercial AP products use one of BRS for multicast frames.

commercial access points (APs) use a fixed and low transmission rate (typically, one of basic rates) for multicasting. Therefore, the performance of unicast flows with high transmission rates is seriously degraded as multicast flows overwhelm the wireless link bandwidth due to the fixed and low transmission rate. To solve this problem, the previous studies [1, 2, 7, 18] focus on the provisioning of the same channel usage time to all stations. They can lessen the performance anomaly problem. However, there is still a link efficiency problem since multicasting uses only the basic rate. For example, even though all multicast recipients can successfully receive a multicast frame transmitted at a higher transmission rate, the AP will always use a low transmission rate. Therefore, a new rate adaptation mechanism for multicasting is required for efficient link utilization.

For *reliability*, we adopt a similar approach as Leader-Based Protocol (LBP) [12], which selects a leader that gives feedback on frame losses on behalf of other multicast recipients. Employing LBP achieves fairness between multicast flows and unicast flows since the AP can now perform binary exponential backoff for multicast frame losses. However, although authors mentioned that the Internet Group Management Protocol (IGMP) can be exploited, there is no mention which recipient will be a leader, that is the missing key part in LBP. Hence, we propose semi-reliable multicasting that extends LBP by leveraging IGMP in WLAN environments. For the *performance anomaly problem*, we also need a rate adaptation mechanism. Hence we enhance ARF to adapt to changes of link conditions fast. The main contributions of this work are as follows:

- Designing a leader-based multicasting mechanism for reliability in the IEEE 802.11 compatible fashion,
- Developing a rate adaptation mechanism for efficiency in the IEEE 802.11 compatible fashion, and
- Embodying the first IEEE 802.11-compliant multicasting framework that deals with semi-reliability and rate adaptation jointly.

In Sect. 2, we first combine LBP for reliable multicasting and ARF for rate adaptation into a single framework, which is labeled as *LBP + ARF*. Although the framework can handle both the *reliability* and the *performance anomaly* problems, LBP is not a practical solution for multicasting in IEEE 802.11 WLANs, to be detailed later.

Therefore, in Sect. 3, in order not to modify the legacy IEEE 802.11 MAC standard, we propose Semi-Reliable Multicasting (SRM) which uses only the legacy 802.11 frames. The term “semi-reliability” means that it cannot provide a fully reliable delivery service for multicasting. Note that LBP cannot achieve full reliability either. Assuming the carrier sense range is so wide that the hidden node problem is negligible, SRM seeks to handle collision and channel errors. As multimedia streaming services does not require 100% reliability, we believe SRM can fit into many multicasting applications.

In Sect. 4, we propose a probing-based auto-rate fallback (PARF) mechanism, which extends ARF and AARF, for multicast transmissions. We present a framework that combines SRM and PARF, labeled as *SRM + PARF*. Then implementation issues in the *SRM + PARF* framework are discussed in Sect. 5. In Sect. 6, we compare SRM + PARF to LBP + ARF by simulation. Finally, we introduce related work in Sect. 7, and then give concluding remarks in Sect. 8.

## 2 LBP + ARF

### 2.1 LBP overview

Leader-Based Protocol [12] is proposed for reliable multicasting in IEEE 802.11 WLANs. If multiple recipients reply with ACK frames simultaneously, there will be collisions. Thus LBP assumes that one of multicast receivers has been chosen to be a leader that sends feedback to a multicast sender (typically an AP). There are two modes in LBP: default and RTS/CTS modes.

By default, the AP sends a multicast frame and if the transmission to every recipient is successful, only the leader replies with an ACK frame. If the multicast frame is corrupted, any of the leader and other recipients sends a negative acknowledgement (NAK); thus, by receiving a NAK or collision, the AP can figure out the multicast frame should be retransmitted.

In RTS-CTS mode, the AP first sends a multicast-RTS. If the leader is ready, it replies with a CTS. Other multicast recipient sends an NCTS (Not Clear To Send) if it is not ready. If the AP successfully receives the CTS, it starts transmitting the multicast frame then the same procedure as the default mode proceeds.

However, LBP [12] does not embody how to elect a leader among the multicast recipients for the same multicast flow, which is crucial since it affects the performance of reliable multicasting. Note that LBP cannot achieve full reliability; depending on who will be the leader among multicast recipients, the performance of LBP (i.e., reliability) can vary significantly. LBP, moreover, does not utilize a multi-rate capability, thus still suffering from the *performance anomaly problem*.

### 2.2 LBP with ARF (LBP + ARF)

Auto-Rate Fallback [11] is the most popular rate adaptation mechanism implemented in off-the-shelf WLAN products. Because the ARF mechanism has to know whether a frame is successfully received by a receiver or not, it can be used not in multicasting, but in unicasting. However, if LBP is employed for multicasting, the feedback information becomes available from the leader and hence we can apply ARF for multicasting flows.

We first combine LBP and ARF as a reference framework, which is labeled as LBP + ARF. In ARF, if two consecutive multicast frames are not acknowledged by an AP, the AP decreases the current transmission rate. When ten consecutive ACKs are successfully transmitted or the timer expires, the transmission rate for multicasting is increased to the next higher rate and the timer is reset. If an ACK responding to the first multicast frame after transmission rate increase is not received by an AP, the transmission rate for multicasting goes back to the previous one.

Note that there is an additional modification in LBP + ARF. A multicast recipient in LBP + ARF first needs to identify whether an arriving frame is for unicasting or multicasting. The reason is that it should send a NAK frame whenever an erroneous multicast frame is received. In order to send a NAK frame, at least the MAC header of the multicast frame should be correctly decoded. Therefore, in LBP + ARF, the MAC header of a multicast frame is always transmitted at the lowest transmission rate, independently of a multicast transmission rate for payload. Otherwise, multicast recipients with low SINR link conditions may not correctly receive the MAC header and hence cannot recognize whether an incoming frame is for multicating.

## 3 Semi-reliable multicasting (SRM)

LBP + ARF has a compatibility problem since the current IEEE 802.11 standard supports neither NCTS nor NAK frames. Our goal is to propose a multicasting framework that can be implemented in the current commercial IEEE 802.11 products. Our proposal provides not *fully-reliable* but *semi-reliable* multicasting due to limitation of feedback from a leader only. However, we believe this "semi-reliability" can fit into loss-tolerant multimedia streaming services. To achieve "semi-reliability", an AP will retransmit a lost multicast frame up to a predetermined number of times. Each station (or multicast recipient) has an unique *Leader ID* that is assigned by an AP. The AP dynamically and arbitrarily chooses one of *Leader IDs* (or one of multicast recipients) as a leader, so that the chosen station is responsible for acknowledging the following multicast frames. Each multicast frame from the AP contains the selected *Leader ID* in its MAC header.[2] If the *Leader ID* of a station is equal to the one in the received multicast frame, the station will reply with an ACK frame for the multicast frame. To assign and release an unique *Leader ID* for each station, we propose a novel Leader ID management protocol which specifies how to leverage IGMP concretely.

### 3.1 Leader ID management protocol (LIMP)

To join a multicast group, a station should send an IGMP Membership Report to a multicast router according to IGMP [5]. In LIMP, the station first records its SINR in the Maximum Response Time[3] (MRT) field of the IGMP Membership Report. An AP is assumed to be able to perform IGMP snooping. Thus, when the AP receives the IGMP Membership Report with a non-zero MRT field, it deems that the newly joining station supports SRM, and assigns a new *Leader ID* to the station. That is, the AP rewrites the MRT of the IGMP Membership Report with the assigned *Leader ID*, and then broadcasts the IGMP Membership Report to all the stations in the WLAN. In LIMP, for each multicast flow, the AP maintains the IP multicast address and the corresponding MAC multicast address. Also, the AP keeps track of the MAC address and the SINR of each multicast recipient by snooping IGMP Membership Report messages.

In IGMP [5], a station may or may not send a Leave Group message when it leaves a multicast group.[4] On the other hand, in LIMP, each station should immediately send a Leave Group message when it leaves the current multicast group. In this way, if the AP receives the IGMP Leave Group message, it releases the *Leader ID* assigned to the leaving station.

For the compatibility with legacy IEEE 802.11 stations, an AP should know whether the newly joining station supports SRM or not before assigning a *Leader ID*. Therefore, the AP checks the MRT of an IGMP Membership Report generated by the newly joining station. If the MRT is equal to zero, the AP classifies the station as a legacy IEEE 802.11 station. Furthermore, stations also need to know whether the AP supports SRM or not. For this purpose, we partition the MRT values into two ranges: from 1 to 127 for a *Leader ID*, and from 128 to 255 for an average SINR, respectively. If the *Leader ID* in an IGMP Membership Report broadcast by the AP is 0, a station can figure out that the AP does not support SRM.

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[2] In Sect. 5.1, how to utilize an unused field of a multicast frame header for this purpose is described, which is compliant with the legacy IEEE 802.11 standard.

[3] The MRT specifies the maximum allowed time before sending a responding report but is meaningful only in an IGMP Membership Query message sent by a multicast router. Thus, in IGMP Membership Report messages, the MRT is normally set to 0.

[4] To reduce IP multicast traffic, if a station was the last one to reply to a Membership Query with a Membership Report for the multicast group, it has to send a Leave Group message. Otherwise, it may not send any message since there must be other members on the subnet.

### 3.2 Leader selection protocol (LSP)

To improve the reliability of multicasting, it is desirable that a station with the worst SINR among recipients should be selected as a leader [4]. However, it is impossible to select the station with the worst SINR link every transmission because it is difficult to keep track of time-varing SINRs of all multicast receivers in real-time. Therefore, in our proposal, an AP selects a leader among stations in a round-robin fashion. That is, after an AP successfully delivers $N_{Leader}$ consecutive multicast frames with the current leader, it will select a station with the next higher *Leader ID* and the same process will be iterated. As a result, although a multicast receiver with poor wireless channel conditions may be excluded from a multicast session for an instant, in the end the multicast receiver will serve as a leader for semi-reliable multicast service. Instead of always selecting a station with the worst SINR as a leader, our proposal allows a station with the worse SINR to serve as a leader for a longer duration. That is, for a station with a worse SINR link, time to deliver $N_{Leader}$ successful frames will become higher due to transmission errors. LSP will adjust the value of $N_{Leader}$ as follows. $N_{Leader}$ is initially set to the minimum threshold, say *4*. If there is no transmission failure during 4 multicast frames, the leader will be switched to the next station. For each transmission failure of a multicast frame, $N_{Leader}$ is incremented by a certain stepsize, say *5*, until the maximum threshold, say *50*. Whenever a leader is switched to the next station, $N_{Leader}$ is reset to the minimum threshold. In this way, a station with the worse wireless link will be selected as a leader longer than a station with the better link.

If a station leaves the associated AP without sending an IGMP Leave Group message, LSP has a problem. When the leaving station has been selected as a leader, the AP cannot receive $N_{Leader}$ consecutive ACK frames from the current leader. Therefore, in order to enhance the robustness of LSP, each station sets a membership timer, say 100 ms, after receiving a multicast frame. If the membership timer is expired, the station sends an IGMP Membership Report message to inform the AP that it is still associated with the current AP.[5] In this way, if the AP does not receive any ACK frame or IGMP Membership Report message from the current leader during the membership timeout, it releases the *Leader ID* and then selects the station with the next *Leader ID* as a leader.

## 4 SRM with probing-based auto-rate fallback (PARF)

In SRM, a station with the worst SINR is not always chosen to be a leader due to round robin-based leader selection. Thus, when the station with the worst SINR is not selected as a leader and the AP performs rate adaptation depending on the feedback from the current leader, the stations with the worse SINR links than the leader may experience frame losses. We have to reduce the performance degradation due to rate adaptation based on imperfect knowledge of links of multicast recipients. To do so, a rate adaptation mechanism should take into account the wireless channel condition of the station with the worst SINR. Therefore, we propose to combine SRM with probing-based auto-rate fallback (PARF), which is an enhanced version of ARF and AARF mechanisms for multicasting environments. SRM + PARF uses the unused field in the MAC header of a multicast frame, which is the sequence control field. This reused field is termed *Target Transmission Rate* (TTR). TTR in a multicast frame means the *transmission bit rate* that the AP wishes to use for the *next multicast frame*. The details of rate increase/decrease mechanisms will be explained later.

Whenever a station receives a multicast frame, it decodes the TTR and checks whether a frame with the bit rate TTR can be successfully received. It first calculates the bit error rate (BER) by using the TTR and the SINR values. Then, it derives the frame error rate (FER) from the BER and the average length of multicast frames. For simplicity, we assume that all the multicast frames are of the similar size. If the expected FER is higher than the application-specific requirement, the station should block the AP from increasing the bit rate, to be detailed later.

### 4.1 Rate increasing algorithm for multicasting

Suppose two consecutive multicast frames are successfully transmitted with $i$th bit rate and the AP wishes to increase the bit rate. The AP then makes the TTR of the 3rd multicast frame indicate the next higher bit rate, the $i + 1$th bit rate, but the actual transmission rate remains unchanged. On receiving the 3rd multicast frame, other stations except for the current leader compute the expected FER of a frame assuming the TTR (the $i + 1$th bit rate) is used. However, since this computation may take some time (longer than SIFS), a station can send feedback for the TTR at the next frame. Thus, if the expected FER of the station is higher than the multicasting application requirement, it becomes a leader for the 4th multicast frame by itself. Then, the station as well as the original leader will send an ACK frame, which results in ACK collision at the 4th multicast frame. Therefore, if the AP correctly receives an ACK frame corresponding to the 4th multicast frame, it is guaranteed that the FER of a multicast frame with the TTR can satisfy

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[5] We can utilize this high-cost periodic operation to check multicast recipients with poor wireless channel conditions.

the application requirement for all the multicast recipients, and hence the transmission rate is increased.

After four consecutive successful multicast transmissions, the AP now increments the transmission rate to the $i+1$th bit rate for the 5th muticast frame. If the leader cannot successfully receive this frame, it will not reply with an ACK frame. Then the AP falls back to the $i$th bit rate as the ARF mechanism does. If the 5th multicast transmission is also successfully completed, the AP deems that transmitting a multicast frame with the $i+1$th bit rate can satisfy the application requirement. Finally, after five consecutive successful multicast transmissions, the AP completes the multicast rate increasing procedure as shown in the left part of Fig. 1.

### 4.2 Rate decreasing algorithm for multicasting

After two (i.e., the 1st and 2nd frames) consecutive transmission failures, the transmission rate and the TTR are decreased. That is, the AP probes the wireless channel conditions of stations by transmitting two multicast frames (i.e., the 3rd and 4th frames) with the next lower rate. If either the 3rd or the 4th frame is successfully transmitted, the AP stops the rate decreasing mechanism and then uses the decreased multicast rate for the following multicast frames. If both transmissions fail, the above procedure is repeated until multicast transmissions succeed. The right part of Fig. 1 shows a state transition diagram of the rate decreasing algorithm.

### 4.3 SRM + PARF illustration

Figure 2 illustrates how SRM + PARF adjusts the transmission rate depending on channel conditions of multicast recipients. Suppose that two stations, STA1 and STA2, are multicast recipients, and that STA1 is the current leader. Suppose that the AP is using 24 Mbps for transmitting multicast frames now. Suppose two consecutive multicast frames (the 1st and 2nd frames) are successfully transmitted at 24 Mbps, and the rate increasing process is invoked. First, the third frame is for probing purposes and is transmitted at 24 Mbps with TTR indicating 36 Mbps to check channel conditions of multicast recipients except the leader can accept 36 Mbps. On receipt of the third frame, every station will start computing the expected FER to check whether it can allow 36 Mbps (or TTR).

The fourth frame whose TTR field is 24 Mbps is transmitted at 24 Mbps and the AP waits for feedback for the TTR in the 3rd frame from the stations. Now every station has finished computation about whether 36 Mbps is acceptable or not. Suppose STA2 cannot allow 36 Mbps and thus transmits an ACK frame which collides with the one from the leader (case (1) in Fig. 2). This collision means if the next multicast (or the fifth) frame is actually transmitted at 36 Mbps, one or more multicast group members (excluding a leader) cannot receive it successfully. Therefore, the rate increasing process is aborted and the multicast rate is kept as 24 Mbps.

If the TTR specified by the 3rd frame is acceptable, STA2 takes no action. Then only the leader, STA1, transmits an ACK frame. After the successful transmission of the fourth multicast frame, the fifth multicast frame whose TTR indicating 36 Mbps is actually transmitted at 36 Mbps to check whether the leader can receive the frame. If the leader, STA1, does not receive the frame successfully due to its channel condition, it cannot transmit an ACK frame corresponding to the fifth multicast frame (case (2) in Fig. 2). Then, the multicast rate falls back to 24 Mbps, and thus the rate increasing process is aborted. If an ACK frame corresponding to the fifth multicast frame is successfully

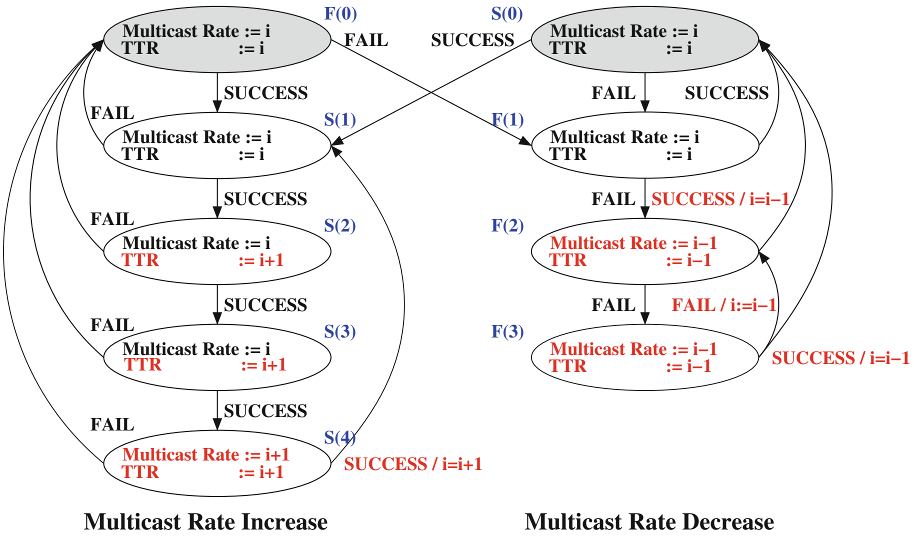

**Fig. 1** A state transition diagram is shown for multicast rate adaptation. For brevity, rate increase/decrease is invoked in the diagram when two successive transmissions succeed/fail

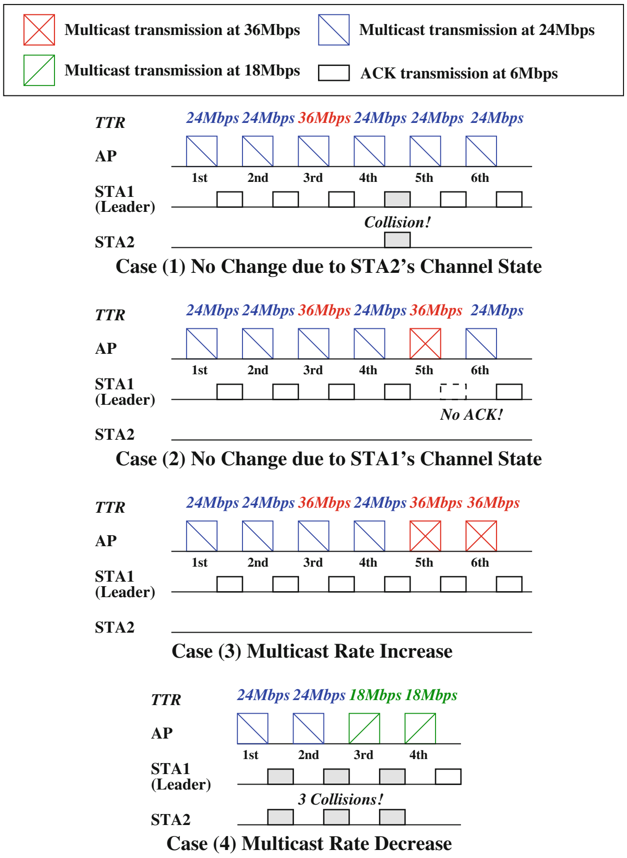

**Fig. 2** Four cases of multicast rate adjustment are illustrated with TTR indication. Rate increase attempt fails since the estimated FER at STA2 is less than the application requirement in *case (1)*. The leader (or STA1) cannot receive a frame transmitted at 36 Mbps in *case (2)* and hence the rate falls back to 24 Mbps. Rate increase is performed successfully in *case (3)*. Transmission rate is decreased after two successive failures in *case (4)*; note that the feedback from STA2 due to the estimated FER from the 2nd frame is transmitted after the 3rd frame

received by the AP, the rate increasing process is completed, and the following multicast frames will be transmitted at 36 Mbps (case (3) in Fig. 2).

Let us illustrate the rate decreasing case as follows. After two transmission errors, the next two multicast frames whose TTR fields are set to 18 Mbps are transmitted at the same rate, 18 Mbps (case (4) in Fig. 2). Note that, on receipt of the third frame, STA2 sends an ACK to indicate that 24 Mbps (TTR in the second frame) is not acceptable due to computation delay (as similar to case (1)). Thus, the AP should see the feedback from the recipients after the fourth frame for final conclusion. In this way, the process for multicast rate decrease is finished, and the following multicast frames will be transmitted at the current rate, 18 Mbps. If both the 3rd and 4th frames fail, the above procedure for decreasing multicast rate is repeated until the multicast rate becomes acceptable or the lowest one.

## 5 Implementation issues of SRM + PARF

### 5.1 Reusing MAC header for multicasting

We reuse the MAC header of a multicast frame in order to implement SRM, which does not conflict with the current IEEE 802.11 standard. The idea is that multicast and broadcast frames cannot be retransmitted or fragmented according to the IEEE 802.11 standard and hence the sequence control field, which is 16 bit long, is not used. We propose to split the sequence control field into two subfields: (1) the *Leader ID* subfield occupies 7 bits, so that an AP can accept maximum 127 multicast receivers per multicast group, and (2) the length of the *TTR* subfield is 5 bits, which supports 32 different transmission rates. If next generation WLANs need more bit rates, we can allocate more bits for the TTR field.

### 5.2 Retransmission mechanism

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 not handled by the upper layer, we can use a virtual BSSID for retransmissions as a possible solution. In infrastructure mode, the transmitter address field of a multicast frame is the address of the AP, which is the BSSID. Whenever 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 for retransmission purposes, a multicast recipient can figure out whether the incoming frame is duplicate. This technique is similar to the *virtual AP* defined in IEEE 802.11v standard [10].

In order to optimize retransmission strategy in SRM + PARF, different long and short retry counters can be applied depending on the rate of retransmitted multicast frames. For example, lost multicast frames with a high bit rate are transmitted more times than ones with a low bit rate to increase channel utilization. Moreover, in conjunction with this retransmission strategy, admission control should be applied to mitigate performance anomaly [6]. That is, some intelligent admission control techniques can prevent stations with continuously poor wireless channels from participating in a multicast session dynamically and adaptively.[6] Then, SRM + PARF provides semi-reliable multicasting with efficiency to all the STAs satisfying admission control policies. Even for STAs currently participating a multicast session, if a STA suffers from the poor channel condition longer than a certain

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[6] This is out of scope of this paper.

threshold, the STA may be excluded from the multicast session.

### 5.3 Robustness and adaptiveness

We assume that a multimedia streaming application can give the reliability requirement to the MAC layer. For example, the frame error rate should be lower than a certain threshold, *Target FER*.[7] As mentioned earlier, a multicast recipient who cannot agree on the TTR of a multicast frame will make ACK collisions. To this end, a multicast recipient should compute an expected FER and compare it with the *Target FER*. To do so, it should determine the SINR value. For this purpose, SRM + PARF selects $\alpha$ (say, 5th) percentile from the set of the measured SINR values of recently received multicast frames. It means that 5% of the observed SINR values in the set is below the selected threshold. Therefore, if the estimated FER from the TTR and the SINR is less than the *Target FER*, the recipient agrees on the TTR.

When the wireless channel condition is highly fluctuated by multipath fading, mobility and so on, the recipient with the worst SINR will be quickly switched. In that case, the SRM + PARF framework may not keep track of the recipient with the worst SINR. To adapt to fast varying condition of wireless channels, a multicast recipient who experiences its FER higher than *Target FER* will generate an IGMP Membership Report. The measured SINR of the recipient will be contained the IGMP Membership Report message. The AP will snoop this message and may select this recipient as a new leader if the SINR value is worse than other recipients.

In real environments with some obstacles, the situation may happen that a station does not receive the lost frame anymore if the station fails to recognize a multicast data frame at the PHY layer due to severe interference or environmental noise. To mitigate this problem, we can use some mechanism such as CTS-to-Self [2]. For example, the AP first transmits a CTS-to-Self frame at a basic rate (1 or 2 Mbit/s). This CTS-to-Self frame plays a role in announcing the transmission of a multicast frame. That is, 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 the basic service set without error. Then, the multicast receivers can know the loss of the multicast data frame in case of the absence of any multicast data frame after the SIFS, and then request the retransmission of the lost multicast data frame.

## 6 Performance evaluation

LBP + ARF and SRM + PARF are evaluated with ns-2 [19]. Every station communicates with the IEEE 802.11a [8] bit rates in infrastructure mode. For more realistic simulation, we use the enhanced IEEE 802.11a ns-2 module [14] with the following features.

- *BER-based PHY layer models*: As mentioned earlier, the FER is a function of the BER and the length of a frame. And the BER is a function of SINR. When a frame is received, the PHY layer measures its SINR. A mapping table between SINR and BER is stored in the PHY layer. Hence, the PHY layer can compute the BER of a received frame.
- *IEEE 802.11a multi-rate*: IEEE 802.11a supports 6, 9, 12, 18, 24, 36, 48 and 54 Mbps.
- *ARF rate adaptation mechanism*

We compare SRM + PARF with two relevant solutions: (1) multicasting with the legacy IEEE 802.11 standard, and (2) the LBP + ARF framework. Note that as for the leader selection part in LBP, which is missing in [12], we take an omniscient approach. That is, the station with the worst wireless link currently will be the leader throughout the simulation run. This is not feasible in real systems; thus, LBP + ARF should be deemed as an ideal version of reliable multicasting. The multicast source (which is the AP) and unicast stations are assumed to have the saturated traffic.

For comprehensive tests, we consider two channel models and three mobility scenarios. The first channel model is the additive white Gaussian noise (AWGN) channel with the path-loss exponent of three [17]. For the multi-path fading effect, we use the Ricean channel model as the second one [16]. The Ricean channel consists of a dominant stationary signal component, such a line-of-sight propagation radio signal, and other small-scale fading signals. We consider three mobility cases: no mobility, move-away, and random mobility.

### 6.1 No mobility scenario

In this scenario, there is one multicast flow from an AP to five recipients and other stations upload unicast flows individually. All the stations, both unicast stations and the five multicast stations, are located near an AP. Here, we turn off the rate-adaptation functions of LBP + ARF and SRM + PARF to focus on the reliability. Hence, the transmission rate for multicasting is fixed to 6 Mbps, the lowest IEEE 802.11a rate.

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[7] Cross layer optimization is needed to maximize and optimize such high-level performance objectives, e.g., we can apply different transmission multicast rates to I, P, and B packets in layered multicasting coding. However, this paper focuses only on the MAC layer, so cross layer optimization is out of scope in this paper.

Figure 3 shows the frame loss rates (FLRs) of the three solutions. As the number of unicast stations increases, the collision with a multicast sender becomes more and more severe. Hence, the loss rate of multicast frames in the legacy IEEE 802.11a multicasting becomes higher than 40% as the number of unicast stations reaches 20.[8] In contrast, both LBP + ARF and SRM + PARF achieve much lower loss rate due to retransmissions compared to the IEEE 802.11a standard. In addition, Fig. 3 exhibits the throughput ratio (TR) between unicasting and multicasting, which is defined as the ratio of the average per-station unicast throughput to the average per-station multicast throughput. A multicast source in the current IEEE 802.11 standard does not perform a binary exponential backoff mechanism, which leads to the severe fairness problem between unicast flows and the multicast flow as mentioned in [3]. However, both LBP + ARF and SRM + PARF frameworks perform a binary exponential backoff mechanism for multicasting. That is, they behave as stations with unicasting flows, and hence the multicast flow obtains the same average per-station throughput as the other unicast flows on good static wireless channel conditions.

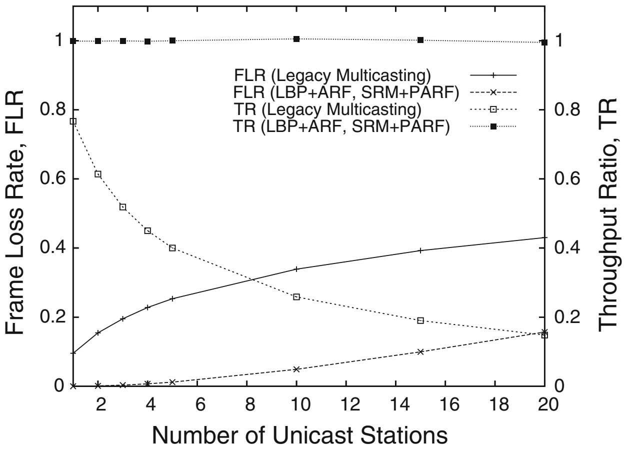

**Fig. 3** Reliability and Fairness versus the number of stations with unicasting flows. If all multicast recipients have the same good wireless channel and the rate-adaptation functions are disabled, LBP + ARF and SRM + PARF behave identically. Thus, the throughputs of LBP + ARF and SRM + PARF are also the same and hence only SRM + PARF is plotted. Legacy 802.11 multicasting suffers from high FLR as collision intensifies. Also, there is no exponential backoff in legacy multicasting, which results in the poor throughput ratio

## 6.2 Move-away scenario

Five multicast recipients are located near an AP, all of which have good channel conditions; that is, 54 Mbps transmission is possible. Among those, only one recipient is moving away from the AP at 0.1 m/s. There are also two static unicast stations near the AP, each with saturated traffic to the AP. We try to observe the performance deviation depending on the wireless link conditions of multicast recipients. Hence we select measure the average throughputs of the *best multicast receiver* and the *worst multicast receiver*, which correspond to stations with the best and the worst wireless channels, respectively.

### 6.2.1 AWGN channel model

Under the AWGN channel model, both LBP + ARF and SRM + PARF decrease the transmission rate for multicasting as the worst multicast recipient is moving away from an AP, that is, as its wireless channel condition gets worse, as shown in Fig. 4. However, multicasting in the legacy 802.11 standard shows the lowest and steady throughput due to no rate adaptation. Especially, when the transmission rate for multicasting is high (i.e., the AP and the worst multicast receiver is close), SRM + PARF achieves the somewhat higher throughput than LBP + ARF. Because the MAC header of LBP + ARF is always transmitted at the lowest rate, the overhead per multicast frame of LBP + ARF is larger than that of SRM + PARF. The throughput of the best multicast receiver is similar to that of the worst multicast receiver, and hence the best receiver's throughput is skipped for space limit.

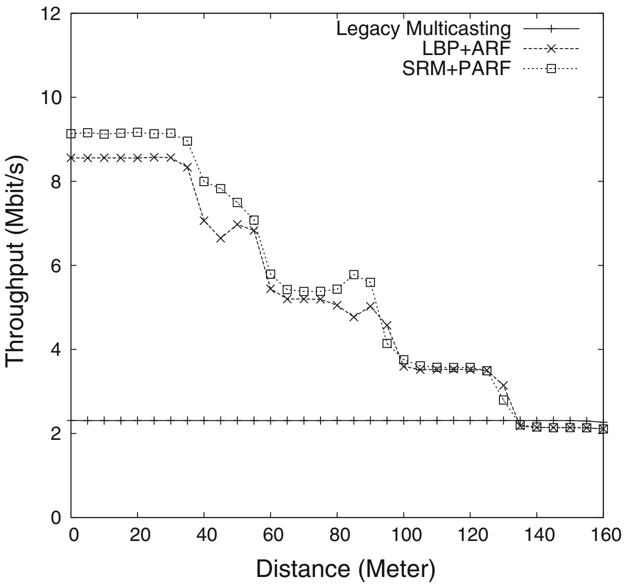

**Fig. 4** Throughput of the worst multicast receiver is plotted for legacy multicasting, LBP + ARF and SRM + PARF with the AWGN channel model in move-away scenario. As there is little deviation of frame delivery rates among receivers, we plot the throughput of the worst receiver only

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[8] In this simulation, nearly every frame loss is caused by collisions with unicasting flows.

### 6.2.2 *Ricean channel model*

We use the Ricean channel model in order to find out the effect of the multipath fading. Again, the *X*-axis represents the distance between an AP and the moving-away (worst) multicast recipient. In Fig. 5, we notice that the throughput of the worst multicast receiver in legacy multicasting is decreased after 100 m due to wireless channel errors caused by the multipath fading. Even though legacy multicasting uses the lowest bit rate, some frames are still lost because there is no retransmission mechanism for multicasting.

In Fig. 5(a), the throughputs of the best multicast receiver and the worst multicast receiver are almost the same. This is because LBP + ARF is configured to be omniscient in the sense that the worst multicast receiver is always selected as a leader. Figure 5(b) shows that in SRM + PARF, the worst and the best multicast receivers achieve the similar throughput due to relatively fast change in turns as leaders. Note that SRM + PARF achieves a little gain over LBP + ARF when the distance is small since LBP + ARF transmits the MAC header with the basic rate. As the distance increases, SRM + PARF with 5th percentile eSINR conservatively decides the bit rate and hence achieves a slightly less throughput than LBP + ARF. As mentioned in Sect. 5.3, the performance of SRM + PARF depends on the estimated FER. Therefore, when we estimate the wireless channel conditions from the set of measured SINRs, SRM + PARF conservatively estimates the FER in order to satisfy the *Target FER*. Therefore, from Fig. 5(a) and (b), LBP + ARF achieves a slight gain over SRM + PARF as the worst multicast receiver moves away from the AP.

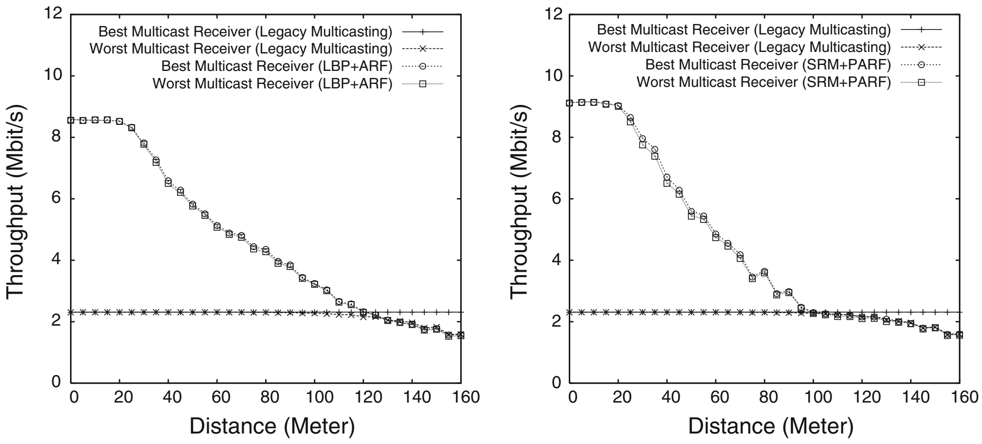
## 6.3 Random mobility scenario

We compare the scalability of LBP + ARF and SRM + PARF by increasing the number of multicast receivers, each of which moves with the random waypoint mobility model. The number of multicast receivers increases from 2 to 20. We arbitrarily designate one of the receivers, which is statically located near an AP, which corresponds to the best multicast receiver. The others move about within the 60 m × 60 m area. The maximum velocity of moving receivers is 1 m/s and the pause time is 1 s. Additionally, two static stations are used to generate saturated unicast traffic. They are also located near the AP.

As discussed in Sect. 5.3, each receiver in SRM + PARF needs to calculate the *estimated SINR* (eSINR). For the eSINR, we consider two percentile values for the eSINR: the 5th percentile eSINR and the 50th percentile eSINR. In case of the 50th percentile eSINR, SRM + PARF uses the median in the set of SINRs as the estimated SINR for the following multicast frame.

### 6.3.1 *AWGN channel model*

We first use the AWGN channel model in order to show the baseline performance of LBP + ARF and SRM + PARF when the multicast receivers are moving randomly. As shown in Fig. 6, the throughputs of the best multicast receiver and the worst multicast receiver are almost equal. However, as the number of multicast receivers increases, the average multicast throughput decreases. This is because, with the random waypoint mobility, the distance between the AP and the worst multicast receiver increases as the



**(a)** LBP+ARF **(b)** SRM+PARF

**Fig. 5** Throughput is compared between legacy multicasting, LBP + ARF and SRM + PARF with the Ricean channel model in move-away scenario. *X*-axis indicates the distance between the AP and the moving away multicast receiver. Note that SRM + PARF achieves a little gain over LBP + ARF when the distance is small since LBP + ARF transmits the MAC header with the basic rate. As the distance increases, SRM + PARF with 5th percentile eSINR conservatively decides the bit rate and hence achieves a slightly less throughput than LBP + ARF number of multicast receivers increases. In Fig. 6, SRM + PARF using the 50th percentile eSINR outperforms LBP + ARF due to the large header overhead of LBP + ARF. The case of the 5th percentile eSINR exhibits the similar pattern and hence is skipped. Thus we can see that how to set the percentile for eSINR does not affect the performance when the channel is relatively stable.

### *6.3.2 Ricean channel model*

From Figs. 6 and 7, we observe that the average multicast throughput on the Ricean channel is smaller than that on the AWGN channel due to the multi-path fading effect. Especially, as shown in Fig. 7(a), LBP + ARF has a throughput gain over SRM + PARF using the 5th percentile eSINR. Because the wireless channel conditions are highly fluctuated due to the multi-path fading, SRM + PARF with the 5th percentile eSINR conservatively estimates the FER for the next multicast rate selection. However, in case of Fig. 7(b), SRM + PARF using the 50th percentile eSINR achieves the performance similar to LBP + ARF. Because SRM + PARF using the 50th percentile eSINR takes a higher value for the FER estimation, it can achieve the higher throughput compared to the 5th percentile eSINR. Note that the throughput deviation between the best and the worst multicast receivers becomes slightly wider due to less conservative eSINR selection.

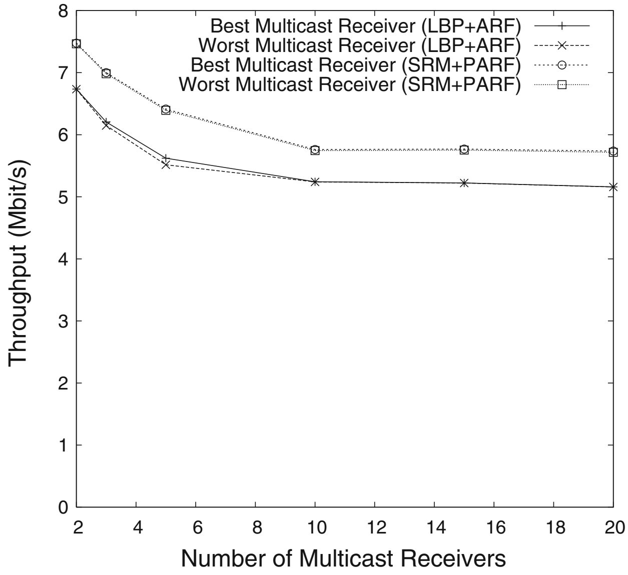
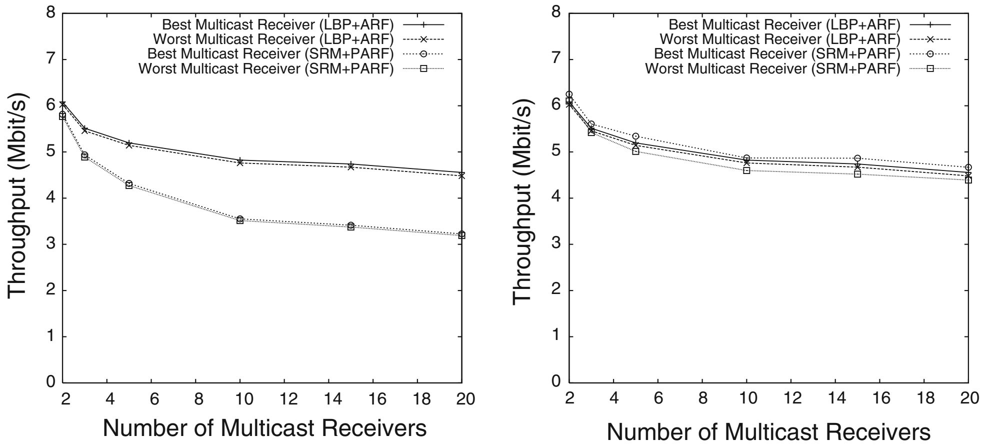


**Fig. 6** Throughput is compared between LBP + ARF and SRM + PARF (50th percentile) on the AWGN channel in the random mobility scenario. SRM + PARF using the 50th percentile eSINR outperforms LBP + ARF due to the large header overhead of LBP + ARF. The case of the 5th percentile eSINR exhibits the similar throughput and hence is skipped

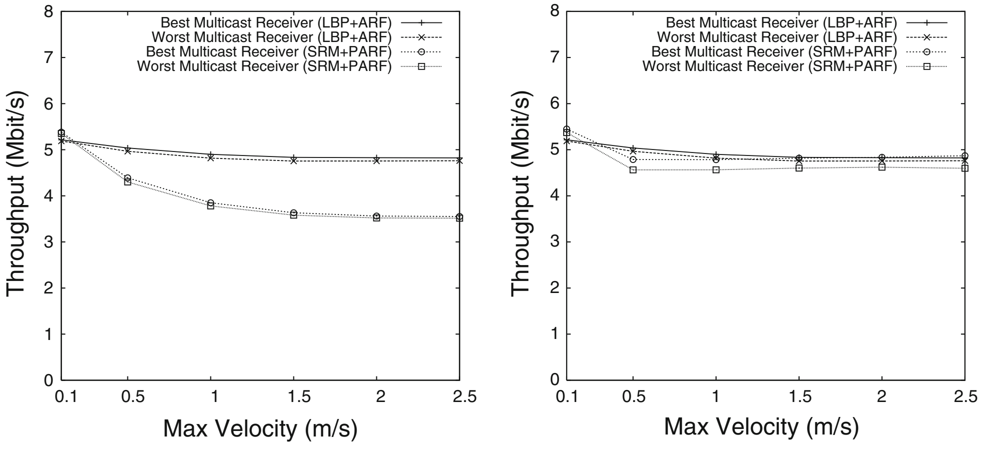
We also carry out additional simulation experiments to show the relationship between the throughput (or transmission rate) and the maximum velocity of mobile stations in the case of the Ricean channel. The *Max velocity* refers to the maximum possible speed of a mobile station in the Ricean channel model. If the *Max Velocity* is low, the wireless channel condition will be relatively stable. As the *Max Velocity* increases, the wireless channels will be more and more fluctuated. In this scenario, the number of multicast receivers is fixed to 10. Figure 8 shows the throughputs of the best and the worst multicast receiver. The *X*-axis is the *Max Velocity* in the Ricean channel model, which ranges from 0.1 to 2.5 m/s. As shown in Fig. 8(a) and (b), the multicast receiver's throughput of SRM + PARF decreases as the *Max Velocity* increases. Especially, in Fig. 8(a), SRM + PARF using the 5th percentile eSINR experiences performance degradation. In Fig. 8(b), by using the 50th percentile eSINR, SRM + PARF computes the FER more optimistically and hence achieves similar throughput to that of LBP + ARF.

To observe the effect of mobility on LBP + ARF and SRM + PARF in other aspects, Fig. 9 shows the average frame loss rate (FLR) and the average transmission rate for

**Fig. 7** Throughput is compared between LBP + ARF and SRM + PARF on the Ricean channel with the 5th and 50th percentiles in the random mobility scenario. SRM + PARF with the 5th percentile eSINR conservatively decides the rate and hence achieves less throughput than LBP + ARF. However, SRM + PARF using the 50th percentile eSINR achieves the performance similar to LBP + ARF due to less conservative rate adjustment



**(a)** SRM+PARF ($5^{th}$ percentile) **(b)** SRM+PARF ($50^{th}$ percentile)



**(a)** SRM+PARF ($5^{th}$ percentile) **(b)** SRM+PARF ($50^{th}$ percentile)

**Fig. 8** Throughput is compared between LBP + ARF and SRM + PARF as mobility increases on the Ricean channel in the random mobility scenario. The *X*-axis is the maximum possible speed of a multicast station. The throughput of SRM + PARF decreases as the *max velocity* increases. SRM + PARF using the 5th percentile eSINR experiences performance degradation due to conservative rate adaptation. SRM + PARF using the 50th percentile eSINR computes the FER more optimistically and hence achieves similar throughput to that of LBP + ARF

multicasting as the *Max Velocity* of the Ricean channel model increases. For a given mobility (or the level of channel fluctuation), SRM + PARF can control the tradeoff between the transmission rate (TxRate) and the FLR by adjusting the percentile of eSINR. Compared to SRM + PARF with 5th percentile eSINR, SRM + PARF with the 50th percentile eSINR optimistically adjusts the TxRate and hence exhibits the higher FLR and the TxRate as shown in Fig. 9. LBP + ARF is configured to be omniscient and always adjusts the TxRate considering the worst link condition. That is why the FLR of LBP + ARF is similar to that of SRM + PARF with 5th percentile eSINR (conservative case) and yet the TxRate of LBP + ARF is even higher than that of SRM + PARF with 50th percentile eSINR. However, from Fig. 8, we can observe that there is not so much difference in the achieve throughput between LBP + ARF and SRM + PARF with the 50th percentile eSINR. One of the reason is that the MAC header of LBP + ARF is always transmitted at the basic rate, which degrades the throughput to a certain degree.

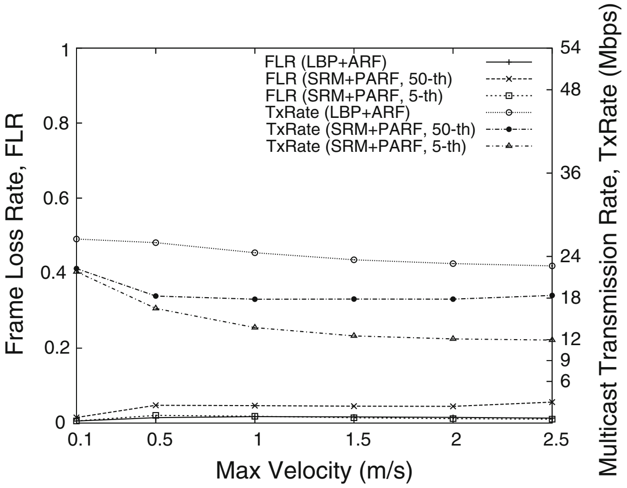


**Fig. 9** Frame loss rate (*FLR*) and average transmission rate (*TxRate*) are plotted as mobility on the Ricean channel increases in the random mobility scenario. We can control the performance of SRM + PARF by adjusting the percentile of eSINR. Compared to SRM + PARF with 5th percentile eSINR, SRM + PARF with the 50th percentile eSINR achieves the higher TxRate and hence exhibits the higher FLR

## 7 Related work

Kuri et al. [12] proposed a novel mechanism called a leader-based protocol (LBP) for multicasting in IEEE 802.11 wireless LANs in order to improve the reliability of multicast frames. LBP selects one of multicast receivers as a leader, so that the leader will send an ACK frame to a multicast sender. However, LBP requires non-IEEE802.11-compliant frames and mechanisms. Dujovne et al. [4] experimentally test LBP by emulating LBP multicasting. That is, an AP sends unicast frames to a particular node and other nodes overhears those frames. And all the receptions by the nodes are logged for reliability analysis. The experimental study confirms that LBP outperforms the legacy IEEE 802.11 standard by lowering the packet loss rate significantly. However, it does not detail how to select the multicast receiver with the worst channel condition as a leader.

Peng et al. [15] proposed a new Automatic Repeat reQuest scheme for reliable Broadcasting (BARQ). It incurs the light control overhead by introducing a virtual ACK bitmap. In BARQ, a sender needs to specify the following elements in this bitmap: the starting time, the timeslot length, and the assignment of the timeslots to broadcasting receivers. When a receiver needs to confirm its reception of a frame with the sender, it transmits the carrier (or an ACK pulse) for a specified period of time in the assigned timeslot announced in the bitmap. Basically, a sender constructs a virtual ACK bitmap after sending a frame and the receivers fill in the bitmap to indicate their reception status of the frame. The sender then checks the filled-in bitmap to determine if retransmission is needed. However, BARQ does not comply with the IEEE 802.11 standard.

Villalon et al. [20] proposed Auto Rate Selection for Multicasting (ARSM). ARSM adopts LBP for reliability and improves network throughput by allowing an AP to dynamically select the bit rate for multicasting based on the feedbacks on multicast receivers' channel conditions. If the AP detects the losses of consecutive multicast frames, it sends a Multicast Prove (MP) frame to the receivers to reduce the transmission bit rate for multicasting. The MP frame contains the Signal-to-Noise Ratio (SNR) of the current leader. Upon receiving the MP frame, each multicast receiver estimates its own SNR and replies to the AP by issuing a Multicast Response (MR) frame containing its estimated SNR. Depending on the estimated SNR value, each receiver sets its backoff timer to reduce the collision probability among MR frames. After receiving MR frames, the AP chooses its transmission bit rate to adapt to the lowest SNR value. However, the ARSM requires new MAC control frames and modifies the PHY layer header as well.

## 8 Conclusion

We propose a new multicasting framework in wireless LANs, SRM + PARF, to enhance multimedia streaming services in terms of reliability and link efficiency. The key building blocks of the SRM + PARF framework are the leader selection and the rate adaptation mechanisms. For operational robustness, the leader selection protocol makes every multicast receiver take its turn as a leader, who is responsible for reliability. To efficiently handle reliability, a station with the worse signal-to-interference-noise ratio (SINR) serves as a leader for a longer time. The SINR also determines the frame error rate. By making each station monitor its own SINR, rate adaptation is performed to satisfy the frame error rate required by streaming applications. Compared to the prior multicasting solutions in wireless LANs, one of the key advantages of SRM + PARF is the compatibility with the legacy 802.11 standard and IGMP. Comprehensive simulation reveals that SRM + PARF achieves the throughput and the reliability similar to those of an omniscient multicasting framework.

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## References

1. Cantieni, G. R., Ni, Q., Barakat, C., & Turletti, T. (2005). Performance analysis of finite load sources in 80211b multirate environments. *Elsevier Computer Communications Journal, 28*(10), 1095–1109.
2. Choi, S., Choi, N., Seok, Y., Kwon, T., & Choi, Y. (2007). Leader-based rate adaptive multicasting for wireless LANs. IEEE GLOGBECOM 2007, Washington, USA, November 2007.
3. Choi, N., Ryu, J., Seok, Y., Choi, Y., & Kwon, T. (2006). Unicast-friendly multicast in IEEE 802.11 wireless LANs. IEEE CCNC 2006, Las Vegas, USA, January 2006.
4. Dujovne, D., & Turletti, T. (2006). Multicast in 802.11 WLANs: An experimental study. INRIA research report, May 2006.
5. Fenner, W. (1997). Internet group management protocol, version 2. RFC 2236, November 1997.
6. Heusse, M., Rousseau, F., Berger-Sabbatel, G., & Duda, A. (2003). Performance anomaly of 802.11b. IEEE INFOCOM 2003, San Francisco, USA, April 2003.
7. Heusse, M., Rousseau, F., Guillier, R., & Duda, A. (2005). Idle sense: An optimal access method for high throughput and fairness in rate diverse wireless LANs. ACM SIGCOMM 2005, Philadelphia, USA, August 2005.
8. IEEE WG. (1999). Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: High-speed physical layer in the 5GHz Band. IEEE 802.11 Standard, 1999.
9. IEEE WG. (2008). Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Enhancements for higher throughput. IEEE 802.11n D7.0, November 2008.
10. IEEE WG. (2008). Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Wireless network management. IEEE 802.11v D3.0, November 2008.
11. Kamerman, A., & Monteban, L. (1997). WaveLAN II: A high-performance wireless LAN for the unlicensed band. *Bell Labs Technical Journal*, 118–133 (Summer 1997).
12. Kuri, J., & Kasera, S. (2001). Reliable multicast in multi-access wireless LANs. *ACM Wireless Networks, 7*(4), 359–369.
13. Lacagne, M., Manshaei, M. H., & Turletti, T. (2004). IEEE 802.11 rate adaptation: A practical approach. IEEE/ACM MSWiM 2004, Venice, Italy, October 2004.
14. New 802.11 PHY and MAC modules. http://yans.inria.fr/ns-2-80211/, online link.
15. Peng, J. (2008). A new ARQ scheme for reliable broadcasting in wireless LANs. *IEEE Communications Letters, 12*(2).
16. Punnoose, R., Nikitin, P., & Stancil, D. (2000). Efficient simulation of Ricean fading within a packet simulator. IEEE VTC Fall 2000, Boston, USA, September 2000.
17. Rappaport, T. S. (1996). *Wireless communications: Principle and practice*. Englewood Cliffs, NJ: Prentice-Hall.
18. Seok, Y., Choi, Y., Kwon, T. & Bonnin, J. (2006). Temporal fairness guarantee in multi-rate wireless LANs for per-flow protection. ACM/Kluwer Wireless Networks (WINET).
19. The network simulator - ns-2. http://www.isi.edu/nsnam/ns/, online link.

20. Villalon, J., Seok, Y., & Turletti, T. (2006). Auto rate selection for multicast in multi-rate wireless LANs. IFIP PWC 2006, Albacete, Spain, September 2006.

## Author Biographies

**Nakjung Choi** received the B.S. and Ph.D. degrees in computer science and engineering from Seoul National University (SNU), Seoul, Korea, in 2002 and 2009, respectively. From September 2009 to April 2010, he was a postdoctoral research fellow in the Multimedia and Mobile Communications Laboratory, SNU. Since April 2010, He is a member of technical staff at Alcatel-Lucent, Bell-Labs Seoul. His research interests are mobile and wireless networks, such as wireless LANs, wireless mesh network, and delay/disruption tolerant networks (DTNs).

**Yongho Seok** received B.S. in computer engineering from Handong University, M.S. and Ph.D. in computer engineering from Seoul National University, in 2000, 2002 and 2005, respectively. From October 2005 to September 2006, he was a postdoctoral researcher in PLANETE group, INRIA, France. Since November 2006, he is a senior researcher in Mobile Communication Technology Laboratory, LG Electronics Institute of Technology. His research interest lies in the field of wireless LAN and ireless mesh networking, such as IEEE 802.11s, IEEE 802.11z and Very High Throughput (VHT) WLAN.

**Taekyoung Kwon** is an associative professor in the school of computer science and engineering, Seoul National University (SNU) since 2004. Before joining SNU, he was a post-doctoral research associate at UCLA and at City University New York (CUNY). He obtained B.S., M.S., and Ph.D. degree from the department of computer engineering, SNU, in 1993, 1995, and 2000, respectively. During his graduate program, he was a visiting student at IBM T. J. Watson research center and University of North Texas. His research interest lies in sensor networks, wireless networks, IP mobility, and ubiquitous computing.

**Yanghee Choi** received B.S. in electronics engineering at Seoul National University, M.S. in electrical engineering at Korea Advanced Institute of Science, and Doctor of engineering in computer science at Ecole Nationale Superieure des Telecommunications Paris, in 1975, 1977, and 1984, respectively. He has been with Electronics and Telecommunications Research Institute during 1977–1979 and 1984–1991 as director of Data Communication Laboratory, and Protocol Engineering Center. Since 1991, he is a professor at school of computer science and engineering, Seoul National University. He was a president of Korea Information Science Society. He is now director of Computer Network Research Center at Seoul National University, and leads Multimedia and Mobile Communications Laboratory. He was Associate Dean of Research Affairs of Seoul National University. He is also chair of the Future Internet forum of Korea.