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Efficient Retransmission Methods in Wireless MAC Protocol for Multicast

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Abstract Recent studies on reliable wireless multicast have focused on sending acknowledgement packets from all member stations to the source. Although these studies provide methods of improving the reliability, there have not been any studies on retransmission methods for wireless multicast. Multicast packets are retransmitted based on the unicast transmission rule, which retransmits until all members successfully receive the packet. In this paper, an efficient retransmission method is proposed. The retransmission lasts until the target packet delivery ratio of each member is met. Moreover, the contention window size for retransmission is adjusted based on the reception status of the previous transmission. The performance of the proposed wireless multicast is evaluated by extensive simulations.

Keywords Wireless · Multicast · Retransmission · MAC

1 Introduction

Multicast is used to transmit data to a group of nodes identified by a single destination address. Only one transmission is required to deliver a data packet to many receivers (multicast members). Thus, multicast is a potential bandwidth-efficient technique for group communications such as tactical communications, public safety networks, and wireless Internet Protocol

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Television (IPTV). A particular emerging technology based on multicast is the IPTV service. IPTV multimedia traffics are delivered through IP multicast [1]. Multicast over wired lines has been extensively studied over a period of decades and there appears to be no reliability issue, because wired lines provide pretty static and clean channels. Recently, IPTV has tried to provide seamless and ubiquitous services. This can be achieved by extending the wired-based IPTV service to the wireless-based one. However, IPTV over a wireless channel has emerged as a challenging topic due to the error-prone characteristic of the wireless channel. To make matters worse, wireless multicast uses no acknowledgement (ACK) from member stations (STAs), because of the large overheads that increase as a function of the number of members. This overhead negates the advantage of multicast. Therefore, many wireless standards such as WiMax, Wireless Local Area Networks (WLANs), and cdma2000 (1xEV-DO) use multicast as a broadcast method that does not require retransmission and feedbacked ACK frames [2–4]. In these standards, multicast has been used for broadcasting periodic control messages and real-time traffic including voice and video. These require fast delivery rather than reliability. Therefore, the ACK and packet retransmission are not necessary. However, many recent multimedia applications use play-back systems which first store the traffic and then play it later. In addition, many multicast-based communication networks such as public safety networks and tactical networks have started to use multimedia traffic over wireless links. In these networks, reliability is inherently required for any data transmissions. That is, multicast is not a one-time transmission but needs to provide reliable transmissions.

The source node has to receive ACKs from all multicast members in order to achieve reliability over wireless multicast. However, these multiple ACKs cause increasing overhead as the number of members increases. Although the provision of multicast reliability at the Medium Access Control (MAC) layer has received increasing attention, as shown in [5–12], most of these studies have not resolved the overhead issues associated with acknowledging multicast packets over wireless links. Although there is no increase in overheads as the number of member stations increases in the protocols proposed in [13,14], they still have an additive frame that causes overhead and the hidden node problem. On the other hand, the Orthogonal Frequency-Division Multiple Access (OFDMA)-based ACK (OMACK) in [15] remarkably reduces the overhead by incorporating the OFDMA characteristics into the ACK frame format. In OMACK, each subcarrier in an Orthogonal Frequency-Division Multiplexing (OFDM) symbol is assigned to each multicast member, and the members make one OFDM symbol to allocate their ACK on their sub-carrier. The sub-carrier indicates the members' reception status. All members simultaneously transmit their OFDM symbols after receiving a multicast packet.

Although the issue of ACKs transmitted by members can be solved by using OMACK, the problems associated with the retransmission method have not been resolved by any protocol in [5–12,14]. Problems include the number of times a source retransmits a multicast packet and when it retransmits the packet. The retransmission in OMACK follows the unicast retransmission rule, which retransmits until all members successfully receive the packet for each transmission and increases the contention window size for each retransmission. This rule causes too many retransmissions, and makes the contention window size too large. Thus, the efficiency of wireless multicast is diminished.

In this paper, two characteristics of wireless multicast and unicast are observed. The first characteristic is that not all multicast packets need perfect reliability. That is, some packet losses for streaming video or audio can be tolerated by members depending on the traffic Quality of Service (QoS), such as priority, delay constraints, etc. This is achieved by modern coding technologies, as illustrated in [16]. Therefore, the level of retransmission required to achieve perfect reliability may waste limited network resources, which not only diminishes the efficiency of wireless multicast, but also deteriorates the overall network performances. The second characteristic is the increase of the contention window size for retransmission. Unlike unicast, multicast retransmits a packet if any members do not acknowledge it, even when the other members have done it. Since multicast retransmission follows the unicast rule, the contention window size increases for each retransmission up to the maximum contention window size. As a consequence, retransmission in wireless multicast is hampered by the large backoff time. However, in a one-hop communication environment, if any members acknowledge the multicast packet, the packet loss by the members is most likely due to a channel error rather than collision. Therefore, increasing the contention window size for each retransmission is inefficient.

In this paper, an efficient retransmission method for wireless multicast is proposed based on the aforementioned two characteristics of wireless multicast. We first review the OFDMA-based Automatic Repeat Request (ARQ) for wireless multicast as a preliminary study. In Sect. 3, the proposed protocol is illustrated. In Sect. 5, the proposed protocol is thoroughly evaluated through simulations and the performance enhancement is shown. Finally, our conclusion is given in the last section.

2 Preliminaries

OMACK proposes not only an ACK method for multicast, but also a new ACK format for multicast, as shown in Fig. 1. OMACK is a simple packet consisting of a preamble and an OFDM symbol with a cyclic prefix. Each member STA has a pre-assigned unique sub-carrier number for each group ID. The details of the sub-carrier assignment are given in [15]. When a member STA receives a multicast packet from the sender, it allocates one of the two BPSK symbols (1 or -1) on the pre-assigned sub-carrier as an ACK for the packet. '1' indicates a successful reception of the multicast packet on the sub-carrier, and '-1' indicates a failed reception. It is assumed that all member STAs simultaneously send their OMACKs after a Short Interframe Space (SIFS) idle period. At the multicast sender, the sub-carriers of the received OMACK are loaded with BPSK symbols in order to indicate each member's reception status. Therefore, all ACKs from all members are simultaneously received at the sender without any collisions, due to the orthogonality of the subcarriers. Thus, this scheme does

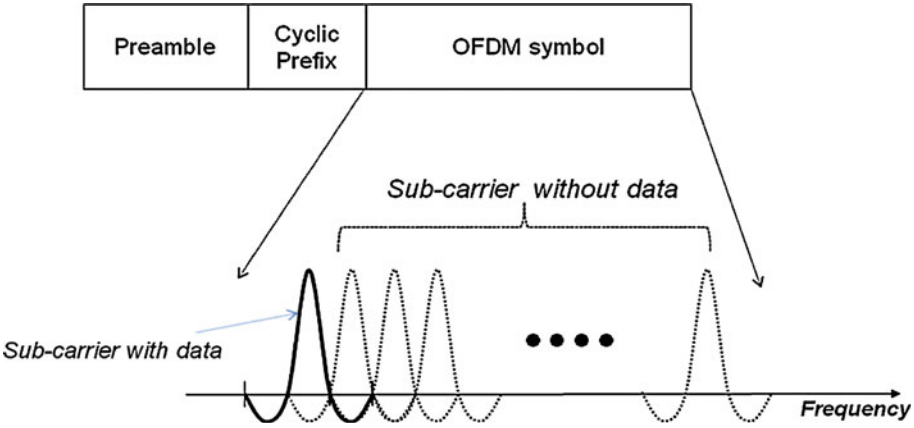


Fig. 1 Frame structure and subcarriers of OMACK

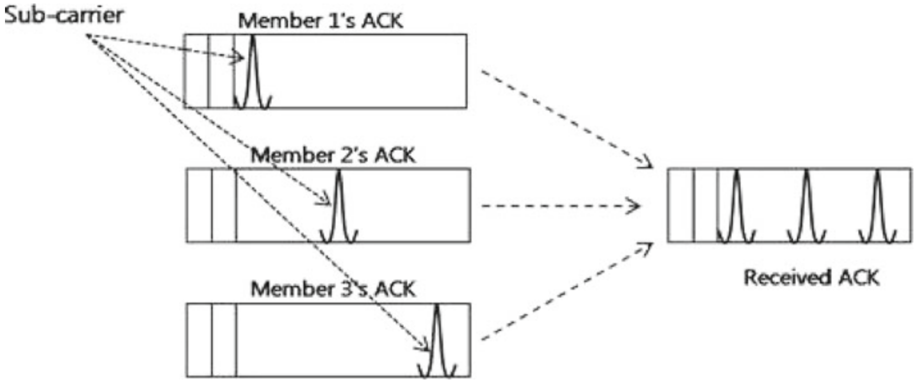


Fig. 2 OMACK transmitted by each STA (*left*) and a received OMACK at the source (*right*)

not incur additional overhead. Figure 2 illustrates the OMACKs transmitted from multicast member STAs and a received OMACK at a source STA. In OMACK, the retransmission policy follows the unicast rule defined in the IEEE 802.11 standard.

The time and frequency offset problems due to the imperfect time synchronization and different propagation delays of the various member nodes have been addressed in [17–22]. This problem can violate the sub-carriers' orthogonality in an OFDM symbol and make channel estimation difficult. To resolve this problem, various solutions have been proposed [17–19]. These works show that the problem can be solved by using a longer cyclic prefix than any of the delay spread profiles. In [20], a novel preamble structure and a process method are proposed. In [21] and [22], link protocols are proposed to synchronize OFDMA-based packets from multi-users over ad-hoc networks.

Regarding backward compatibility, it is assumed that the source can recognize OFDMA-multicast-enabled nodes and legacy nodes through the process of association or multicast group join. Therefore, if there are any legacy nodes in a multicast group, multicast traffic will be transmitted in a legacy manner, which is the transmission scheme without ACKs described in IEEE 802.11.

3 Proposed Protocol

In this section, an efficient retransmission strategy is proposed and illustrated in an OMACK system. However, the proposed method can also be used in the other ACK-based multicast systems described in [5–8,13] and [14]. The proposed method is composed of three strategies, Contention Window Adjustment (CWA), Check-Failed-Node (CFN), and Check-Packet- delivery-Ratio (CPDR) that are involved in the retransmission decision. As mentioned above, all members acknowledge their reception status using their pre-assigned subcarrier in an OMACK packet. In addition, the network topology is based on one-hop communication. Thus, it is assumed that all nodes can hear each other's transmissions if there are no channel errors.

3.1 Contention Window Adjustment

In IEEE802.11, an STA has to perform a backoff procedure before starting a transmission, in order to reduce the collision probability. The duration of the backoff is determined by the contention window size (CW), which is initially set to $CW_{\min}$. This value is used to randomly choose the number of slot times in the range $[0, CW - 1]$, which helps determine the backoff duration. In the case of an unsuccessful transmission, the CW value is updated to $CW \times 2$ provided it does not exceed $CW_{\max}$. This will guarantee that, in the case of a collision, the probability of another collision at the next transmission attempt is further decreased. The retransmission finishes and the packet is dropped when the number of retransmissions reaches the maximum value, *Retry-Limit*.

When no ACK is received, it can be due to both collision and channel errors. The contention window is designed to resolve the problem of collisions due to simultaneous transmissions by multiple nodes. Thus, backoff is not necessary in the case of channel errors. In unicast, a sender cannot distinguish between a collision and channel error, and backoff is done in both cases. In multicast, we propose the following method of differentiating these two cases in order to improve the backoff performance.

If at least one member acknowledges the sender, it means that there might not be any collisions in one-hop communication. When other ACKs are not received, it might be due to a channel error rather than a collision in one-hop communication. Therefore, in the proposed CWA, the contention window size for the retransmission only increases if none of the members acknowledges the currently transmitted multicast data packet. If any members acknowledge the data packet, even when the other members do not, the contention window size is reset to the minimum value. The contention window size at the nth retransmission, CW_n, is updated as follows:

$$CW_n = \begin{cases} CW_{\max}, & \text{if} CW_{n-1} = CW_{\max} \text{ and there is no ACK,} \\ CW_{n-1} \times 2, & \text{if } CW_{n-1} < CW_{\max} \text{ and there is no ACK,} \\ CW_{\min}, & \text{if there is any ACK} \end{cases} \tag{1}$$

where n is the number of retransmissions. Minimizing the contention window size at any successful transmission ensures that the size of the contention window does not increase unnecessarily, and as a result, the time wasted due to the resulting large backoff-time period is reduced.

3.2 Check Failed Node

OMACK [15] retransmits a multicast packet when ACKs are not received from all members, even when some members successfully return their ACKs in the first transmission or previous retransmissions. That is, the retransmission is decided by the ACK-status of the currently transmitted packet. However, this is inefficient and causes unnecessary retransmissions. For example, *Node A* may successfully receive the packet and acknowledge it whereas some other nodes may fail to receive it, so the source retransmits the packet. In this retransmission, *Node A* may fail to receive it whereas the other nodes successfully do so and send an acknowledgement to the source. Because *Node A* does not acknowledge the retransmission, the source will retransmit the packet once more. That is, the retransmission continues until ACKs from all members are simultaneously received by the sender.

To solve this problem, the source temporally stores each member's reception status for the current multicast data packet. Once a node successfully receives the data packet (i.e., once a node sends an ACK back to the source), this node is excluded from the set of nodes which are expected to send an ACK on subsequent retransmissions. Therefore, when all member nodes have sent an ACK at least once, the retransmission is stopped and the next multicast data packet is transmitted. In this method, the contention window size for every retransmission increases according to the rule given by the IEEE802.11 standard.

3.3 Check Packet Delivery Ratio

In CPDR, the need for a retransmission is decided based on how many multicast data packets have successfully been delivered to each member. We define the Packet Delivery Ratio (PDR) as the ratio of the number of successfully delivered data packets to the number of transmitted data packets. The PDR for member i is defined as follows:

$$PDR_i = \frac{m_i}{M}, \quad i \in \{1, \cdots, N\}, \tag{2}$$

where M is the total number of multicast packets transmitted up to now, m_i is the number of multicast packets acknowledged by member i, and N is the number of multicast group members. Before a new multicast packet transmission, M is updated to M+1. After the first transmission or retransmission of the multicast packet, PDR_i is updated based on the ACK packets received from members as follows;

$$PDR_i = \frac{m_i + \alpha}{M}, \quad \alpha = \begin{cases} 1, & \text{if ACK from member } i \text{ is received} \\ 0, & \text{otherwise} \end{cases}. \tag{3}$$

Because ACKs are checked by the source in order to update PDR_i, CPDR implicitly includes the CFN method described in Sect. 3.2.

The PDR update of a member stops when the member acknowledges the multicast packet. The $Target\_PDR_i$ is the required PDR for member i and is a predefined value from 0 to 1 depending on the reliability level of the multicast traffic. Moreover, the *Target_PDR* for each member can be set depending on the priority or required reliability level of the member. If a multicast traffic needs perfect reliability for all members, the *Target_PDR*s for all members are set to 1. If the *PDR* of a member is higher than its *Target_PDR,* this member is considered to return the ACK for each transmission, even when it does not do so. In other words, this member does not affect the retransmission policy, because it systematically achieves the target PDR.

In this method, the contention window size for each retransmission increases according to the rule given by the IEEE802.11 standard, as in the CFN method.

3.4 Protocol Operation

The process used to retransmit a multicast packet is described as follows.

Step 1. The sender transmits a multicast packet to all members, and all members are required to acknowledge it by sending an ACK packet to the sender. Even if a member successfully received the multicast packet in the previous transmission, the retransmitted packet must be acknowledged.

Step 2. When an ACK packet is received, the sender checks whether the members send their ACKs using their subcarriers in the ACK packet.

Step 3. There are two methods to decide whether a retransmission is necessary.
In CFN-based retransmission, each member's reception status for the multicast packet is initialized to 'fail' at the start of a data packet transmission. Then, the status is changed to 'success' if the member returns an ACK for the packet. The 'success' status remains until the retransmission is finished and the next packet is transmitted. If any member's reception status is 'fail', then the source retransmits the multicast packet. Otherwise, the retransmission process is stopped and a new multicast packet is transmitted.

The CPDR method includes the CFN-based retransmission. Additionally, in CPDR, the sender updates the *PDR*s of the multicast group members using (3). Each member's *PDR* is compared with its *Target_PDR*. If any member's *PDR* is less than its *Target_PDR* and the member does not return an ACK packet, the current multicast packet is retransmitted. On the contrary, if all members meet at least one of these two requirements (i.e., an ACK is returned or the *PDR* of the member is higher than its *Target_PDR*), then the retransmission of the multicast packet is stopped and a new packet is transmitted.

Step 4. In CWA-based retransmission, the sender adjusts the contention window size for the retransmission according to (1). For the system without CWA-based retransmission, the contention window size is updated for each retransmission until the number of retransmissions reaches *Retry-Limit* or ACKs are received from all members.

4 Performance Evaluation

The performances of the retransmission methods are evaluated by simulation. We consider an OFDM-based physical layer as defined in the IEEE 802.11a standard [23] operating in the 5 GHz frequency band. The wireless channel characteristics are modeled by three components: path loss, shadowing and multipath fading. The path loss is modeled as

$$PL(d) = PL(d_0) + 10\alpha \log\left(\frac{\alpha}{d_0}\right) \tag{4}$$

where d0 is the reference distance and α is the path loss exponent. We consider the case where d0 = 1 m and $\alpha = 2.56$. To represent fading, we consider the "ETSI indoor channel A" delay profile described in [24], which models a typical office environment with no line-of-sight. The power delay profile has an RMS delay spread of 50 ns and a maximum delay spread of 390 ns. This delay profile results in frequency selective fading in the IEEE 802.11a 20 MHz band. In the computation of the Signal-to-Noise Ratio (SNR), the noise is modeled as Additive White Gaussian Noise (AWGN). We consider a hard-decision Viterbi decoder in the receiver and assume the perfect synchronization of the receiver to the transmitted signal [25]. This is allowed by our assumption that one of the synchronization methods described in [17–22] is adopted. The simulation results in this paper were obtained using the event-driven simulator used in [26]. The simulator is extensively modified to accurately model the actions of the receiver. The Clear Channel Assessment (CCA) is modeled as per the IEEE 802.11 standard, which defines an Energy Detect (ED) threshold. A node is blocked if either it is busy receiving a signal on the medium or the signal strength is greater than the ED threshold, which is set to −85 dBm. The system under consideration is an IEEE 802.11a-based Basic Service Set (BSS), in which a group of multicast members are communicating with multicast packets. A communication channel between two members experiences a particular fading realization which may be different from that experienced by another communicating pair in the BSS. All members are randomly distributed in a 100 × 100 m square area and move randomly at a speed of 0.1 m/sec. The transmission queue of the multicast source node is always assumed to be nonempty. Packets that wait in the transmission queue for more than 20 msec are dropped from the queue. Each plot in the simulation results is obtained by running the model for 50 hours. The physical (PHY) data rate is 6 Mbps and the packet size is 2000 bytes. The *Target_PDR* for all members is set to 0.99.

In this simulation, the three proposed methods, CWA, CFN, and CPDR, are compared to the legacy method. Retransmission in the legacy method follows the unicast rule in the

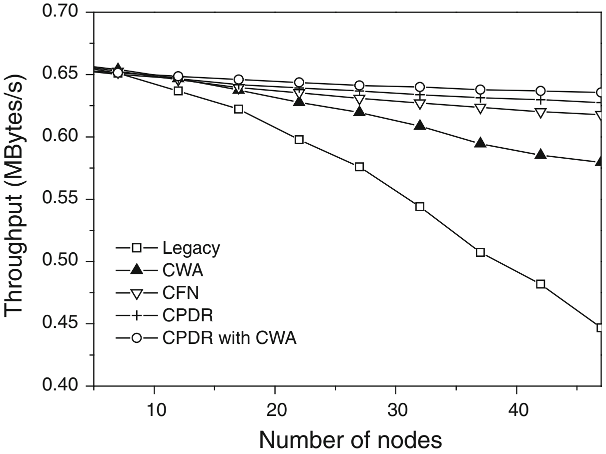


Fig. 3 Throughput for each retransmission method

IEEE 802.11 standard. That is, the retransmission continues until all members send their ACKs for each retransmission. Retransmission in CWA follows the legacy system rule, but the contention window size for retransmission is different, as explained in Sect. 3.1. The contention window sizes in CFN and CPDR differ from that in CWA, but follow the unicast rule in the IEEE802.11 standard. In addition to the proposed three methods, we also evaluate the performance of a system combining CWA and CPDR.

Figure 3 shows the throughput for each retransmission method. The legacy method checks for ACK packets from all members for each retransmission. If any node does not send an ACK packet due to channel error or collision, the source node retransmits the packet, even if the node already sent an ACK packet in the previous transmission or retransmission. Thus, the probability of retransmission increases as the number of nodes increases and as a result, the throughput also decreases. The CWA method minimizes the size of the contention window if an ACK is received from any members. On the other hand, the contention window size increases if none of the members sends an ACK. This reduces the time wasted during the backoff stage. Thus, the throughput of the CWA method is improved compared with that of the legacy method. The CFN method checks for ACKs from those members that did not return ACK packets in the previous transmission or retransmissions for the same data packet. In other words, if a member returns an ACK for the data packet at least once during the retransmissions, then that member is excluded from the check for ACKs in subsequent retransmissions. This method reduces the number of retransmissions, thus enhancing the throughput. The CFN method achieves greater performance enhancement than the CWA method. This is because reducing the number of retransmissions has a greater effect than reducing the backoff-time. In the CPDR method, those members with a PDR higher than the *Target_PDR* are excluded from the list of members required to send an ACK. Thus, the number of retransmissions is reduced and the throughput is improved. The degree of improvement in this method depends on the *Target_PDR*. The CPDR-with-CWA method shows the best throughput. The improvement of the throughput in the CPDR-with-CWA method is due to the combination of all proposed methods, CFN, CPDR, and CWA.

Figure 4 shows the packet transmission delay for each method. The packet delay is inversely proportional to the throughput. The legacy method provides a lower throughput, which incurs a longer delay. CPDR-with-CWA shows the shortest delay.

Fig. 4 Packet delay for each transmission method

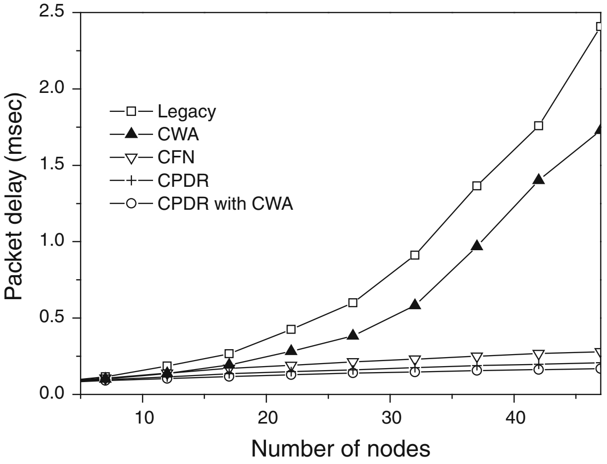


Fig. 5 Average number of retransmissions

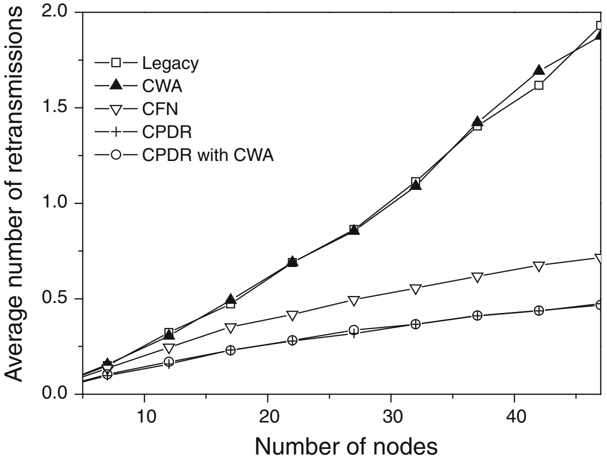
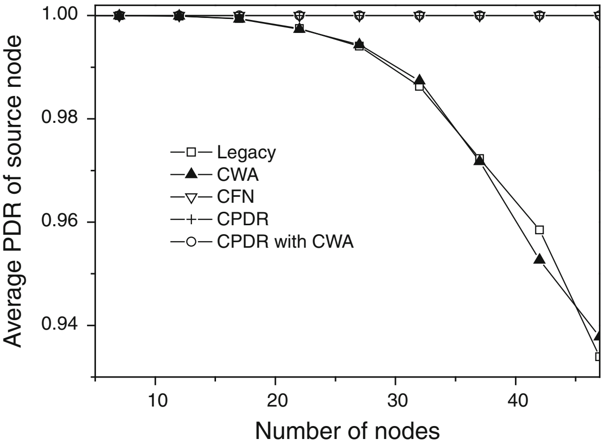


Figure 5 shows the average number of retransmissions at a source node for a packet transmission. The legacy and CWA methods show the same results, because their retransmission decisions are based on the same criterion. These two methods backoff when any member fails to return an ACK. The CPDR and CPDR-with-CWA methods show the same results, because they apply the same criterion to decide whether a retransmission is necessary. These two methods backoff when those members with a PDR lower than *Target_PDR* do not return their ACKs. The backoff method of CFN differs from that of the other methods.

As the number of retransmissions increases, the backoff stage increases, thus, the node has to wait a longer time for the packet transmission. Thus, the delay increases and the throughput decreases when the backoff stage increases. The legacy and CWA methods experience more retransmissions (backoff), which incurs lower throughput and longer delay, as shown in Fig. 3 and Fig. 4.

The PDR described in Sect. 3.3 mainly indicates how many packets are successfully received by each member node (not a source node). However, in this simulation, we evaluate the PDR of a source node.

Fig. 6 Average PDR of source node



The PDRs of the source node and destination node are different. The destination node considers the packet to be lost when it fails to receive the packet, whereas the source node considers the packet to be lost when it is not successfully received by all destination nodes, even if some do successfully receive it. In other words, a packet which is dropped at the retry-limit is considered to be lost for the source node. Figure 6 shows the average PDR of the source node. In the legacy and CWA methods, the source node checks all destination nodes at every backoff stage, and packets are dropped, because the retry-limit is reached during the retransmissions. These two methods experience excessive retransmissions (backoff), as shown in Fig. 5, so their PDRs are less than those of the other methods.

The PDR decreases as the number of nodes increases. This is because, as the number of nodes increases, the probability of success for all nodes decreases, and the average number of retransmissions increases. Thus, more packets are dropped at the retry-limit. In the other methods, such as CFN, CPDR, and CPDR-with-CWA, because the source node checks the failed nodes for each transmission, their average numbers of retransmissions are smaller, as shown in Fig. 5. Thus, the retry-limit is rarely reached and their PDRs are nearly one.

Note that the PHY layer uses the lowest data rate, 6 Mbps, for reliable transmission. For transmissions over a harsher wireless channel environment or with a higher data rate, packet errors may occur more frequently in the other methods. However, in our channel model, the other methods can finish the backoff process within the retry-limit. Therefore, the average PDRs of the source node are nearly one.

Figure 7 shows the average PDR of the destination nodes. The legacy, CWA, and CFN methods show the highest PDR of the destination nodes. The retransmissions in the legacy and CWA methods have redundancies, as shown in Fig. 5 and, as a consequence, they achieve high average PDRs of destination nodes. This high average PDR comes at the expense of a low average PDR of the source node, as shown in Fig. 6, and redundant retransmissions, as shown in Fig. 5. The CFN method retransmits the packet until all destination nodes return ACKs. Thus, it achieves a high PDR. Also, note that, for transmissions over a harsher wireless channel environment or with a higher data rate, these three methods may show a lower PDR of destination node. The CPDR and CPDR-with-CWA methods allow for some packet losses, while the PDR threshold is met. Thus, their PDRs are lower than those of the other methods and higher than the threshold, 0.99.

The performances of the CPDR and CPDR-with-CWA methods depend on the PDR threshold, *Target_PDR*, whereas the other methods are independent of the threshold. Figure 8 shows

Fig. 7 Average PDR of destination nodes

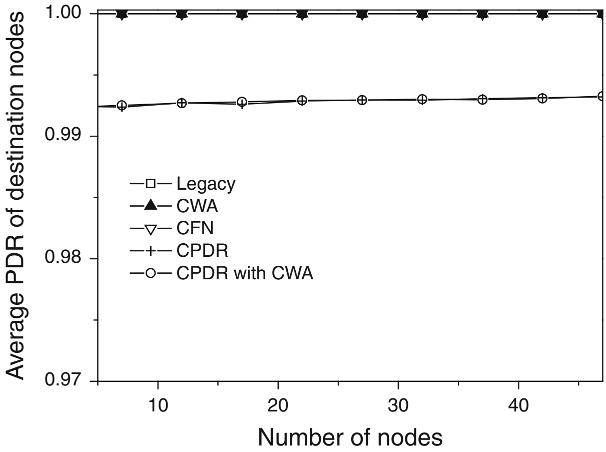
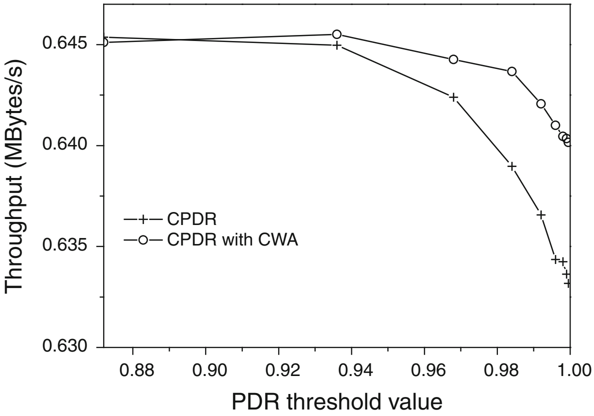


Fig. 8 Throughput as a function of the PDR threshold



the throughputs of the two methods that depend on the PDR threshold. The number of nodes is set to 25. The throughput of CPDR-with-CWA is better than that of CPDR, because the wasted backoff time is reduced by initializing the backoff window after any return of an ACK. The throughput difference increases as the PDR threshold increases. This is because the number of retransmissions increases as the threshold increases. When the value is higher, more nodes fail to satisfy the threshold. Therefore, the number of retransmissions increases and, as a consequence, the packet transmission finishes with a higher contention window size. Thus, the effect of initializing the contention window size increases as the PDR threshold increases.

The throughput is saturated when the threshold is less than 0.93. This is because the packet error rate in our system model is less than 0.07. Thus, the threshold has no effect on the retransmission decision in these regions. The threshold is low enough and the retransmission rarely happens. Most nodes achieve the threshold without the retransmission and the throughput remains constant. The saturation point depends on the packet error rate of the system.

5 Conclusion

In this paper, efficient retransmission methods for wireless multicast over contention-based wireless networks are proposed. The first method concerns adjustment of the contention window for retransmission. In order to ensure that the size of the contention window does not increase unnecessarily, it will not be increased provided at least one member sends an ACK back. In the second method, retransmission decisions are based on the reception status of the current multicast packet. Once all members successfully receive the packet at least once during the retransmissions, the retransmission is stopped. In the third method, retransmission decisions are based on the required reliability of each member. For the current multicast packet, if a member meets the required level of reliability (defined as the PDR) from previously transmitted packets, then the ACK for the current packet does not affect the decision on whether a retransmission is necessary. The proposed three methods and the combined method are evaluated through extensive simulations, and it is proved that they improve the network performances compared to the legacy system. In this paper, it is assumed that all members require the same PDR. The proposed method can be extended to multi-hop networks. The only difference from one-hop networks is that a member node in the current transmission can be a source node for the next hop transmission. Therefore, the node needs to manage the proposed methods such as PDR and contention windows. As a future work, differentiating members' PDRs will be investigated over a particular network where members have different priorities.

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