Impact of Multicast Flow for Performance of IEEE 802.11e in Wireless LAN

Howard Brown*, Min Gyung Kwak**, Jinsuk Baek***, Paul S. Fisher***

*The Agency Consulting Group, Columbia, MD, USA

**Pangyo R&D Center, Samsung Techwin, Korea

***Department of Computer Science, Winston-Salem State University, Winston-Salem, NC, USA

nebrown@nsa.gov, baekj@wssu.edu, m.kwak@samsung.com, fisherp@wssu.edu

Abstract— **In IEEE 802.11e, a multicast sender transmits multicast frames using a simple broadcasting mechanism at a low, fixed, rate without binary exponential back-off process. This simplicity reveals unfair shared channel access between unreliable multicast flows and reliable unicast flows. In this paper, we evaluate how negatively the single multicast flow affects multiple the unicast flows when they compete for a single communication channel access. We also observe the transition of the channel condition by progressively applying conservative back-off scheme for the multicast flow. Our evaluation indicates the channel condition-adaptive, back-off scheme for multicast flow is required to alleviate the negative impact and ultimately provide more reliable multicast transmission as well as fair resource sharing with the low-priority unicast flows.**

Keywords— **IEEE 802.11e, Multicast, Fairness, Performance evaluation, Contention window**

I. INTRODUCTION

In the MAC layer (e.g. IEEE 802.11a/b/g/e Wireless LAN) [1]–[3], the multicast sender locally transmits multicast frames by using a simple broadcasting mechanism. This mechanism transmits frames at a low, fixed, rate without any back-off process. Moreover, it does not require multicast receivers to send feedback, such as ACKs and NAKs, to their senders, resulting in the existence of unreliable multicast frames.

There are a couple of problems with this system. First, this simplicity fails to provide local reliability for multicast frames. It results in end-to-end error recovery overhead to the application layer, eventually causing bandwidth consumption at the IP core network. Second, it prevents the multicast sender from performing a back-off process. Instead, the sender maintains its initial minimum contention window size until the multicast session ends. This differs from unicast flows however. In unicast flows, the sender infers the unsuccessful reception of the unicast frame if an ACK for the frame has not been properly received within a given ACK time window. In such a case, the sender enters a binary exponential back-off phase, where it adjusts its contention window size within a pre-determined range. This range is dependent on the priority of the frame in the case of IEEE 802.11e Enhanced Distributed Coordination Function (EDCF). When the back-off timer expires, it retransmits the unicast frame. These processes are repeated until the contention window size reaches its maximum size or it receives ACK for the frame. Accordingly, when reliable low-priority unicast flows and unreliable multicast flows compete to access the shared channel at the same QoS basic service set (QBSS), the greedier multicast flows will get more access chances than the lower-priority unicast flows. It should be noted that low-priority unicast flows already have lower channel access chances than the higher-priority multicast flows (e.g. video or audio) at the same station.

In this paper, we evaluate the performance of the IEEE 802.11e protocol with ns-2 based simulation as well as probabilistic analysis. We consider the case when a single multicast sender and multiple unicast senders compete for a single communication channel. In order to observe the status of the channel condition with differentiated multicast flow, we require the multicast sender to progressively adjust its contention window size to contend with other unicast senders having low-priority unicast flows. Our evaluation results suggest network condition-adaptive, intelligent, back-off scheme should be developed to provide reliable multicast transmission as well as fair channel access chances between low-priority unicast flows and multicast flows. We clarify this research is based on [4] to include more extensive experiment.

II. BACKGROUND

The IEEE developed international WLAN standard we call IEEE 802.11a. This standard is used for a 54Mpbs WLAN. It also developed 802.11b for an 11Mbps WLAN. However, neither standard supports prioritized Quality of Service (QoS) for different frames having different priorities. In IEEE 802.11e, the differentiated, distributed channel accesses for frames have been designed with an EDCF. That is, each incoming frame from the higher layer has a specific priority value (from 0 to 7) and is mapped into one of the four access category (AC) queues (from 0 to 4). The four AC queues contend for the shared channel with assigned Arbitration Inter-Frame Space (AIFS) value, AIFS[*i*], where *i* is a priority of the given flow and is determined by the associated AC. Each AC queue also has a different minimum and maximum contention window size. These priorities are summarized in Tables 1 and 2 [5].

TABLE 1. USER PRIORITY TO AC MAPPLING

Priority	User Priority	AC	Destination (Informative)
Lowest ↓ Highest	1 or 2	AC_BK	Background
	0 or 3	AC_BE	Best Effort
	4 or 5	AC_VI	Video
	6 or 7	AC_VO	Voice

TABLE 2. DEFAULT EDCA PARAMTER SET

AC	AIFS[AC]	$W_{\min}$[AC]	$W_{\max}$[AC]
AC_BK	7	$W_{\min}$	$W_{\max}$
AC_BE	3	$W_{\min}$	$W_{\max}$
AC_VI	2	$W_{\min}/2$	$W_{\max}$
AC_VO	2	$W_{\min}/4$	$W_{\max}/2$

Many studies [6]–[12] have been proposed to provide rate control for fair channel sharing. However, most of studies are focused on providing fair resource sharing among the unicast flows or preventing performance degradation of the unicast flows from the multicast flow. As such, the performance degradation of the multicast flow is relatively overlooked. That is, the simple but efficient back-off scheme for the multicast flow should be developed to provide the fairness with the unicast flows. More importantly, the scheme should not introduce significant performance degradation of multicast flows. Our evaluation results show the scheme has to adaptively adjust the contention window size of the multicast sender based on the number of current contenders within a QBSS. Our results also indicate the upper-bound and lower-bound of such a scheme in terms of performance.

III. MODIFICATION OF MULTICAST BACK-OFF

We consider the multicast flow and low-priority unicast flows (e.g. best effort or video probe). For unicast flows, the back-off mechanism is invoked whenever the sender has a frame to transmit and detects a busy channel. It begins its back-off mechanism by setting its back-off timer to a random back-off time using the Equation (1).

$$B[i] = \text{random}\,(W_i)\cdot S_e\,,\quad (0 \le i \le 3) \qquad (1)$$

where i is a priority of the given flow, random (W_i) is a random integer, and S_e is a slot time. The sender sets its new contention window size W_{new} whenever the ACK for a frame has not been properly received. This process is repeated until the W_{new} reaches the maximum size or the frame is successfully received at the receiver. This can be expressed as Equation (2).

$$W_{new} = [(W_{old} + 1)\cdot \alpha] - 1,\ (W_{new} \le W_{max},\ \text{and}\ \alpha \ge 1) \qquad (2)$$

where α is the persistence factor and its size is dependent on the priority of the flow. Therefore, in Equation (1), the value of random (i) is generated from a uniform distribution over the interval [0, W_i].

On the other hand, multicast sender maintains its minimum window size W_{min} during the session by setting its α to 1. With our modification, we defined a new scale value β such that $\beta \le \alpha$, and we require the multicast sender to dynamically resize the β value. We also require the receivers to send NAKs for incorrectly received frames to request retransmission from the sender.

IV. PERFORMANCE ANALYSIS

For accurate performance analysis, we adopt the previously proposed IEEE 802.11b/g DCF Markov model [13] as a basis. We modify this model to reflect IEEE 802.11e EDCF with multicast flow.

In our analysis, we consider n contending senders including one a multicast sender. Our analysis considers two different cases. The first case is when the one multicast sender uses the legacy IEEE 802.11e EDCF scheme by setting β to 1. The second case is when it uses the back-off scheme by setting β to α. We eventually show how the two different schemes affect the throughput of the multiple low-priority unicast flows by showing the saturation throughput for n different number of senders.

Let $s(t)$ and $b(t)$ be the stochastic process representing the back-off stage and back-off time counter for a given station at time t, respectively. Also, let P_c be the independent probability that a transmitted frame is collided in a slot time.

These assumptions allow us to model the process $\{s(t), b(t)\}$ with the Markov chains for the two schemes with different transition probabilities as shown in Figure 2 and Figure 3. In the Markov chain for the proposed scheme, if we adopt the notation $P\{i_1, j_1 \mid i_0, j_0\} = P\{s(t+1) = i_1, b(t+1) = j_1 \mid s(t) = i_0, b(t) = j_0\}$ and m is the maximum value of back-off stage, we now have the following one step transition probabilities [13].

$$\begin{cases} P\{i,j \mid i,j+1\} = 1 & (0 \le i \le m,\ 0 \le j \le W_i-2) \\ P\{0,j \mid i,0\} = (1-P_c)/\,W_0 & (0 \le i \le m,\ 0 \le j \le W_0-1) \\ P\{i,j \mid i-1,0\} = P_c/W_i & (0 \le i \le m,\ 0 \le j \le W_i-1) \\ P\{m,j \mid m,0\} = P_c/W_m & (0 \le j \le W_m-1) \end{cases} \qquad (3)$$

Let $s_{i,j}$ and $p_{i,j}$ be the stationary distribution of the Markov chains for multicast flow with back-off and without back-off, respectively. We have:

$$s_{i,j} = \lim_{t\to\infty} P\{s(t) = i,\ b(t) = j\},\quad (0 \le i \le m,\ 0 \le j \le W_i-1).$$

$$p_{i,j} = \lim_{t\to\infty} P\{s(t) = i,\ b(t) = j\},\quad (i = 0,\ 0 \le j \le W_0-1).$$

We can obtain a closed-form solution for the $s_{i,j}$ based on the following three facts:

$$\begin{cases} s_{i,0} = P_c\cdot s_{i-1,0} = P_c^i\cdot s_{0,0} \qquad (1 \le i \le m), \\ P_c\cdot s_{m-1,0} = (1-P_c)\cdot s_{m,0} \\ s_{m,0} = \dfrac{P_c^m}{1-P_c}\cdot s_{0,0}\,. \end{cases} \qquad (4)$$

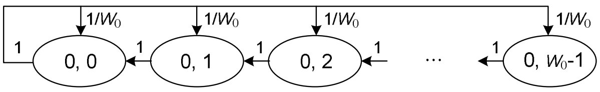

Figure 1. Markov chain model for multicast flow without back-off

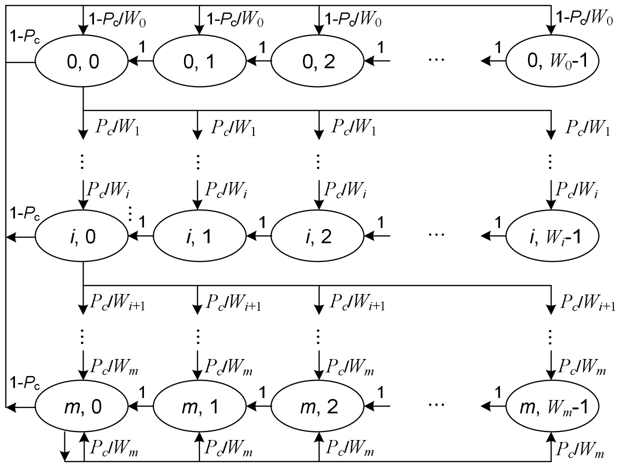

Figure 2. Markov chain model for multicast flow with back-off

The $s_{i,j}$ can be now separately expressed as Equation (5) depending the different ith stage.

$$s_{i,j} = \frac{W_i - j}{W_i} \cdot \begin{cases} (1-P_c)\sum_{k=0}^{m} s_{k,0} & (i=0) \\ P_c \cdot s_{i\text{-}1,\,0} & (1 \le i < m) \\ P_c \cdot (s_{m\text{-}1,\,0} + s_{m,\,0}) & (i=m), \end{cases} \qquad (5)$$

which can be simplified into:

$$s_{i,j} = \frac{W_i - j}{W_i} \cdot s_{i,\,0}\,, \qquad (0 \le i \le m),\ (0 \le j \le W_i\text{–}1). \qquad (6)$$

On the other hand, the $p_{i,j}$ can be expressed as:

$$p_{i,j} = \frac{W_i - j}{W_i} \cdot p_{i,\,0}\,, \qquad (i=0),\ (0 \le j \le W_0\text{–}1). \qquad (7)$$

Recall the contension window size is adjusted by Equation (2) and the scale value β is equal to α in saturation state. Now, by relations (4) and (6), all the values $s_{i,\,j}$ are expressed as function of the value $s_{0,0}$ and probability P_c. We also can obtain the value $s_{0,0}$ by imposing the normalization condition.

$$\begin{aligned} \sum_{i=0}^{m}\sum_{j=0}^{\omega_i-1} s_{i,j} &= \sum_{i=0}^{m}\sum_{j=0}^{\omega_i-1} \frac{W_i - j}{W_i} s_{i,0} \\ &= \sum_{i=0}^{m} s_{i,0} \sum_{j=0}^{\omega_i-1} \frac{W_i - j}{W_i} = \sum_{i=0}^{m} s_{i,0} \frac{W_i + 1}{2} \\ &= \sum_{i=0}^{m} P_c^i s_{0,0} \frac{W_i + 1}{2} = \frac{s_{0,0}}{2} \sum_{i=0}^{m} P_c^i (W_i + 1) = 1. \end{aligned} \qquad (8)$$

It can be rewritten by:

$$\frac{s_{0,0}}{2}\left[\frac{(W_0+1)(1-P_c\alpha^{m+1})}{1-P_c\alpha}\right] = 1.$$

Accordingly, we have:

$$s_{0,\,0} = \frac{2(1-P_c\alpha)}{(W_0+1)(1-P_c\alpha^{m+1})} \qquad (9)$$

Note that $p_{0,0}$ is equal to $2/(W_0{+}1)$ when no retransmission is required. Let us turn out attention to the probability τ that the sender transmits the frame in a randomly chosen slot time. As any transmission occurs when the back-off counter is equal to zero, τ can be given by:

$$\begin{aligned} \tau &= \sum_{i=0}^{m} s_{i,0} = \sum_{i=0}^{m-1} s_{i,0} + s_{m,\,0} \\ &= \frac{1-P_c^m}{1-P_c} s_{0,0} + \frac{P_c^m}{1-P_c} s_{0,0} = \frac{s_{0,0}}{1-P_c}\,. \end{aligned} \qquad (10)$$

The $p_{0,0}$ should be considered as τ_m that is a probabiliy of any transmission of multicast sender when beta is β equal to 1.

$$\tau_m = \frac{2}{(W_0+1)} \qquad (11)$$

The probability P_c can be expressed as:

$$P_c = \begin{cases} 1-(1-\tau)^{n-1} & \text{, if } \beta = \alpha \\ 1-(1-\tau)^{n-2}(1-\tau_m) & \text{, if } \beta = 1 \end{cases} \qquad (12)$$

The value of P_c and τ can be found by applying numerical solution for nonlinear system. On the other hand, the probability P_s that the frame is successfully transmitted to the receiver will obey:

$$P_s = \begin{cases} {}_nC_1 \cdot \dfrac{\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} & \text{, if } \beta = \alpha \\ {}_nC_1 \cdot \dfrac{\tau(1-\tau)^{n-2}(1-\tau_m)}{1-(1-\tau)^{n-1}(1-\tau_m)} & \text{, if } \beta = 1 \end{cases} \qquad (13)$$

That is, P_s is conditional probability that exactly one sender transmits a frame on the channel, conditioned on the probability P_t that a least one sender transmits.

$$P_t = \begin{cases} 1-(1-\tau)^{n} & \text{, if } \beta = \alpha \\ 1-(1-\tau)^{n-1}(1-\tau_m) & \text{, if } \beta = 1 \end{cases} \qquad (14)$$

Finally, we can determine the normalized saturation throughput, T, defined by:

$$T = \frac{P_s P_t L_f}{(1-P_t)S_e + P_s P_t T_s + (1-P_s)P_t T_c}, \tag{15}$$

where L_f is the average frame length, and S_e is the average size of a slot time, T_s is the average time that the channel is busy for frame transmission while T_c is the same for frame collision. In our evaluation, we set the initial contention window size W_0 to 15 and scale value α to 2, imposing an exponential back-off process. We also consider 5 stages ($m = 5$).

In both average times T_s and T_c, multiple parameters should be considered including the size of RTS, SIFS, CTS, ACK, AIFS[i], which are set to default values by [1]. On the difficulty to get a value of P_c through the practical experiment, we simply set it to 0.25. Once it is assumed, we can get the important values such as P_t, P_s, and $s_{0,0}$.

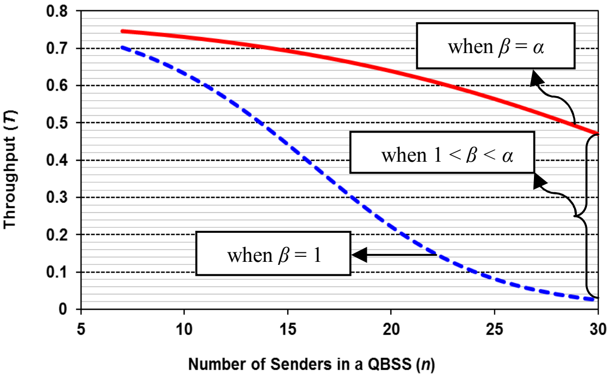

Figure 3. Saturation througput

The saturation throughput for different number of senders is shown in Figure 3. Note that there is only one sender having multicast flows. As we can see, in legacy EDCF scheme, the throughput becomes significantly worse as the number of senders increases, because the one greedy multicast flow gets more access chances than low-priority unicast flows by setting β to 1.

In contrast, if we set β to α, it shows relatively consistent throughput regardless of the number of senders. These results also show the throughput difference between the two different schemes becomes more prominent if there are multiple senders having multicast flows. The results also indicate if we adaptively adjust the size of β such that $1 < \beta < \alpha$, it will bring acceptable compromise of the throughput.

V. SIMULATION

In addition to the performance analysis, we performed a simulation to evaluate the performance of the IEEE 802.11e in a more practical environment. Our modification for multicast back-off is implemented on an existing IEEE 802.11e EDCA Model [14] by TKN developed in the ns-2 simulator.

TABLE 3. NS-2 NODE CONFIGURATION

Radio Propagation Model	Two Ray Round
MAC Type	802.11e
Antenna	Omni Antenna
Channel	Wireless Channel
Queue Type	Droptail
Max Queue Length	10
Routing Protocol	Dynamic Source Protocol

The node configuration is given in Table 3 and the simulation topology is depicted in Figure 4. We defined six network entities including four senders, one receiver, and one router. Each of the four senders is connected to the receiver through the wireless communication link having 1.5Mbps bandwidth. We set the frame size to 1000 bytes.

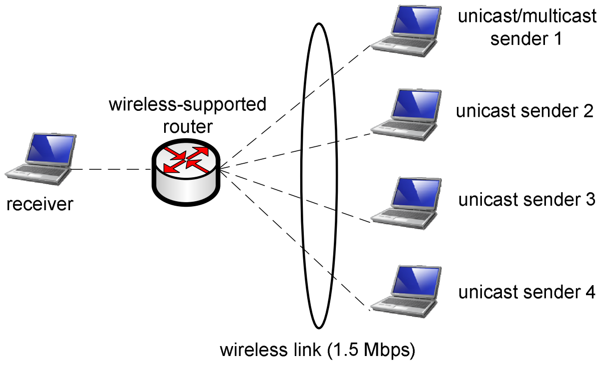

Figure 4. Simulation topology

In our simulation, we considered three different scenarios. First, a single communication channel is shared with four unicast-only senders running an exponential back-off mechanism. Second, we substitute a multicast sender using a legacy EDCA multicast mechanism for one of the four unicast senders. Third, we required the multicast sender to use the modified, back-off scheme by linearly increasing its contention window size by 1 and 1.5, respectively. With the given scenarios, we performed simulation for 10 ns-2 system seconds and evaluated how much bandwidth was consumed by each sender.

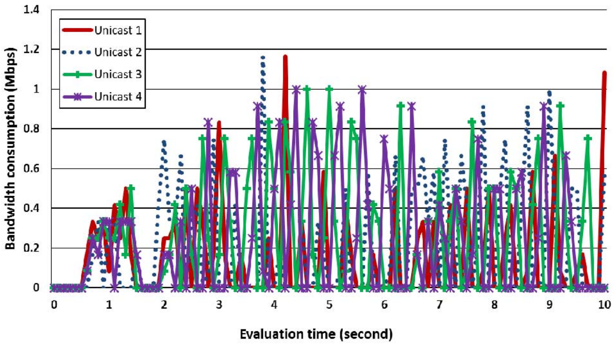

Figure 5. Result with all unicast senders with exponential back-off

Figure 5 shows the simulation results for the first scenario. As we see, the limited bandwidth is fairly shared with all four senders. For 10 seconds, each sender occupied 18%, 25%, 29%, and 28% of available bandwidth, respectively. Owing to the exponential back-off mechanism, if the session lasts long-term, the four senders will eventually have equal chances for fair channel access.

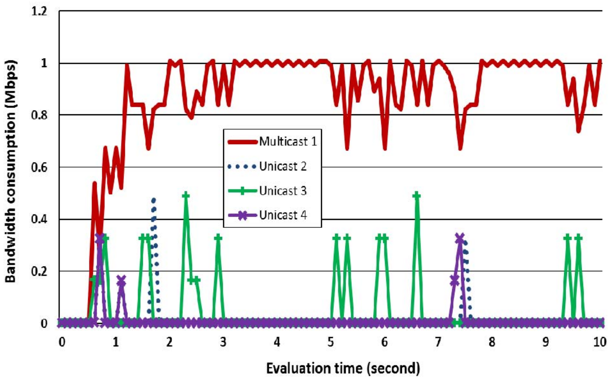

Figure 6. Result with one multicast sender without back-off

Figure 6 shows the simulation results for the second scenario. We see most of the available bandwidth, showing 92.2%, is occupied by the greedy, multicast sender. On the other hand, other unicast senders have a more limited chance to access the channel. Numerically, each unicast sender occupied only 1.3%, 5.5%, and 1% of available bandwidth, respectively. This result shows even one multicast flow can negatively affect the performance of other unicast flows.

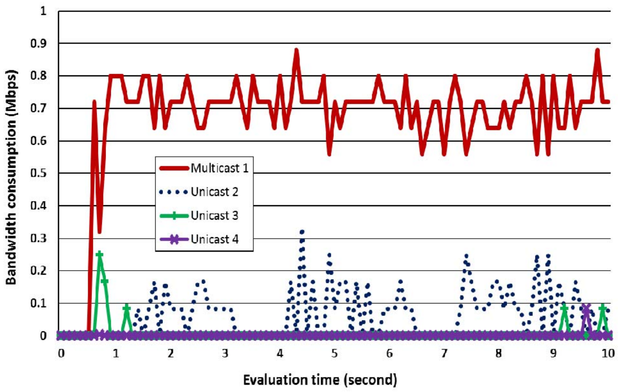

Figure 7. Result with one multicast sender with linear back-off by 1

We now require the multicast sender to adjust its contention window size by linearly increaing by 1 whenever it detects a frame loss. The result is shown in Figure 7. Compared to Figure 6, even though the difference is not too significant, the bandwidth consumption of multicast sender is decreased to 90% while other unicast senders shared the remaining 10 % of the available bandwidth. Note that other unicast senders still use an exponential back-off mechanism while the multicast sender is using a linear back-off one. When we linearly increase the contention window size of the multicast sender by 1.5, we could get a more meaningful result as shown in Figure 8. Numerically, each sender occupied 57%, 11%, 21%, and 11% of the available bandwidth. Especially, the unicast sender 2 and 3 showed even better performance than that of multicast sender at 9.4 seconds and 6.6 seconds, respectively.

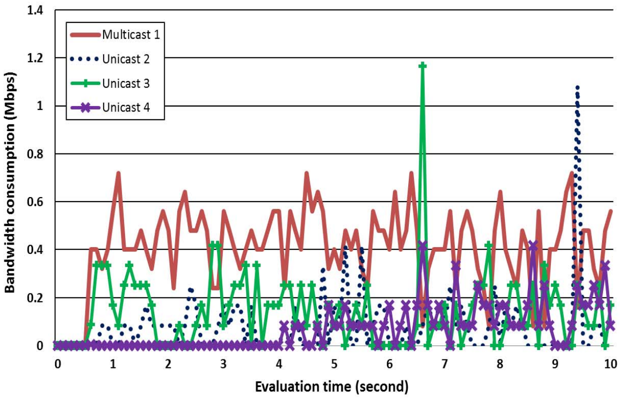

Figure 8. Result with one multicast sender with linear back-off by 1.5

A. Discussions

We recognize that a new MAC layer approach is required for multicast flow to:

- Provide a long-term, fair transmission opportunity for unicast flows by strategically adjusting the contention window size for the multicast flow;
- Provide at least a minum level of MAC layer support for transmission relaibility of the multicast flow reducing the required burden associated with the application layer error recovery; and
- Avoid significant performance degradation of the multicast flow.

Our simulation results indicate the optimal size of the linear back-off increament of the multicast flow should be decided by the network administator depending upon the requirements of the given applications. For example, in IEEE 802.11e, the standard includes various management frames. Among them, the QBBS load element frame contains information on the current station population and level of congestion within the QBBS. Based on the congestion level compared to the pre-defined threshold value, the value β or the linear back-off increament value can be dynamically adjusted. In addition, in order to provide a reliable multicast transmission, the modification may require the receivers to send NAKs for incorrectly received frames to request retransmission from the sender. The NAK-based approach reduces the number of feedback messages as long as the network is farily reliable. Also, based on the pattern of the arriving NAK frames, the sender can selectively decide if the retransmission is necessary. Once it decides retransmission is required, the sender can perform a fast retransmission mechanism by maintaining its initial contention window size without any back-off requirement.

VI. CONCLUSION

We discussed how one greedy multicast flow negatively affects the throughput of the multiple, low-priority, unicast flows. We showed the expected amount of negative impact through numerical performance analysis. We also show the amount of the impact using a simulation. Finally, we suggested a potentially adaptive, multicast, back-off mechanism to overcome this problem. The contention window size of the multicast flow should be adaptively adjusted depending on the level of population over the same QBSS. We are extending this research to efficiently and dynamically decide the optimal size of β depending on the current network condition. Also, we will consider the case when there are multiple senders requiring multicast flows. In this case, a new solution to provide fair channel access between the multicast flows and unicast flows having various levels of priority will be required.

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