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High throughput MAC layer multicasting over time-varying channels ☆

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A B S T R A C T

Efficient, scalable and robust multicasting support from the MAC layer is needed for meeting the demands of multicast based applications over WiFi and mesh networks. However, the IEEE 802.11 protocol has no specific mechanism for multicasting. It implements multicasting using broadcasting at the base transmission rate. We identify two fundamental reasons for performance limitations of this approach in presence of interference and realistic time-varying channels: (a) *Channel-state Indifference:* irrespective of the current quality of the channel to the receivers, the transmission always uses the base transmission rate; (b) *Demand Ignorance:* packets are transmitted by a node even if children in the multicast tree have received those packets by virtue of overhearing. We propose a solution for MAC layer multicasting called HIMAC that uses the following two mechanisms: *Unary Channel Feedback (UCF)* and *Unary Negative Feedback (UNF)* to respectively address the shortcomings of 802.11. Our study is supported by measurements in simulations. We observe that the end-to-end throughput of multicast sessions using MAODV can be increased by up to 74% while reducing the end-to-end latency by up to a factor of 56.

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1. Introduction

Wireless LANs and mesh networks based on the 802.11 technology are being rapidly deployed in public hotspots to provide ubiquitous coverage. With increasing wireless data coverage and increasing capabilities of hand-held devices, multimedia streaming based applications are becoming critical to support. The success of multimedia devices has already established the surprisingly high demand for live and stored streaming multimedia content. These applications can significantly benefit from multicasting support from the network.

Although multicasting has been studied at routing and higher layers, MAC layer multicasting has not been well explored. The current 802.11 protocol achieves multicasting at the MAC layer using broadcasting, as there is no explicit mechanism for multicasting. Two inherent problems of this approach arising due to interference and time-varying channels are as follows: (a) *Channel-state Indifference:* broadcasting uses the base transmission rate which may be much lower than the highest acceptable rate for the multicast neighbors. (b) *Demand Ignorance:* recent enhancements to multicast protocols [1] use packet overhearing in the multicast tree. If the children nodes of a given node have received a packet, there is no demand for that packet from the children nodes. However, 802.11 transmits multicast packets regardless of their demand. *In this paper we propose HIMAC, a solution for efficient, scalable and robust multicasting at the MAC layer. Our focus here, is on improving the throughput, which is required by multimedia applications, by solving the above mentioned drawbacks of 802.11 based multicasting.*

MAC layer multicasting with time-varying data rates has not been studied before, although some multicasting solutions at the routing layer have accounted for links with different data rates [2–4]. Most MAC layer multicast protocols focus on the reliability metric. Kuri and Kasera [5] provided a reliable multicast protocol for WLANs, which is not suitable for ad hoc networks. BMW [6] proposes an approach for reliable multicasting using a round-robin approach that amortizes the cost of querying each node for ensuring reliability, but it can introduce arbitrary long latency for data packets. The BMMM [7] approach increases reliability of the MAC layer, but it is not fully scalable. Several approaches [8–10] use busy-tone on a separate channel to implement multicast reliability, but the use of a secondary channel increases the hardware complexity. In [11], authors present an approach that tries to increase throughput by enhancing the resource utility in networks. This approach uses queue-lengths and estimates of the number of responding neighbors by measuring the busy-tone power level,

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to determine whether to defer or continue with a multicast transmission. It has been evaluated primarily for single-hop scenarios. But, it can introduce arbitrary long latency for data packets and has a divergent behavior when the network traffic is heavy in multi-hop scenarios. Another problem of this approach is that it is difficult to accurately estimate the number of responding neighbors by measuring the power level because of fading in wireless links [12]. Time-varying channels and rate control has been studied by other researchers for unicast transmissions [13–15]. To the best of our knowledge, our approach is the first MAC layer multicasting solution that accounts for realistic time-varying channels and uses multiple rates supported by the physical layer.

HIMAC uses two novel mechanisms namely, *Unary Channel Feedback (UCF)* and *Unary Negative Feedback (UNF)* to respectively address the above mentioned two limitations of 802.11 based MAC layer. Both UCF and UNF are unary signals. The duration of the unary signal is used to encode information. A node can receive several unary signals simultaneously without losing the required information (i.e., the longest length among all received unary signals), which ensures the scalability of HIMAC. Unary signals are also more robust compared to binary signals. A naive implementation of unary signals is to use the baseband signal to send a tone of the desired duration. However depending on the wireless channel properties, multiple such overlapping signals may cancel each other. In Section 4.3, we discuss a robust implementation for obtaining scalable feedback from multiple receivers using the OFDM [16] technology.

In HIMAC, before the transmission of every packet, the sender first broadcasts an RTS. On receiving the RTS, the receivers that have overheard this data packet respond with a UNF. Other receivers respond with a UCF to inform the sender about its highest acceptable rate. If the sender only receives UNF, which means that no receiver needs this data packet, the sender simply drops the data packet. If the sender receives UCF, it estimates the highest tolerable rate supported by all its receivers and forwards the data packet.

The organization of the rest of the paper is as follows. Related work is discussed in Section 2. Section 3 presents the two limitations of 802.11 based MAC layer. Section 4 presents the complete design of HIMAC. Analysis of our protocol is presented in Section 5. The detailed performance evaluation using simulations are presented in Section 6. Finally, Section 7 concludes the paper with pointers to future work.

2. Related work

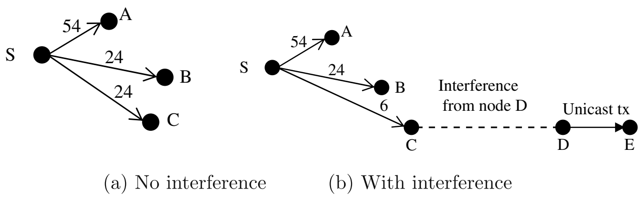
Prior research in wireless multicast and broadcast has focused on the transport layer [17,18], network layer [19–27] and MAC layer [5–11,23,28–31]. Time-varying channels and rate control has been studied by researchers for unicast transmissions [13–15].

Transport layer and network layer multicast protocols: end-to-end multicast and broadcast protocols [17,18] address mechanisms to reliably recover lost packets and minimize overhead of information exchange among nodes. Network layer multicast protocols [19–22] address efficiency and reliability considering various aspects of wireless links such as mobility and shared broadcast medium. Some multicast and braodcast routing protocols [23–25] address the issue of energy efficiency. Zhou and Singh [27] presented a new multicast model based on the content of the multicast data for ad hoc wireless networks. Nagy and Singh [26] investigated how to efficiently multicast data to mobile users in cellular networks. Bhatia and Li [32] analyzed techniques for maximizing multicast rate in multi-hop wireless networks. Although most transport and network layer multicast protocols work with any MAC layer protocols, the efficiency of the MAC layer protocol affects the efficiency of higher layer protocols.

MAC layer multicast protocols: IEEE 802.11 MAC protocol implements multicast using broadcast. As the 802.11 broadcast is unreliable, several protocols [5,7,6,8–10,29,30] have been proposed to improve the reliability. Kuri and Kasera [5] proposed a reliable multicast protocol for WLANs. This protocol is based on many assumptions, such as direct communication and perfect synchronization, which are not suitable for ad hoc networks. Moreover, it uses negative acknowledgments which can not ensure reliable transmission because when the receiver does not receive both RTS and the data packet, the receiver will not send NAK to the sender. Tang and Gerla [29,30] extended the broadcast mechanism of 802.11 that tries to confirm that at least one receiver receives the broadcast packet in ad hoc networks. In [6], Tang and Gerla proposed the BMW (Broadcast Medium Window) protocol which implements broadcast based on unicast and lets receivers overhear packets. BMW is a scalable protocol, but it can introduce an arbitrary long latency for data packets. In [7], Sun et al. proposed the BMMM (Batch Mode Multicast MAC) protocol to implement reliable MAC layer multicast. Basically, BMMM needs n pairs of RTS/CTS exchange and n pairs of RAK (Request for ACK)/ACK exchange for the transmission of one data packet to n receivers. This approach is not scalable and is not practical in high-traffic networks. Some MAC layer multicast/broadcast protocols, such as BPBT [8], RMAC [9], and 80211MX [10], use busy-tone to implement multicast reliability. Busy-tones can prevent data frame collisions and solve hidden terminal problem. However, it requires a separate channel, which increases the hardware complexity.

Singh et al. [23] proposed a MAC layer protocol to support power-aware broadcasting in mobile ad hoc networks. Jaikaeo and Shen [28] investigated the benefits and the impact of using directional antennas for multicast communications in ad hoc networks. Chaporkar et al. [11,31] proposed algorithms for maximizing throughput for MAC layer wireless multicast using busy-tones. Their basic idea is that after the sender sends RTS to the receivers on the message channel, all receivers that are ready to receive the data packet send a busy-tone on a busy-tone channel. Then, the sender estimates the number of ready receivers by measuring the power of the busy-tone signal. If the power of the busy-tone signal is higher than the threshold, the sender will send data packets; otherwise, the sender retransmits RTS. The power threshold is decided by the queue length of the sender, which makes this protocol simple. The shorter the queue length, the higher the threshold to confirm more receivers are ready to receive the data packet. This protocol has three problems. First, it is difficult to accurately estimate the number of responding neighbors by measuring the power level because of fading in wireless links [12]. Second, it can introduce an arbitrary long latency for data packets. For example, if only one packet is in the sender's queue, the threshold is very high. But if the link quality is bad and no other data packets arrive at the sender's queue, this packet will always stay in the sender's queue because the power level is always lower than the threshold. Third, if the network's traffic is heavy, this protocol will let the senders set the threshold to 0, and force senders to transmit the multicast data packets as fast as possible, which can increase collisions. It can thus reduce the throughput of multicast communication. Although the authors have shown their analysis for a single-hop network, we believe that the protocol has a divergent behavior in multi-hop scenarios. Their simulations are also limited to single-hop scenarios.

MAC layer multi-rate unicast protocols: as the IEEE 802.11 physical layer supports multi-rate transmissions, several unicast protocols have been proposed to exploit this capability. In [13], Kamerman and Monteban present the ARF (Auto Rate Fallback) protocol for IEEE 802.11, used in Lucent's WaveLAN II devices. In ARF, senders increase their transmission rates after consecutive transmission successes and reduce their rates after consecutive



(a) No interference (b) With interference

Fig. 1. Channel-state Indifference: 802.11 always transmits at the base-rate. (a) 24 Mbps multicast transmission rate is the best. (b) 24 Mbps multicast transmission rate is the best if the packet transmission from *D* to *E* interferes with *C*'s multicast transmission.

transmission failures. RBAR (Receiver Based Auto Rate) protocol is proposed in [14]. The key idea of RBAR is to let the receiver measure the channel quality. The receiver then determines the transmission rate for the data packet as the highest feasible value allowed by the channel condition. Sadeghi et al. proposed the OAR (Opportunistic Auto Rate) protocol in [15]. The major difference between OAR and RBAR is that OAR lets the sender send more packets when the channel quality is high.

3. Problems with 802.11 multicast

IEEE 802.11 implements multicasting by transmitting packets at the base transmission rate upon observing a clear channel. Unlike the RTS/CTS mechanism designed for unicast transmissions, it does not have any mechanism to obtain feedback from the intended multicast receivers. In this section we present two fundamental problems of multicasting using 802.11: *Channel-state Indifference and Demand Ignorance*, which justify the need for a new MAC layer approach for multicasting.

3.1. Channel-state Indifference

The properties of wireless channels are time-dependent due to factors such as interference, multi-path effects, and fading. As a result of these time-varying channels, the data rates supported by different users at different instances of time can fluctuate. As these channel properties are determined at the receiver, the sender needs to obtain feedback about the channel quality to each receiver in order to identify the best data rate to transmit the multicast packets. As the multicast implementation in 802.11 does not estimate the quality of this time-varying channel, it has to consider the worst case and hence transmit all packets at the base-rate which is 6 Mbps for 802.11g/a and 1 Mbps for 802.11b. Consider an 802.11g/a MAC layer with one sender and 3 receivers as shown in Fig. 1(a). The 802.11 protocol transmits packets at 6 Mbps. But, if the sender *S* can learn about the quality of the channel to the receivers, it can transmit at 24 Mbps, thus obtaining a four times speedup in transmission time. If multicast packet transmissions at 54 Mbps are feasible considering the link qualities of all the receivers, the speedup is by a factor of 9.[1] Of course, the overheads of feedback communication, back-offs, and physical layer header (always transmitted at base-rate) will have to be accounted for, in order to obtain the net performance gain.

Fig. 1(b) shows three receivers with maximum supportable rates of 54, 24, 6 Mbps. We can see that the receiver with the poorest channel can support a maximum rate of only 6 Mbps and hence the sender needs to transmit at 6 Mbps. It may seem that in this scenario, the channel feedback will be wasteful. However, suppose that an ongoing transmission on another link causes interference for user *C* with 6 Mbps channel to result in a collision with the multicast transmission. If the sender can learn about it in advance, it can still transmit at 24 Mbps maintaining a speedup factor of 4, without affecting the delivery ratio compared with the 802.11 MAC layer approach, in which node *S* transmits at 6 Mbps while node *C* still does not receive the data packet.

Although the MAC layer can be modified to obtain feedback from all the receivers, the challenge is to do so in a scalable fashion such that the total time for communication is independent of the number of receivers.

3.2. Demand Ignorance

Most ad hoc multicast protocols construct a tree [19] or mesh based sub-structure [33] in the network to forward multicast packets. However, recent advances in AODV [1] have suggested a solution involving packet overhearing to supplement forwarding losses on the tree. By taking advantage of the broadcast nature of the channel, this approach improves packet delivery ratio as nodes on the multicast tree can overhear multicast packets from other on-tree nodes in addition to receiving from its parent. This improvement in MAODV brings out another shortcoming of 802.11 based multicasting. Although the sender may know the list of its children in the tree, it does not know whether any children are still missing a multicast packet or not. Thus the multicast packet transmitting node is ignorant of the demand for the packet. If all the children have received a packet by virtue of overhearing, then the multicast transmission may be wasteful.

Consider the example shown in Fig. 2 which shows an MAODV session with sender *S*, receivers *A*, *B* and a forwarding node *F*. If a packet transmitted from *S* is overheard by all nodes, then for that packet the multicast transmission from node *F* is not needed. However, in absence of feedback from nodes *A* and *B*, *F* will end up transmitting the packet unnecessarily.

Thus, feedback from the receivers regarding the status (received before or not) of the current packet will help the sender in avoiding unnecessary transmissions. Implementing this approach in a scalable way is challenging. Observe that lack of feedback can not be used as an indication for lack of need for the packet, as feedback may also be suppressed by the receivers due to interference from hidden terminals.

4. Protocol description

HIMAC consists of two mechanisms namely *Unary Channel Feedback (UCF)* and *Unary Negative Feedback (UNF)* to address the limitations of multicasting in 802.11. UCF can work as a stand alone model to solve the Channel-state Indifference problem stated previously. UCF in combination with UNF solves the Demand Ignorance problem. In this section, we also discuss briefly about the implementation of unary feedback in the physical layer.

4.1. Unary Channel Feedback (UCF)

The UCF mechanism addresses the Channel-state Indifference problem. The state of the channel, which can rapidly vary over

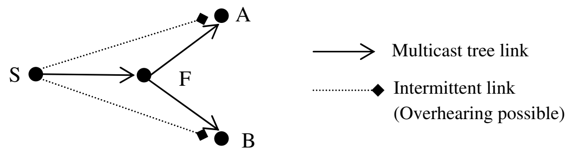


Fig. 2. Demand Ignorance: In absence of feedback, *F* can not know whether its downstream nodes have received the packet by virtue of overhearing or not.

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[1] Transmitting at higher data rates always increases the error rate. But for good channel conditions, the increase in error rate may be acceptable. Most researchers [14] use 1% packet error rate as the guideline for determining the best data rate for unicast packets.

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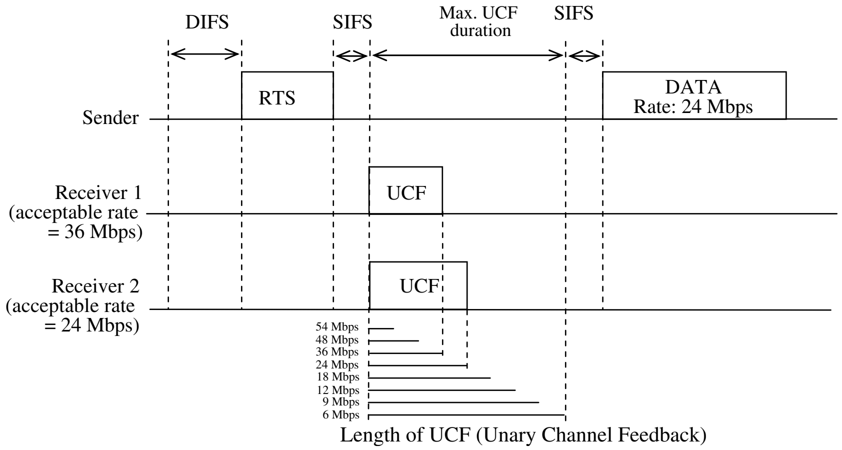

Fig. 3. Unary Channel Feedback: multiple UCF signals from receivers will overlap but the sender can still determine the highest required rate based on the longest UCF signal.

short durations [14], is known only at a receiver. In order for the sender to choose the optimal data rate for transmitting multicast packets, it needs to learn the current state of the channel at all the receivers. A naive approach of obtaining separate feedback from each receiver just before transmitting the packet does not scale with the number of neighboring receivers. In addition, the delay and overhead of multiple feedbacks from receivers can easily outweigh any possible savings in data transmission time.

In order to ensure scalability, robustness and low overhead, HIMAC uses unary encoding of feedback from the receivers. In our approach, the duration of the unary signal is used to encode information. Before the transmission of every data packet, the sender broadcasts an RTS (Request To Send) packet. The RTS packet contains the MAC layer multicast address[2] to enable the receivers to determine if they need to respond with a UCF. In response, each potential receiver sends a unary signal (UCF) that encodes the highest acceptable rate based on the channel quality measured after receiving the RTS. As the rate selection is performed by every receiver immediately before the data packet transmission, the selected rate is always suitable for the data packet transmission to each receiver. As opposed to binary encoded packets that are susceptible to collisions, we claim that the receivers of unary signals can determine the length of the longest unary signal even after multiple unary signals are received simultaneously, which is possible even in cases with destructive interference as long as the sender can hear some activity in the channel near the end of the longest unary signal. Also, the information stored at every bit is important for a binary signal to decode it, while in our encoding using the unary signals, only the duration of the signal matters, which makes unary signals more robust. The highest data rate is encoded with a short duration unary signal and progressively lower rates are encoded with longer unary signals. Therefore collective unary responses at the sender are sufficient to determine the optimal data rate for transmission. We emphasize here that all the receivers need not be synchronized when sending the UCF signals according to the implementation of UCF specified in Section 4.3. The absence of any UCF after sending the RTS indicates that the receivers (if any are still present in the neighborhood) are not in a position to accept the data packet. Thus, when UCF is absent, unnecessary data transmissions can be avoided to improve performance. The sender then re-attempts to transmit the packet after backing off according to unicast transmission rules in 802.11.

Fig. 3 shows an example where the maximum possible rate is inferred from the longest UCF signal. In this example there are two receivers with channel rates of 36 and 24 Mbps. As the UCF for the 24 Mbps is longer than the UCF from the 36 Mbps receiver, the sender will learn that it needs to transmit the packet at 24 Mbps.

Although a separate channel will be ideal for the UCF packets, it requires two radios and increases the hardware complexity. Instead, we assume that the UCF packets are sent in-band.

The UCF mechanism introduces overhead (RTS and UCF packets) for multicast in the MAC layer. But it provides the following benefits:

- The sender can confirm there is at least one receiver ready to receive the packet, which improves the packet reliability compared with 802.11.
- The sender can use higher rate than the base-rate to send data packets, which reduces latency.

For example, if the size of the data packet is 1000 bytes, the packet transmission time is 1333 μs at the base-rate of 6 Mbps in 802.11g/a. The next higher rate in 802.11g/a is 9 Mbps. The transmission time at 9 Mbps is 889 μs. The overhead of RTS + UCF is only 94 μs.[3] Thus we could see that even if we go to the next possible higher rate, the latency is reduced from 1333 μs to 889 + 94 μs. The latency for the data packet transmission is 148 μs at 54 Mbps which is much smaller than the latency at 6 Mbps. Thus we can conclude that the transmission at any rate higher than 6 Mbps will surely reduce the latency and improve throughput.

Note that the UCF approach can not confirm 100% reliability although it is better than 802.11 standard. However, it is not necessary for multimedia applications to support 100% reliability, and high throughput is much more important.

4.2. Unary Negative Feedback (UNF)

The UNF approach is designed for a multi-hop network where over-hearing is possible. In the plain UCF approach (without UNF), the receivers always respond to an RTS with the UCF packets even if they have overheard that data packet before. We now present our solution to address the problem of Demand Ignorance. A simple extension to UCF, where the recently overheard data packets could be cached, can avoid transmitting the UCF in case the packet has been overheard. This requires the maintenance of a cache that is indexed by packet IDs. Although locally unique packet IDs can be used for such purposes, a naive ap-

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[2] Every multicast IP address is mapped to a MAC layer multicast address.

[3] It includes 20 μs of 2 SIFS intervals. We assume that the longest UCF signal is 40 bits.

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proach is to use a globally unique packet ID formed by the IP address of the source and a unique sequence number assigned at the source to identify the packets. The RTS will also contain the packet ID. This extension to UCF saves network resources by avoiding unnecessary feedback from the receivers that have overheard the packet. But if all the receivers have received the packet, there will be no UCF received by the sender and this will lead to multiple retransmission attempts by the sender till it exceeds the maximum limit for retries. This is wasteful as retransmissions are preceded by backoff periods that increases exponentially with each attempt.

The UNF approach attempts to differentiate the scenarios of no demand for a packet and heavy interference. In the former case, the sender needs to drop the packet whereas in the latter case, the packet transmission is re-attempted. In this approach, the receivers who have previously overheard the packet respond with UNFs to inform the sender while the receivers who have not previously overheard the packet respond with UCFs. Like UCF, multiple UNFs may overlap without loss of any relevant information. The sender needs to learn the presence or absence of the UNF in case there is no UCF. The UNF signal is useful for the sender only if there are no UCF transmissions. In such a case, the presence of UNF indicates that the receivers that heard the RTS and that have a clear channel to receive this transmission have already received the packet. Thus, the absence of UCF and the presence of UNF triggers the sender to drop the packet. The absence of both UCF and UNF strongly indicates that the receivers (if any are present in the neighborhood) are not in a position to receive the packet. So, the sender backs off and then retransmits the RTS. If the sender receives both UNF and UCF, only the information contained by UCF is useful. Therefore, we let the length of the UNF to be shorter than the shortest UCF.

Fig. 4 shows an example where the two neighbors of a sender have received the packet by overhearing. On receiving the RTS, each receiver responds with a UNF. As both the receivers send the UNF, the sender sees no UCF and decides to drop the packet.

When the UNF approach is implemented, there is a possibility that only UNF signals are sent by some receivers while the receivers that have not received the data packet are not able to send the UCF signals to the sender because they have not received the RTS sent by the sender, which results in no data packet transmission. However, if in this case 802.11 MAC layer multicasting/broadcasting approach was used and the sender broadcast the data packet without first sending the RTS packet, those receivers would also not be in a position to receive the data packet. Because the transmission time for RTS and UNF is much shorter than the transmission time for the data packet, HIMAC saves the channel resources, which helps to increase the throughput of the network.

Combining UCF and UNF, HIMAC works as follows:

1. When the sender has multicast data packet to send, it sends an RTS to the receivers.
2. On receiving the RTS from the sender, the receivers who have the data packet send UNF and the receivers who do not have the data packet send UCF to indicate the highest acceptable rates to the sender.
3. If the sender only receives UNF, the sender drops the data packet and the data transmission is canceled. If the sender receives UCF, it sends the data packet with the highest acceptable rate among all receivers who have sent UCF. If the sender does not receive either UCF or UNF, it retransmits RTS like in the case of 802.11 unicast.

The NAV set in the RTS is the duration from the end of the RTS transmission to the beginning of the data packet transmission as shown in Fig. 4.

4.3. Implementation of unary feedback

The feedback from the receivers should enable the sender to reliably compute the minimum of the data rates of channels to the receivers. A naive implementation is to use the baseband signal to send a tone of the desired duration. However depending on the channel properties such as attenuation, multi-path effects and phase, multiple such overlapping signals may cancel each other, making it difficult for the sender to extract the minimum channel rate information from the combined feedback. We discuss a robust implementation for obtaining scalable feedback from multiple receivers using the OFDM [16] technology.

The current OFDM based 802.11 a/g hardware can be leveraged to implement the concept of scalable feedback from receivers. OFDM uses 48 sub-carriers to deliver data and four sub-carriers to send reference signals in every channel as shown in Fig. 5. OFDM receivers can decode 52 sub-carriers simultaneously. Thus, if we assign different sub-carriers to different receivers, then simultaneous feedback can be obtained from all the receivers. If each receiver also sends reference signals, then the number of supportable receivers will be reduced. If each receiver sends two reference signals on two sub-carriers along with one sub-carrier containing information on the data rate, then 52/3 = 17 receivers can be supported using this solution. The data-rate information is coded using the length of the signal as discussed before. Although binary encoding of the data-rate feedback is possible with OFDM sub-carriers, unary signal will have the advantage of higher robustness. Even if the feedbacks from the receivers are not synchronized with each other, the sender can compute the duration for each of

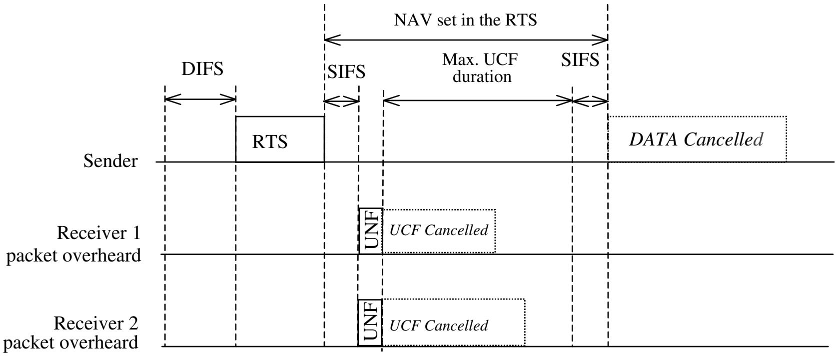

Fig. 4. Unary Negative Feedback: receivers send UNF if they have overheard the packet before. The overlapping UNF signals still carry the message to the sender that all those nodes that can receive the packet do not have demand for this packet any more.

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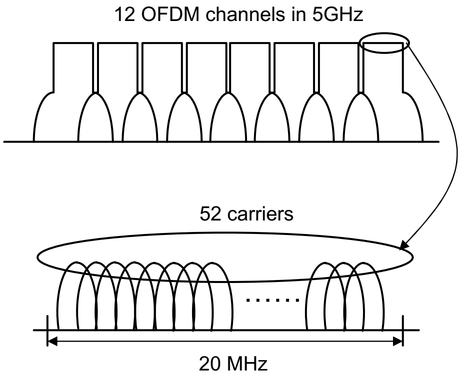

Fig. 5. IEEE 802.11a OFDM PHY channel.

the sub-carriers which encodes the channel quality. As feedback from the receivers is encoded in orthogonal frequencies, our approach can tolerate synchronization differences between receivers. For designing a system that supports more receivers, receivers can be grouped into multiple time slots where up to 17 receivers can use one time slot. However, for higher number of receivers, most transmissions will typically require the base-rate and our approach will have limited advantage over 802.11 which uses transmission at the base-rate for all multicast packets. So for high user scenarios, transmission at base-rate can be used.

The above technique can also be used for encoding the UNF feedback from the receivers. As described in Fig. 4, if a time slot is reserved for the UNF signal, then the mechanism described above for UCF can also be used for UNF encoding. Another approach is to allow the UCF and the UNF signals from multiple receivers to overlap in time while encoding UNF with a duration that is smaller than any UCF. This is possible as a receiver either sends a UCF or a UNF feedback. Thus, our approach provides a scalable encoding for the UCF and the UNF signals that is robust to synchronization differences among the receivers.

5. Protocol analysis

HIMAC uses current information about the channels to the receivers to determine its actions. However the overhead introduced by the extra control packets can reduce the benefits of HIMAC. In this section, we analyze the performance of the UCF mechanism.

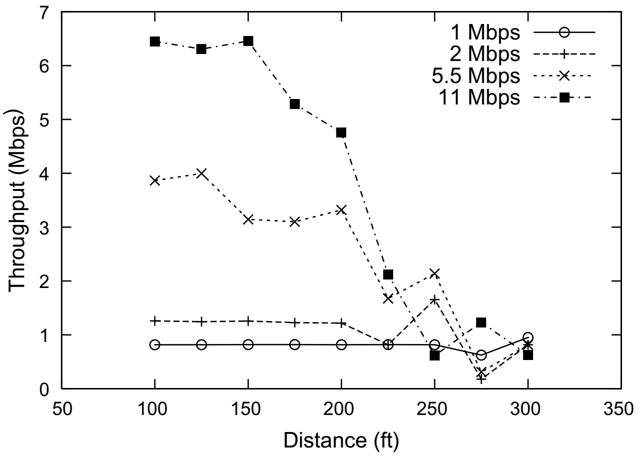

Fig. 6. Experimental throughput between two nodes in a corridor: 11 Mbps is best for a considerable distance. 1 Mbps is the best choice only beyond 275 ft.

We assume that the physical layer supports n different transmission rates: $\rho_1 < \rho_2 < \rho_3 < \cdots < \rho_n$. Corresponding to each ρ_i, there is a circular transmission range $R_i (R_1 > R_2 > R_3 > \cdots > R_n)$ within which that data transmission rate results in an acceptable packet error rate.[4] A data rate ρ_i is said to be *feasible* for a user if the user is within a distance of R_i from the sender. Receivers are uniformly randomly distributed in the circle C_1 of radius R_1 centered at the sender.

Let P_{ij} represent the probability that rate ρ_i is feasible for a given set of j users randomly placed in the circle C_1. (i.e., the probability that j users are all in the circle of radius R_i centered at the sender.) Since the area of a circle of radius R_i is πR_i^2, the probability that rate ρ_i is feasible for a single receiver is

$$P_{i1} = \frac{\pi R_i^2}{\pi R_1^2} = \frac{R_i^2}{R_1^2} \tag{1}$$

The probability P_{im} that the rate ρ_i is feasible for all the m receivers is

$$P_{im} = P_{i1}^m = \left(\frac{R_i^2}{R_1^2}\right)^m \tag{2}$$

To calculate the potential benefit that can be obtained by HIMAC, we conducted an experiment using two laptops equipped with 802.11b NICs. The experiment was conducted in a long indoor corridor. The NIC used for the experiments was Netgear WG511T that is based on the Atheros chipset. As the NIC and the madwifi driver does not support rate adjustments for broadcast packets, we conducted our study using unicast packets. RTS/CTS and retransmissions were disabled to obtain measurements relevant for multicasting. Each point in Fig. 6 is obtained by transmitting 10,000 packets from one node to the other. The graph shows that when all the receivers are located within 225 feet from the transmitting node, transmissions at 11 Mbps performs the best. Surprisingly in this experiment we observe that for a distance up to 275 ft, transmission at 2 Mbps results in higher throughput in comparison to transmission at the base-rate of 1 Mbps. This implies that our UCF approach will improve performance as long as all the receivers are within 275 ft from the sender in the given experimental setting. The transmission range of the sender is about 300 ft. By using these ranges and Eq. (2), we can compute the probability that the feasible rate is higher than the base-rate. Fig. 7 shows this probability for varying number of receivers. In our simulations we observe a typical value of 4 or 5 neighboring receivers. For five receivers, we observe that there is still a 40% chance that the transmission rate can be enhanced using HIMAC.

In HIMAC, the sender always uses the highest rate that it can use to send packets. Therefore, the expected transmission rate E_ρ for m receivers is (assume $P_{n+1,m} = R_{n+1} = 0$)

$$E_\rho = \sum_{i=1}^{n} \rho_i * (P_{im} - P_{i+1,m}) \tag{3}$$

$$= \sum_{i=1}^{n} \rho_i * \left(\left(\frac{R_i^2}{R_1^2}\right)^m - \left(\frac{R_{i+1}^2}{R_1^2}\right)^m \right) \tag{4}$$

We now compute the expected transmission rate for the two classes of 802.11 physical layers.

- *802.11b PHY:* In order to simplify calculating the expected rate for 802.11b, we assume the transmission range is 150, 200, 275, and 300 ft for transmission rates of 11, 5.5, 2 and 1 Mbps, respectively. Using Eq. 4, we obtain Fig. 8(a), which shows the

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[4] We assume it is true to simplify our analysis although the packet error rate is also related to some other factors, such as interference.

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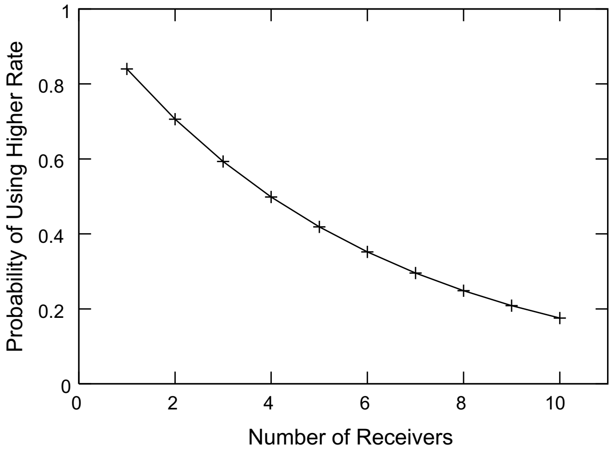

Fig. 7. Probability that the feasible rate is higher than the base-rate based on measurement data (Fig. 6): The probability is still 50% when the number of receivers is 4; 18% when the number of the receivers is 10.

expected rate. Note the expected transmission rate in the legacy 802.11 is constant when the number of receivers is increasing since the sender can only use the base-rate to mulicast/broadcast a data packet in the legacy 802.11. If the size of the data packets is 1000 bytes and there are five receivers, the expected transmission rate is 1.48 Mbps and the expected latency for a data packet is 5284 μs[5] while it is 8000 μs if the base-rate of 1 Mbps is used. The latency of RTS and UCF (including 20 μs of 2 SIFS intervals) is 460 μs. Thus, even after taking into account the overheads of the RTS and UCF packets, HIMAC performs better than 802.11b.

- *802.11a/g PHY:* Using the range ratios in Table 2 and Eq. 4, we get Fig. 8(b). If the size of the data packets is 1000 bytes and there are five receivers, the expected transmission rate is 9.01 Mbps and the expected latency for a data packet is 887 μs while it is 1333 μs if the base-rate of 6 Mbps is used. The latency of RTS and UCF (including 20 μs of 2 SIFS intervals) is 94 μs. Thus, even for 802.11a/g physical layers, HIMAC performs better.

6. Performance evaluation

We have implemented our protocol in ns-2.28. Using extensive simulations we observe that HIMAC performs significantly better than 802.11. We use MAODV [19] as the network-layer multicast protocol. It should be mentioned that HIMAC is independent of the network-layer multicast protocol. HIMAC reduces the one-hop MAC layer latency by up to a factor of 6. The end-to-end throughput of multicast sessions using MAODV can be increased by up to 74% while reducing the end-to-end latency by up to a factor of 56.

6.1. Simulation environment

Table 1 summarizes the simulation settings. These simulation settings are used for both 802.11 and HIMAC in all simulations unless mentioned otherwise. Table 2 shows the transmission rates that the physical layer can support, the corresponding SNR thresholds, and the ratio of the corresponding transmission range to the range for the base-rate. For modeling time-varying channels we implemented the Rayleigh fading model [12] in ns-2. Because of fading, the receiving power changes dynamically even when the transmission power and the distance between the sender and the receiver are fixed. The average transmission range corresponding to the base-rate is about 150 m. For each simulation case, four random scenarios are simulated, and each scenario's simulation time is 400 s. The minimum and maximum values are represented using vertical bars in the graphs.

Table 1
Simulation settings: default environment values unless mentioned otherwise.

Area size	500 × 500 m^2
Number of nodes	50
Maximal node speed	10 m/s
Number of senders	1
Number of seceivers	10
DATA packet size	1460 bytes
Load	200 packets/sender/s
Transmission power	0.28183815 W
Carrier-sensing power threshold	2.35729217e–10 W
Receiving power threshold	6.041482e–09 W
CS/RX range ratio	2.25
Variance of Rayleigh fading	0.6366
MIN (basic) transmission rate	6 Mbps
MAX transmission rate	54 Mbps

The metrics used for performance study are as follows:

- *End-to-end throughput:* the average number of packets received by each receiver per second.
- *One-hop MAC layer latency:* the average latency of the receivers receiving the packets at the MAC layer.
- *End-to-end latency:* the average latency of the receivers receiving the packets at the network layer.

It should be mentioned that the end-to-end latency is not just the summation of the MAC layer latencies. It includes other delays such as queuing delay. In the simulation results discussion, *Throughput* means end-to-end throughput, *MAC latency* means MAC layer (one hop) latency, and *Latency* means end-to-end latency.

6.2. Network density

By changing the network area, we study the impact of the network density. Note that the nodes cannot move out from the network area. When a node reaches the boundary of the network area, it will change its moving direction to stay in the area. So, the average density for the whole network area does not change over simulation time. Fig. 9 shows the results for different area sizes. From these figures, we observe that HIMAC (UCF and UNF mechanisms together) performs better than UCF. When the area is small, the throughput is high for all the three protocols as the receivers are close to the sender which increases the chances of receiving the packets. When the area is 100 m × 100 m, the latency of HIMAC is 0.006 s while the latency of 802.11 is 0.336 s. This can be explained by observing that when the density is very high, most of the nodes in the network share the same medium. Higher transmission rates used in HIMAC and UCF reduce the medium access time for transmissions. So HIMAC and UCF can still withstand the high load of 200 packets/s set in these simulation. For 802.11, this load is not manageable due to the use of base transmission rate. The impact is seen more on the delay experienced by the packets transmitted using 802.11. This is because every sender has to wait longer for accessing the medium, which increases the MAC latency and the queuing delay significantly. As UNF improves performance over UCF, the rest of the simulations in this paper compare 802.11 with HIMAC, which includes both the mechanisms.

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[5] This calculation ignores the fact that the preamble and the PHY headers are always sent at the base-rate.

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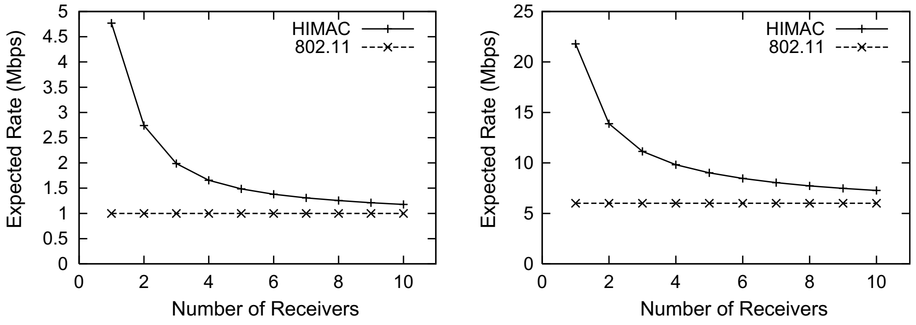
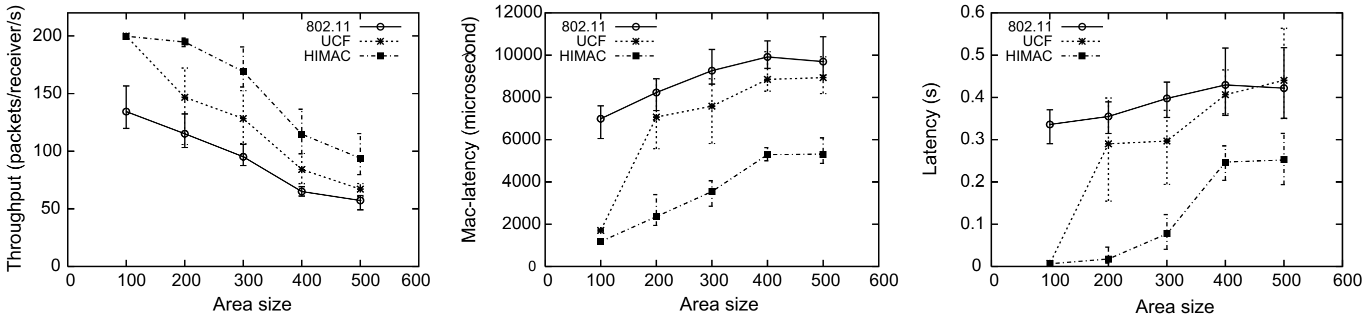


(a) 802.11b (b) 802.11a/g

Fig. 8. Expected rate vs. number of receivers: (a) 802.11b and (b) 802.11a/g.

Table 2
SNR thresholds and transmission range ratios to the base-rate.

Rate (Mbps)	6	9	12	18	24	36	48	54
SNR threshold (db)	21	22	23	26	30	34	38	40
Trans. range ratio	1	0.94	0.89	0.75	0.60	0.47	0.38	0.34



(a) Throughput (b) MAC Latency (c) Latency

Fig. 9. Network density: when the area size is 100 m × 100 m, the latency of HIMAC is 56 times lower than 802.11 because of significant MAC latency and queuing latency reduction.

6.3. Node speed

Fig. 10 shows the impact of the maximum speed for the random way-point mobility model. Fig. 10(a) shows that the throughput is highest when the node speed is 1 m/s as Rayleigh fading is changed slowly. Slow speed also makes the multicast tree more stable. At all speeds, HIMAC has much higher throughput than 802.11. For low speed of 1 m/s, the throughput of HIMAC is 101.8 packets/receiver/s, while for 802.11 it is 65.6 packets/receiver/s. The improvement in throughput is 55.2%. HIMAC's latency and MAC latency are also much smaller than 802.11. HIMAC reduces MAC latency by 40% and latency by 10–20%.

6.4. Packet size

Fig. 11 shows the impact of packet size. It is easy to see from the figures that HIMAC still outperforms 802.11 MAC even when the packet size is small. It implies that the benefit of the reliability and high delivery rate of HIMAC overcomes the cost of the control overhead related to HIMAC even for small packet sizes. When the packet size is 250 bytes, the MAC latency and latency of HIMAC are similar to the ones of 802.11. The throughput of HIMAC is higher than 802.11 by 10% because HIMAC improves the multicast reliability and uses multi-rate multicast in MAC layer. When the packets size is 125 bytes, the performance of HIMAC and 802.11 are almost same while the throughput of HIMAC is still higher than 802.11.

6.5. Network load

Fig. 12 shows the impact of load. We find that the throughput and latency of HIMAC is similar to 802.11 at low network loads, because the network bandwidth is high enough to deliver those packets to receivers, even using 802.11. The MAC latency of HIMAC is always smaller than 802.11 because of high delivery rate of HIMAC. With increasing network load, HIMAC's performance improvement becomes more significant. The reason is that when the load is high, there are more collisions in the network and the bandwidth of the network is not high enough. However, HIMAC makes multicast faster and more efficient compared with 802.11.

6.6. Number of multicast sessions

Fig. 13 shows the impact of the number of multicast sessions. Every multicast session contains 1 sender and 10 receivers. For scenarios with 10 multicast sessions in the network, where every sender sends 200 packets per second, the traffic in the network is very heavy. 802.11 does not have any support for multicast or broadcast reliability. It always tries to broadcast packets as soon as the sender's channel is available regardless of the receivers'

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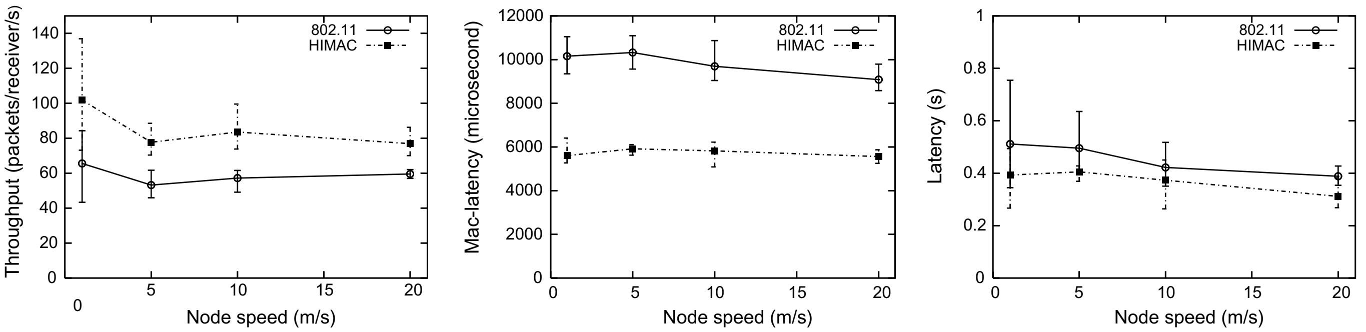
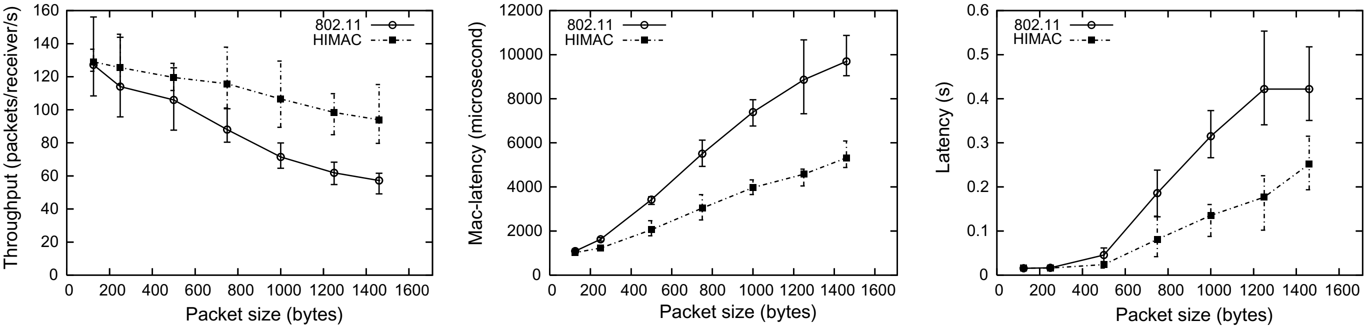


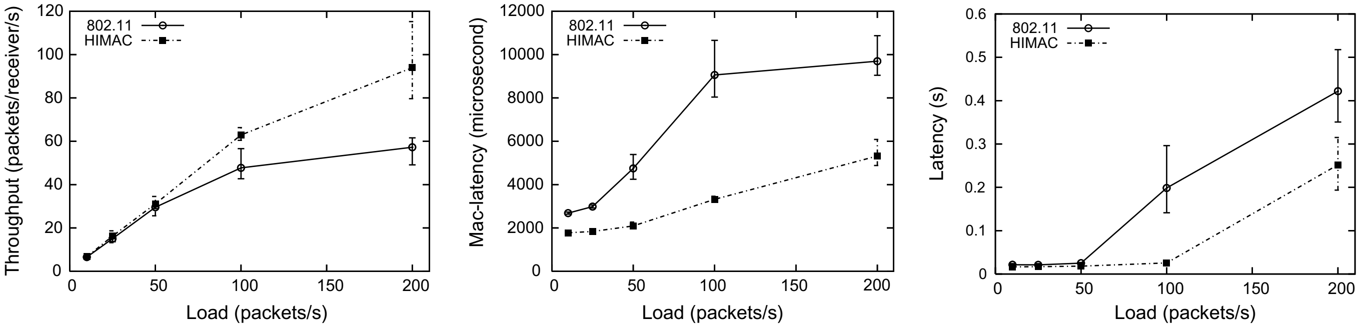
(a) Throughput (b) MAC Latency (c) Latency

Fig. 10. Node speed: when the speed is 1 m/s, the throughput is highest and the improvement of HIMAC in throughput is 55.2% at a speed of 1 m/s. HIMAC reduces MAC latency by 40%.



(a) Throughput (b) MAC Latency (c) Latency

Fig. 11. Packet size: when the packet size is 250 bytes, the throughput of HIMAC is higher than the one of 802.11 by 10% although their MAC latency and latency are similar.



(a) Throughput (b) MA CLatency (c) Latency

Fig. 12. Network load: with increasing network load, HIMAC's performance improvement becomes more significant.

channels. However, HIMAC not only increases the transmission rate, but also enhances the delivery reliability. In HIMAC, the sender does not send packets until some receivers are ready to receive packets. Therefore, when the number of multicast sessions is high, the throughput of HIMAC is much higher than 802.11 although the latency of HIMAC slightly exceeds that of 802.11 for higher number of sessions. The throughput of HIMAC is 74% higher than 802.11 in the scenarios with two multicast sessions.

6.7. Number of receivers

Fig. 14 shows the impact of number of receivers. We observe that HIMAC always outperform 802.11 in all cases. However, when the number of receivers is increased, the improvement of HIMAC reduces. The reason is that when the number of receivers increases, the size of the multicast tree becomes larger and the average number of receivers for a data packet increases in the MAC layer, which reduces the excepted rate for HIMAC and reduces the performance of HIMAC. Another reason is that when the number of the receivers increases for a sender in MAC layer, the probability that all the receivers have overheard the data packet reduces. So, the sender sends more packets when the number of receivers increases, which consumes more network resources and reduces the performance of HIMAC. When the number of the receivers is five, the throughput of HIMAC is 74% higher than 802.11. The MAC latency of HIMAC is 40–53% lower than 802.11.

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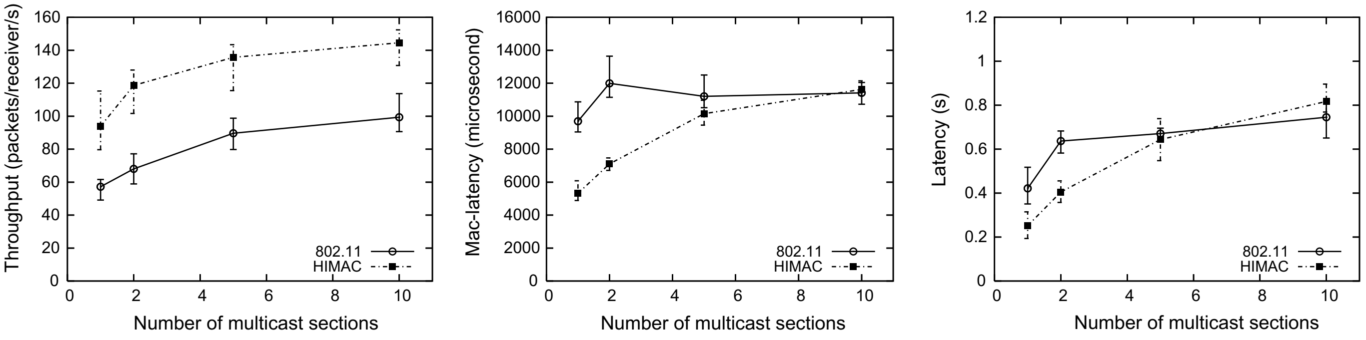
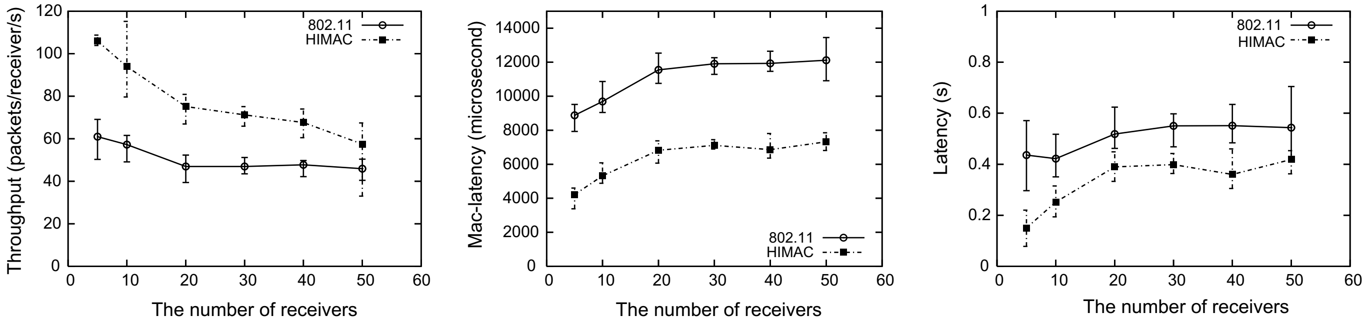


(a) Throughput (b) MAC Latency (c) Latency

Fig. 13. Number of multicast sessions: the throughput of HIMAC is 74% higher than the one of 802.11 in the scenarios of two multicast sessions.



(a) Throughput (b) MAC Latency (c) Latency

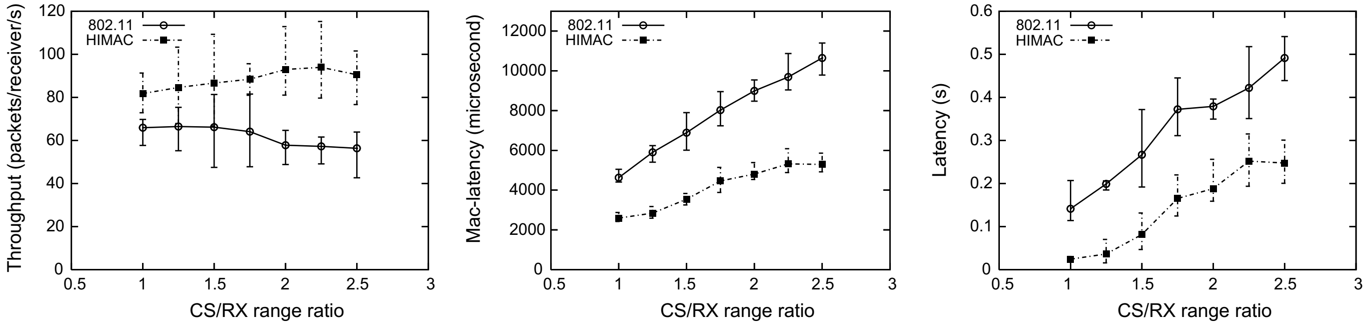
Fig. 14. Number of receivers: when the number of the receivers is 5, the throughput of HIMAC is 74% higher than 802.11.

6.8. CS/RX range ratio

The ratio of carrier sensing threshold and the transmission/reception range depends on factors such as the hardware and the environment [34]. Fig. 15 shows the impact of CS/RX range ratio. In this simulation, we fix the receiving power threshold and change the carrier sensing threshold to change CS/RX range ratio. When the CS/RX range increases, the throughput of HIMAC slightly increases while the throughput of 802.11 slightly reduces. The reason is that when the CS/RX range ratio increases, the interference (noise) reduces in networks because carrier sensing range becomes larger, which makes it possible for HIMAC to use higher rates to transmit data packets and increase throughput. On the other hand, a large CS range reduces the total number of simultaneous MAC layer multicast transmissions, which reduces the throughput of multicast. HIMAC outperforms 802.11 for all CS/RX range ratios. When the ratio is 2.25, the throughput of HIMAC is 64% higher than 802.11.

7. Conclusion

Time-varying channels and multiple physical layer data rates have never been considered in the design of MAC layer multicast protocols. Multicasting in 802.11 is achieved by physical layer broadcast which suffers from the following two problems identified in this paper: Channel-state Indifference and Demand Ignorance. The proposed HIMAC solution addresses these problems using the Unary Channel Feedback (UCF) and Unary Negative Feedback (UNF). HIMAC provides a novel approach to the design of an efficient, scalable and robust MAC layer. We analyze the solution



(a) Throughput (b) MAC Latency (c) Latency

Fig. 15. CS/RX range ratio: HIMAC outperforms 802.11 significantly for all CS/RX range ratios.

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using measurements to support our claims. Extensive performance evaluation with realistic Rayleigh fading model in ns-2 simulations shows that HIMAC performs significantly better than 802.11 in terms of throughput, MAC latency, and end-to-end latency.

As part of our ongoing work, we are studying the performance of unicast as a special case of our approach. We are working on emulating HIMAC in large scale testbeds (ORBIT at Rutgers) by obtaining the receivers' feedback over Ethernet, as current NICs do not allow changes to the MAC layer. We are also trying to address the problem of hidden terminal nodes that are neighbors of the multicast receivers and can only hear the UCF or UNF generated by the multicast receivers. As it is impossible to set NAV in UCF or UNF, which are unary signals, these nodes do not know the length of the duration of data packet transmission. If these nodes and the multicast sender transmit simultaneously, the multicast receivers will not receive the data packets correctly. We will also address how to assign a set of sub-carriers to the receivers in a distributed manner when OFDM technology is used to implement unary signals.

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