A Reliable and Efficient MAC Layer Multicast Protocol in Wireless LANs

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***Abstract*—In IEEE 802.11, multicast protocol is based on the basic access procedure of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This protocol does not provide any recovery mechanism for multicast frames. As a result, transmitted multicast frames may be lost due to collisions or errors. Recently, several reliable multicast protocols at MAC layer have been proposed for 802.11. They can be classified into two categories: one is based on negative feedback (NFB-based) and the other is based on positive feedback (PFB-based). After analyzing the problems with existing reliable multicast MAC protocols, we propose a novel PFB-based multicast protocol, namely DPMM (Double Piggyback Mode Multicast). The protocol piggybacks the ACK in the CTS frame and piggybacks the priority information in the DATA frames. With DPMM, ACK packets are eliminated and collisions of control frames are avoided. A grouping algorithm using RSS (Received signal strength) measurement is also developed to further improve upon DPMM. Simulation results, using the OPNET, confirm that the improvements are encouraging.**

I. INTRODUCTION

A great number of multicast applications, such as multimedia conferencing, distance learning, multi-party games, and distributed computing, require reliable and efficient MAC (Media Access Control) layer multicast. However, in IEEE 802.11 specification, the multicast sender simply performs CSMA/CA before transmitting a DATA frame. There is no MAC-level recovery on multicast frame as in unicast. As a result, the reliability of multicast is reduced due to the increased probability of lost frames resulting from collisions or errors.

Various MAC layer multicast protocols [1-8] have been proposed to enhance the reliability and the efficiency of the 802.11 multicast protocols. They can be classified into two categories: one is based on negative feedback [1-3] and the other is based on positive feedback [4-8]. Unfortunately, these protocols have serious problems in terms of reliability and/or efficiency. In this paper, we show the reliable and efficient problems in the NFB-based protocols (LBP and DBP [1-2]) and demonstrate that while the PFB-based protocols (BMW [4] and BMMM [5]) are logically reliable, they can not be very efficient. Further, towards redressing these reliability and efficiency issues, we design a novel PFB-based multicast MAC protocol, double piggyback mode multicast (DPMM).

The proposed multicast mechanism DPMM has four advantages: (1) The collisions among control frame transmissions can be avoided. For a multicast RTS, if more than one intended receiver replies with a CTS frame, these CTS frames may collide with each other at the sender. In order to avoid this problem, DPMM provides a simple coordination between the multicast receivers. In DPMM, each receiver is assigned with priority. The priority information is piggybacked in *multicast DATA (MDATA)* frame. The CTS frame is sent one after another based on the priority so that the collision of CTS frames can be avoided. (2) The control overhead is reduced by using an implicit acknowledgment scheme. In the traditional reliable multicast protocols, reliable delivery is supported by the RTS/CTS/DATA/ACK scheme. However, in DPMM, the acknowledgement information is piggybacked in CTS, so the control overhead can be decreased highly and collision of multiple ACK frames can be eliminated. (3) "CHs (Cluster Heads) Selection Mechanism" is designed to further improve DPMM. If there are many multicast receivers, the "selection algorithm" is processed at AP to reduce the control packet overhead and waiting time. (4) Multicast throughput is improved by supporting *Multicast frame aggregation*.

The rest of the paper is organized as follows. In section Ⅱ the current multicast MAC protocols and their problems are described. SectionⅢ introduces the proposed DPMM protocol, followed by a selection mechanism in section Ⅳ. Simulation analysis is showed in Section Ⅴ. Finally, Section Ⅵ draws the conclusion and discusses the future research directions.

II. PROBLEMS WITH EXISTING MULTICAST MAC PROTOCOLS

Much work has been done to improve the reliability of the CSMA/CA multicast mechanism. In [1], LBP (leader based protocol) attempts to extend the IEEE 802.11 multicast protocol with handshaking mechanism and recovery mechanism. The protocol assumes that a receiver is selected as the leader. According to the protocol, only the leader transmits a multicast CTS (MCTS) frame in reply to the sender. If the DATA is received correctly, the leader sends an ACK, otherwise sends a NAK. If any other receiver detects a transmission error, a NAK is also sent. This NAK frame will collide with the ACK, if any, sent by the leader. This leads to the AP not hearing any ACK, and thus retransmitting the lost frame.

Applying LBP to IEEE 802.11 suffers from some problems: (1) Unnecessary retransmission [3]. If error occurs at the non-leader receivers, they will send NAK, regardless of whether this erroneous frame has been received successfully before or not, which result in redundant retransmission. (2) Capture effect [12]. When AP receives ACK and NAK at the same time, it is possible for the ACK with the strongest power to be captured by the AP. Thus, the AP will start to transmit a new data packet rather than the lost packet. (3) Type-unknown for lost packet. This problem exists in all NFB-based protocols. When collisions or link error occurs, the group member cannot receive the frame correctly and then it cannot acquire the information contained in the MAC header, such as source address and destination address. So it is difficult for the receiver to decide which node the feedback should be sent to. (4) Difficulty for supporting *Frame Aggregation.* This problem exists in all NFB-based protocols. If a receiver detects a transmission error, it sends a NAK, which will collide with the ACK. When *frame aggregation* is considered, the collision between NAK and ACK will lead to the retransmission of the

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aggregated unit. However, it is unnecessary because not all the frames in the aggregated unit are transmitted unsuccessfully.

The delayed feedback-based protocol, termed DBP [1], is different to LBP in two ways: (1) MCTS frame is sent by each receiver instead of only the leader. (2) Each receiver sends NAK if a transmission error is detected. In order to avoid the collisions of MCTS, each receiver will wait for a random number of time slots to send a MCTS. In comparison to LBP, it would take longer time in DBP to complete a successful MRTS/MCTS exchange. This is because DBP have to deal with the possibility of MCTS collisions. Another problem with DBP is the choice of right parameter for waiting times. This choice is based on the number of the group members.

In [4], the Broadcast Medium Window (BMW) is introduced to provide a reliable broadcast MAC. The basic idea of BMW is to treat each broadcast request as multiple unicast requests. BMW protocol is reliable but not very efficient. In order to improve the efficiency, Batch Mode Multicast MAC Protocol (BMMM) is proposed in [5]. Fig. 1 illustrates the communication process of BMMM. Although BMMM is more efficient than BMW, the control traffic overhead is still very high.

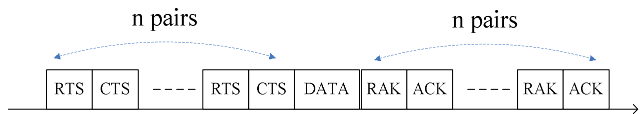

Fig. 1 Primary idea of BMMM

III. Double Piggyback Mode Multicast Protocol

In this section, we discuss the main idea of our proposal in detail. For reliable MAC-layer multicast, two important problems should be resolved: (1) How to decrease the control packet overhead to improve the efficiency? (2) How to avoid the collisions among control frame transmissions?

In DPMM, these problems are resolved by four ways: (1) The acknowledgement information is piggybacked in CTS frame, so the control overhead can be decreased. The main idea is as follows: If there are at least two multicast packets to be transmitted to a group, then the sender requests the receivers not to transmit an explicit ACK packet. Instead, when the RTS/CTS handshake is initiated for the second packet, the receivers can acknowledge the receipt of the first packet by piggybacking the CTS with a *SEQ* field. Similarly, the CTS frame for the third packet carries the acknowledgment information of the second packet, and so on. When it is time for the MAC layer to multicast the last packet, it explicitly informs the multicast receivers through RTS, that the receivers must send an explicit ACK packet now. Clearly, as long as there are packets in the queue, explicit acknowledgments can be eliminated, resulting in potential benefits. (2) *Multicast frame aggregation* is supported. In order to further reduce the control overhead, DPMM introduces *Multicast data aggregation*. Several DATA packets with the same group address will be aggregated into an AU (aggregated unit). The maximum AU length should be 4095 bytes [10]. Only using the *SEQ* piggybacked in CTS cannot clearly indicate which frames in AU are received correctly. Thus, a *Bitmap* is added into the CTS frame. (3) The priority information is piggybacked in *multicast DATA (MDATA)* frame. In order to avoid the collisions among CTS frames, we allow the CTS to be sent one after another by deliberately introducing a fixed amount of delay between successive transmissions. Thus, each receiver calculates the time it must wait before sending its CTS. This time is based on the priority information in *MDATA frame*. (4) *CHs selection mechanism* is designed to further improve DPMM. When the multicast group size is large, the *selection mechanism* is processed at AP to reduce the control overhead and waiting time. In DPMM, several CHs are selected by AP. Only the cluster head needs to send the control frames rater than all multicast receivers. We will discuss the *CHs selection mechanism* separately in Section III.

A. Frame structure

In DPMM, reliable delivery is supported by MRTS/MCTS/DATA scheme. The structure of MRTS (Multicast RTS) frame is the same as RTS defined in IEEE 802.11, which is shown in Fig. 2. It is worth noting that the RA field in the MRTS is the group address instead of the broad address (-1) defined in 802.11. The group address can be derived from the IP-layer multicast address, which is a class D address.

The structure of MCTS (Multicast CTS) frame is defined in Fig. 3, which is modified from the CTS frame by inserting *SEQ* and *Bitmap*. The *SEQ* is the sequence number of the latest successfully received DATA frame at a receiver. The *Bitmap* specify whether the previous frames in the aggregated unit (AU) are transmitted correctly. With reference to *SEQ*, if an earlier frame is lost, the corresponding bit in the *Bitmap* is set to '0', otherwise '1' (see Fig. 3). From *SEQ* and *Bitmap*, the sender can judge clearly which frames in AU are transmitted correctly. If there is error occurred in AU, the sender only retransmits the erroneous frames instead of the whole AU. Therefore, DPMM can effectively eliminate the redundant retransmissions caused by NFB-based protocols.

The structure of *MDATA* (Multicast DATA) frame is defined in Fig. 4, which is modified from the unicast DATA frame by converting the address-4 field to Multicast ID (MID) field. The address-4 field is never applicable in our assumed multicast scenario because this field is only used in special cases where the frame is transmitted from one AP to another AP. The MID is the same as association ID (AID)[9] defined in IEEE 802.11, which is a value assigned by an AP during association that represents the 16-bit ID of a station. In order to keep the MDATA frame no larger than data frame in 802.11, we set three MIDs in this space because the length of MID is 2 octets and the length of address-4 is 6 octets.

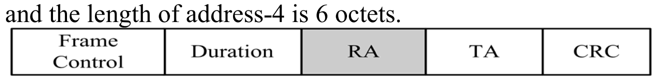

Fig. 2 MRTS Frame Format

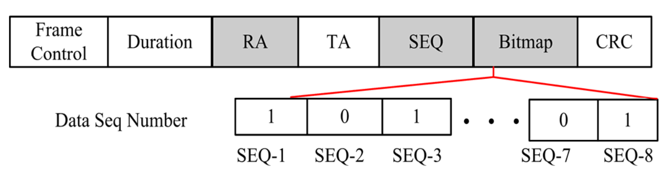

Fig. 3 MCTS Frame Format

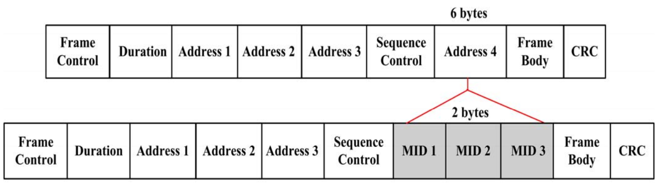

Fig. 4 MDATA Frame Format

B. Protocol description

Consider a simple scenario showed in Fig. 5, in which source node in cell 1 transmits multiple DATA packets to a multicast group, G, in cell 2. We called the mobile stations in group G "multicast receivers". The AP2 transmits these multicast packets using the proposed reliable multicast mechanism, DPMM. The notations used in this paper are summarized in Table Ⅰ.

Table Ⅰ
Definitions of terms used in the paper

R	The number of multicast receivers in the group
N_{MCTS}	The number of MCTS frames received at AP when it is waiting for feedback
Tx_seq	The sequence number of the latest transmitted DATA frame
Rcv_seq	The sequence number of the latest successfully received frame
SIFS	Short Inter-Frame Spacing
T_{MCTS}	The time to transmit a MCTS frame

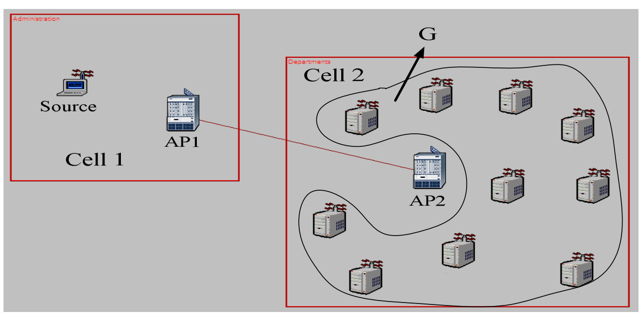

Fig. 5 Multicast Scenario

When the MAC layer at AP2 receives a *MDATA* packet from the upper layer, it first aggregates packets with the same group address into an aggregated unit (AU).

Before initiating an MRTS transmission to group G, the MAC layer at node AP2 determines if there are other AUs for group G in the outgoing queue. If at least one other AU for G is in the queue, then AP2 set the *subtype* value of frame control field in MRTS to 0000 (this value is reserved in IEEE 802.11). If there are no AUs for group G in the queue, then *subtype* is 0001 (this value is reserved in IEEE 802.11). Later, on receiving the AU from AP2, multicast receiver transmits an ACK frame only if the *subtype* in MRTS was set to 0001; otherwise it omits sending the ACK frame.

Let us assume that AP2 had multiple AUs for group G in its queue, and therefore had set the *subtype* to 0000 within the MRTS. After performing the collision avoidance procedure, AP2 multicasts a MRTS frame. On receiving the MRTS from AP2, each multicast receiver records the subtype value, and replies with the MCTS. If all the MCTS frames are sent simultaneously, they may not be correctly received. In order to avoid the collision, we allow the MCTS frame to be sent one after another by deliberately introducing a fixed amount of delay between successive transmissions. Thus, each receiver calculates the time it must wait before sending its MCTS frame. The wait times are calculates as follows. The Mth receiver waits for a time equal to $M \times SIFS + (M-1) \times T_{MCTS}$, where M is the priority order. The priority order can be obtained by two ways: (1) When a node joined to the multicast group, the AP should first assign the priority order to it [8]; (2) Once the multicast receiver correctly received *MDATA*, the priority order should be the position index of each receiver's own MID in the *MDATA* frame (shown in fig. 4).

After successful reception of MCTS from all receivers, AP2 multicasts the *AU*, and record the *Tx_seq*. Later, on receiving the *AU* from AP2, receivers need not reply with an ACK packet but only record the outcome of reception. The outcome of the reception indicates which frames in AU are received successfully.

We observe that at the end of the first dialog (i.e., MRTS/MCTS/AU) AP2 is unaware which frames in AU are correctly received by all receivers. Now, AP2 must initiate MRTS transmission for the next AU in the queue. On receiving the MRTS frame from AP2, each receiver piggybacks the *Rcv_seq* and *Bitmap* recorded previously, on the MCTS. By checking the *Rcv_seq* and *Bitmap* fields in MCTS, AP2 can calculate the sequence number of the lost *MDATA* frames. If the previous AU was successfully delivered to all receivers, AP2 transmits the new AU. Otherwise, AP2 retransmits those lost frames in previous AU. The key ideas are illustrated in Fig. 6.

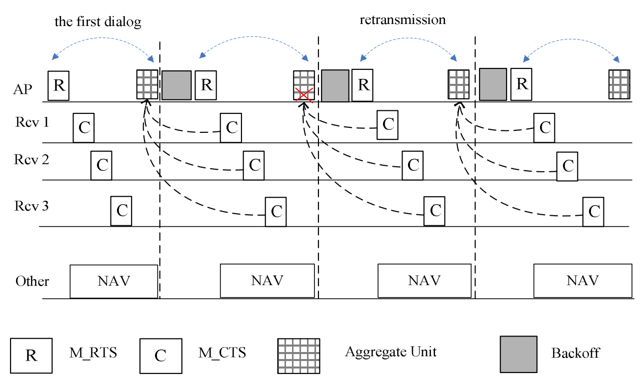

Fig. 6 Transmission between AP and group receivers

In summary, when the sending rate at the source node is high or bursty, the outgoing queue at the AP2 always has multiple packets to group G. This is an opportunity to eliminate the ACK packet for every *MDATA* packet, because the MCTS of the next packet can be piggybacked with an acknowledgment for the previous packet. Clearly, DPMM will decrease the overhead of conventional PFB-based multicast protocols significantly, and then lead to improvements in throughput and delay. In addition, there is always a non-zero probability that multiple ACK packets are lost or collided when using explicit acknowledgement and then the MRTS/MCTS/DATA/ACK dialog is unnecessarily initiated once again. With our scheme such possibilities are eliminated, resulting in encouraging performance improvement.

IV. CHs Selection

Until now we explained how the protocol would works when there are 3 or less group receivers. In case there are more than 3 group receivers, the AP needs to group these nodes into 3 clusters, each with a cluster-header (CH). In this section, we discuss how to group users and how to select the CH.

When multicast-based application is deployed, Internet Group Management Protocol (IGMP) should be used to generate a group membership report [7]. In IGMP, when joining or leaving a group, a terminal sends "group join" or "group leave" message to multicast router. Multicast router send "IGMP query" and "IGMP group-specific query" to terminals periodically to see whether any group members exists on their sub-networks. On receiving query messages, group members reply "IGMP response" message immediately. We tend to use this IGMP feedback mechanism as a way to estimate the link condition between AP and multicast terminals. Depending on this estimation, AP may group terminals into different clusters. Nodes in each cluster have similar link condition.

In our proposal, AP snoops the IGMP message sent from terminals, by which AP has knowledge of all group receivers and maintain a table as in Table Ⅱ. The "*" in the "Priority" column means that no priority is set because the corresponding terminal is not CH.

On receiving "IGMP group join" or "IGMP response" message from a terminal, AP measures the Received Signal Strength (RSS) and then compares it with two predefined thresholds, Th_Rss_1 and Th_Rss_2. AP can group terminals into specific cluster according to Th_Rss_1 and Th_Rss_2. The thresholds selection is the same as that for adaptive rate selection in [11].

Table Ⅱ Information table maintained at AP

Group Address	MID	CH (Yes or Not)	Priority
G_1	S_1	Yes	3
G_1	S_2	No	*
G_1	S_3	Yes	2
……	……	……	
G_1	S_i	No	*

After processing grouping algorithm, AP should select CHs every time it starts to send *M_DATA* frame. The selection of CHs is done in a round-robin style. The MID of the CHs are piggybacked into *M_DATA* frame.

V. SIMULATION RESULT

We have used network simulator OPNET 11.5 to implement the multicast MAC protocols (DPMM, LBP, DBP and BMW). In this section we will describe the simulation results. The following metrics are used to compare the performance of different schemes: (1) Packet Delivery Ratio (PDR). It is the percentage of data packets that are delivered to all the receivers, and is defined as [6].

$$\text{PDR}=\frac{\sum_i \text{number of data packets successfully received by receiver i}}{\sum_i \text{number of data packtes sent from AP to receiver i}}$$

(2) Average Packet Delay. It is defined as the time period from the start of an AP sending a certain multicast frame to the end of the successful reception by all receivers [3]. (3)Delay jitter. (4) Control overhead.

A. Simulation Setting

We have set up the simulations using a grid of size 300 × 300 with 30 nodes. The simulation scenario is shown in Fig. 5. A two-ray propagation model is used in our simulation, with free space path loss 2.0 for near sight and plane earth path loss 4.0 for far sight. Some of the simulation parameters are shown in Table Ⅲ.

Table Ⅲ
Simulation Parameters

Parameters	Value
Application Description	FTP Download
File size	1000byte
Inter-request time	Constant (1 second)
Simulation Time	1 hour
Bandwidth	11M
Node Placement	Random
Propagation model	Two Ray Ground
MAC Protocol	LBP, DBP, BMW, DPMM
Transport Protocol	UDP

B. Simulation Result

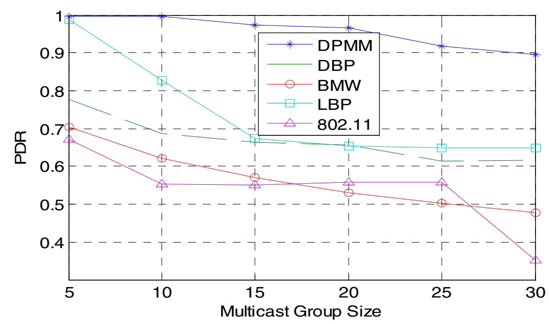

Fig. 7. Packet delivery ratio vs. number of receivers

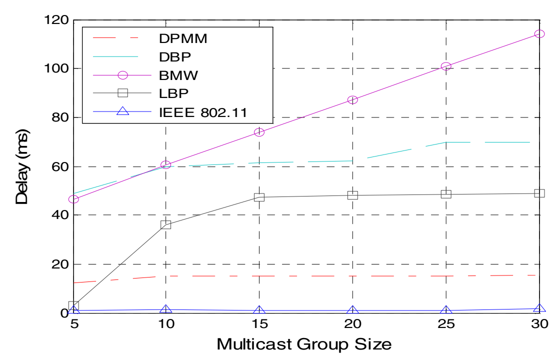

Fig. 8. Average Delay vs. number of receivers

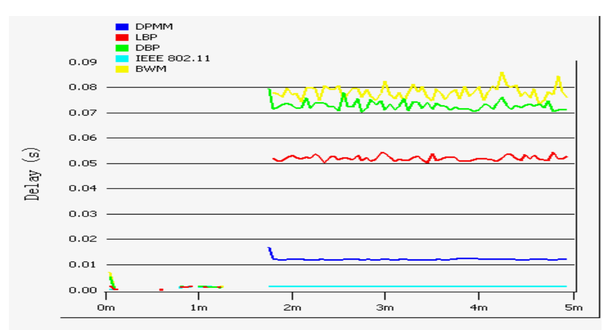

Fig. 9. Instantaneous delay with simulation time (number of receivers = 15)

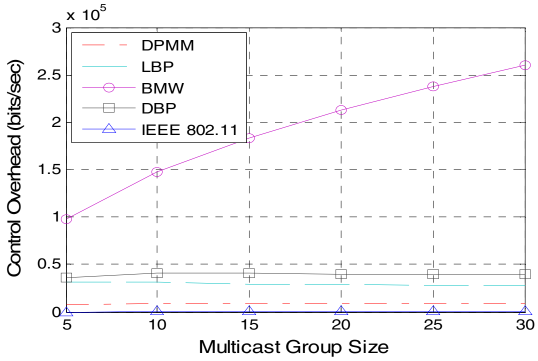

Fig. 10. Control overhead vs. group size

Fig.7 compares the PDR for DPMM, LBP, DBP and BMW. PDR is used to measure the reliability. A multicast protocol is reliable if it has a high packet delivery ratio. As can be seen, the PDR of all protocols degrade when the number of receivers increases. Our DPMM enjoys the highest packet delivery ratio. The high PDR in DPMM is mainly contributed by two aspects. (1)The AP can acquire feedback from CHs which have the bad link quality. AP will not transmit the new DATA frame until every CH receives the packet successfully. However, in other NFB-based algorithms, AP may not get the feedback from all nodes because of the capture effect, collision and so on. It's worth noting that PDR of BMW is even lower than DBP when the number of receivers is more than 15. This is due to the buffer overflow at AP. From Fig.1, we can see that AP has to wait for each receiver's CTS and ACK frame. If the number of receivers is large, the waiting time should be very long, and then the buffer at AP will be overflowed. (2) Unnecessary retransmission is avoided by piggybacking *Rcv_seq* and *Bitmap* within MCTS. In NFB-based protocols, when the received packet is in error, the multicast receiver sends a NAK frame to request retransmission, regardless of whether this erroneous frame has been received successfully before or not, due to the unknown sequence number. This will lead to unnecessary retransmission. In DPMM, because of the announcement from *SEQ* and *Bitmap* in MCTS, AP can judge correctly whether to retransmit the previous packet or not. As a result, DPMM can effectively eliminate the redundant retransmission.

Fig. 8 compares the average delay for DPMM, LBP, DBP, and BMW. The delay of BMW is the highest because AP has to wait for the CTS and ACK from all the multicast receivers. The delay for DPMM is lower than LBP and DBP. The low delay in DPMM is mainly contributed by three aspects: (1) ACK packet is eliminated. Since the acknowledgment information is piggybacked in the MCTS frame, the waiting time at AP will not include the time to transmit ACK. (2) Data aggregation is supported. Data aggregation results in fewer MRTS/MCTS exchange, for each MDATA frame, the waiting time will be decreased. (3) Unnecessary retransmission is avoided because the *Rcv_seq* and *Bitmap* are piggybacked in MCTS.

Next we are going to compare the packet delay jitter for DPMM, LBP, DBP and BMW. From Fig. 9 we can see that the delay jitter for DPMM is lowest. In LBP, DBP and BMW the receivers need to response two control frame (CTS/ NCTS and ACK/NAK) in a round of transmission. There is always a non-zero probability that ACK/NAK packets are lost or collided, and the RTS/CTS/DATA/ACK dialog may be unnecessarily initiated once again. With our scheme such possibilities are eliminated. At the same time, MCTS is responded in sequence, so that the uncertainty of the arriving time for control frame is decreased.

Fig. 10 sketches the system performance as control overhead versus multicast group size. The simulation result shows that DPMM' control overhead is lower than other protocols except for IEEE 802.11 (In IEEE 802.11 the control overhead is always zero because no RTS/CTS/ACK frames are sent). The low control overhead in DPMM is contributed by three aspects: (1) The ACK packets are eliminated when the sending rate at the source node is high or bursty. (2) The unnecessary retransmission is avoided. (3)The grouping algorithm is carried out at AP.

VI. Conclusion

We present a novel PFB-based multicast protocol, DPMM, to support multicasting in IEEE 802.11 networks in this paper. The proposed DPMM addresses two important problems in reliable multicast: (1) How to alleviate the collision of multiple MCTS frames and multiple ACK frames; (2) How to improve the efficiency. The main ideas of DPMM are: (1) Piggyback the acknowledgement information in MCTS; (2) Piggyback the instruction information in *MDATA*. The simulation results have shown that DPMM improves the performance of multicast packet delivery in WLAN. In the future, we plan to investigate the optimal number of CHs.

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