I. INTRODUCTION

Motivation: With widespread adoption of mobile devices such as smartphones and tablets, the traffic volume of multimedia applications over the IEEE 802.11 wireless local area network (WLAN) has grown explosively during the last decade [1]. Such explosive growth of demand has necessitated various solutions. As a major solution, multicast enables efficient video delivery to a large group of users interested in a common venue-specific video, e.g., screen sharing in a conference room or a classroom, live broadcasting in sport stadium. Legacy multicast, however, intrinsically has a low reliability due to the absence of retransmission, and hence, multicast services have not been widely deployed. To enhance the performance of multicast, especially reliability, previous efforts such as forward error correction (FEC), physical (PHY) rate adaptation, and multi-hop extension have been proposed [2–4].

On the other hand, power management mechanism for WLAN is essential to extend the battery life of mobile devices since WLAN chipsets are major energy consuming components in portable devices. For this purpose, the IEEE 802.11 standard defines two power management modes, i.e., power save mode (PSM) and active mode (AM) [5]. A station (STA) in PSM reduces energy consumption by intermittently turning off the radio interface, while STA in AM keeps the radio interface turned on, thus incurring significant energy consumption. Intelligently alternating between PSM and AM based on the network activity, most of the off-the-shelf WLAN chipsets manage their energy consumption, where such a mechanism is called adaptive PSM (A-PSM). With A-PSM mechanism, STA in PSM switches to AM whenever it has unicast packets to send or receive. After the STA switches to AM, it stays in AM until an inactivity timer times out, called tail time, before switching back to PSM.

Previous studies [6, 7] report that many off-the-shelf WLAN chipsets have undesired functions when multicast receiver STA operates in PSM. The reported undesired functions, irrespective of whether they are standard in-compliant or even standard compliant, put STA to sleep while the AP transmits multicast packets, thus resulting in many packet losses.

Our approach: We extend the previous studies by carrying out elaborate measurement with a more diverse set of widely-used off-the-shelf chipsets. In addition, we investigate behavior of the power management mechanism with respect to the power management options provided by the operating system (OS). As a result, we make sure that the behavior of the power management mechanism depends on the power management options of the OS, and the undesired functions are still observed in all the tested chipsets when the power management options enabling PSM are selected. We additionally identify two new undesired functions that also result in multicast packet losses. In our experiments, the packet loss ratio due to the previously reported and/or newly identified undesired functions reaches up to 75.96%, thus making it impossible to provide satisfactory video multicast service to STAs operating in PSM even if the previous efforts [2–4] are applied.

The ultimate goal is for the STA operating in PSM to receive multicast packets without loss, which should require STA-side modifications. However, it is infeasible to modify massively pre-deployed WLAN chipsets. Being motivated by this, we propose a practical solution, called ACTivator-AP (ACT-AP), which requires only AP-side modification to prevent STAs receiving multicast from operating in PSM.

ACT-AP utilizes the feature of A-PSM that STA switches from PSM to AM whenever there are unicast packets to receive. In addition, STA in AM renews its inactivity timer whenever it receives unicast packets. Therefore, by transmitting unicast packets, called ACT-packets, ACT-AP makes STA in PSM go to AM, and STA in AM stay in AM continuously. In order to allow non-multicast receivers to save their energy, ACT-AP distinguishes multicast receivers among connected STAs using internet group management protocol (IGMP),...
and transmits ACT-packets only to the multicast receivers. To reduce overhead caused by ACT-packets, we propose an ACT-packet interval adaptation algorithm, which determines ACT-packet interval for each STA in consideration of behavior of A-PSM mechanism implemented in each STA. With the ACT-packet interval adaptation algorithm, reliable multicast delivery is provided with little overhead, regardless of the power management options or the chipset type in STA.

We prototype ACT-AP with off-the-shelf WLAN chipsets by modifying device driver and conduct experiments to evaluate the performance of ACT-AP. From the experimental results, we show that ACT-AP improves multicast packet delivery ratio (PDR) by up to 216% with little additional overhead.

**Contributions:** Our major contributions are summarized as follows.

- We conduct elaborate experiments with off-the-shelf WLAN chipsets by various manufacturers with various power management options.
- From the experiment results, we observe that the chipsets experience significant multicast packet losses due to undesired functions when power management options enabling PSM is selected, and classify new types of undesired functions.
- We propose ACT-AP, a novel and practical AP-only solution for multicast service, which requires no modification on the STA part.
- We prototype ACT-AP with off-the-shelf WLAN chipsets and evaluate its performance in realistic environment, and demonstrate that ACT-AP significantly improves PDR by up to 216%.

The remainder of the paper is organized as follows. In Section II, we explain power management mechanisms in WLAN. We demonstrate undesired functions in off-the-shelf chipsets via measurement study in Section III. Then, we provide the detailed description of the proposed ACT-AP in Section IV, and evaluate its performance in real environment in Section V. Related work is summarized in Section VI. Lastly, we conclude our work and present future work in Section VII.

### II. Power Management Mechanisms in IEEE 802.11

In this section, we explain power management mechanisms in IEEE 802.11 WLAN. According to the ways how STA determines its power management modes, there are three power management mechanisms, i.e., constant active mode (CAM), static power save mode (S-PSM), and adaptive power save mode (A-PSM).

#### A. Power Management Modes

IEEE 802.11 defines two power management modes, namely, AM and PSM. STA in AM always remains in awake state, in which the STA can transmit or receive frames. On the other hand, STA in PSM remains in doze state most of the time, where STA turns off its radio component and does not transmit or receive frames, and switches to awake state periodically to receive beacon frames and the subsequent unicast/multicast frames if there exist any.

#### B. Power Management Mechanisms

- **Constant AM (CAM):** With CAM mechanism, STA constantly operates in AM, and hence, unicast and multicast packets can be transmitted or received at any time. CAM mechanism does not incur packet delivery delay, while it results in significant energy consumption.

- **Static PSM (S-PSM):** With S-PSM mechanism, STA constantly operates in PSM. Because STA in PSM in doze state cannot transmit or receive packets, AP cannot transmit packets for the STA at any time. For unicast services, AP buffers incoming unicast packets destined to STAs in PSM, and then, announces the presence of the packets through the traffic indication map (TIM) element in the beacon. STA in PSM switches to awake state to receive beacon frames at a predefined time and checks the TIM element. After finding the presence of unicast packets destined to itself, STA requests the buffered packets by sending a power save (PS)-poll frame to the AP, and then, the AP sends the buffered packets to STA. STA keeps requesting the buffered packets until there is no buffered packet in the AP.

On the other hand, multicast packets are buffered in AP and transmitted only right after a delivery TIM (DTIM) beacon transmission. DTIM beacons are special beacons for power-saving delivery of multicast/broadcast, which are transmitted every DTIM interval (an integer multiple of beacon interval). A DTIM beacon includes an indication bit to advertise the existence of buffered multicast packets. If there is at least one buffered multicast packet, the indication bit is set to one, while the bit is set to zero otherwise. When STA in PSM receives a DTIM beacon whose indication bit is set to one, STA continues to be in awake state and receives the multicast packets. The more data (MD) bit in MAC header of the buffered multicast packets is set to one if more multicast frames are still buffered. STA returns to doze state only after it receives a multicast frame whose MD bit is zero or a beacon frame whose indication bit is zero.

- **Adaptive PSM (A-PSM):** Due to practical issues such as long latency [8], most (if not all) chipsets employ A-PSM mechanism instead of S-PSM mechanism [9, 10]. With the A-PSM mechanism, STA switches its power management mode on demand. Similar to S-PSM mechanism, when STA operates in PSM, it switches to awake state to receive beacon frames at a predefined time and checks the TIM element indicating the presence of buffered unicast packets. However, to receive buffered unicast packets, STA switches to AM instead of sending PS-poll frames. To notify the change of the power management mode, STA sends an unicast null frame1 with power management (PM) bit set to zero. Upon receiving such a null frame, AP learns that STA switches to AM, and then, it transmits all the buffered unicast packets. After receiving buffered unicast packets, if there is no packet toward the STA until an inactivity timer times out, called tail time, STA goes

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1It is a medium access control (MAC) frame composed of only MAC header and error detection code, but no payload.
back to PSM by sending a unicast null frame whose PM bit is set to one.

For multicast services, if all STAs associated with AP operate in AM, the operation for AP to transmit multicast packets is the same as that of CAM. Otherwise, AP transmits multicast packets with the same mechanism as that of S-PSM. Note that, with A-PSM mechanism, STA in PSM does not go to AM in order to receive multicast packets.

The A-PSM behavior varies and depends on chipset manufacturers and power management options of STA. We focus on two A-PSM properties: 1) tail time and 2) renewal-by-multicast. As mentioned above, tail time is the inactivity timer timeout until STA in AM switches to PSM if there is no packet. Some chipsets which have renewal-by-multicast property renew its inactivity timer upon the reception of not only unicast packets but also multicast packets, while others renew their timer only when receiving unicast packets.

Fig. 1 shows the aforementioned power management operation between one AP and one STA with the A-PSM mechanism. In Fig. 1, STA has renewal-by-multicast property, and hence, STA remains in AM by receiving multicast packets. If STA does not have renewal-by-multicast property, STA goes back to PSM after tail time regardless of multicast packet reception. We explain the detailed A-PSM behavior of off-the-shelf WLAN chipsets in the following.

III. MEASUREMENT STUDY

In this section, we present our measurement study on various widely-used off-the-shelf chipsets with respect to the power management options provided by the operating system (OS). In this measurement study, we focus on three issues. First, we investigate multicast packet losses due to powersaving operation of off-the-shelf WLAN chipsets. Second, from the above observation, we examine undesired functions which incur multicast packet losses. Lastly, we investigate detailed A-PSM behavior of off-the-shelf WLAN chipsets.

A. Multicast Packet Losses of STA in PSM

Measurement setup: To investigate multicast packet losses of off-the-shelf WLAN chipsets, we consider a WLAN composed of one AP and one STA. We locate the AP and the STA closely each other to minimize packet losses due to channel error.

The AP sends multicast packets to the STA using Iperf [11] (2 Mb/s) for 1 minute. To capture beacon and null frames, a laptop with Airpcap Nx [12] capturing packets on the air is deployed. We capture and analyze packets at the AP, STAs, and on the air.

We test the following five off-the-shelf WLAN chipsets in this measurement study.

- 533AN_HMW: Intel WiFi Link 5300 (IWL5300).
- 6235AN_HMW: Intel Centrino Advanced-N 6235 (IWL6235).
- AR5BHB112: Qualcomm Atheros AR9380 Mini PCIe (half-size) card reference design (AR9380).
- AR5B22: Qualcomm Atheros AR9462 Mini PCIe (half-size) card reference design (AR9462).
- DHXB-81: Broadcom BCM94313HMGB Mini PCIe (half-size) card (BCM94313HMGB).

We use LG XNote A515 laptop as the STA after replacing its factory-installed WLAN chipset by one of the above chipsets. Samsung Ativ Pro (X700T1C-F53) with AR9462 chipset is configured as the AP with Ubuntu 14.04 by using HostApd 2.4 [13]. The DTIM interval is set to three beacon intervals and PHY rate for multicast is set to 6 Mb/s. The measurement is repeated five times to obtain the average.

Power management options: Microsoft Windows series provide basic options for power management of wireless adapter [14]. In Windows 7, there are four power management options, namely, Maximum Performance (Max Perf.), Low Power Saving (Low PS), Medium Power Saving (Med PS), and Maximum Power Saving (Max PS). Power management operation of WLAN chipset is changed according to the above options. On the other hand, we find that these five chipsets are not affected by the change of the power management options offered by their device driver configuration.

Measurement results: The measurement results are summarized in Table I. All the five chipsets operate with CAM or A-PSM mechanism instead of S-PSM mechanism. Power management mechanism depends on OS’s power management option. If the power management option is Max Perf. or Med PS, the power management mechanism is set to CAM, while the mechanism is set to A-PSM otherwise.

All the tested chipsets with Max Perf. or Med PS, which employ CAM, receive most (i.e., over 98.99%) multicast packets. It represents that multicast packet losses due to channel error occur infrequently in this measurement since AP and STA are located closely each other. On the other hand, some chipsets with Max PS or Low PS, which employ A-PSM, lose a lot of multicast packets. Especially, all the tested chipsets with Max PS experience significant multicast packet losses, where PDR ranges from 24.03% to 47.03%. We observe that off-the-shelf WLAN chipsets have three undesired functions when the power management option is set to Max PS or Low PS, which result in significant packet losses. Note that Windows 7 selects Max PS as a default power management option when the power plan of the laptop without charging battery is power.
TABLE I
Summary of Experimental Results

<table>
<thead>
<tr>
<th>Chipset</th>
<th>Option</th>
<th>Mechanism</th>
<th>PDR</th>
<th>Undesired functions</th>
<th>Tail time</th>
<th>Renewal-by-multicast</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWL5300</td>
<td>Max Perf.</td>
<td>CAM</td>
<td>99.66%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Low PS</td>
<td>A-PSM</td>
<td>71.48%</td>
<td>Inappropriate wakeup &amp; Early sleep</td>
<td>205 ms</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
<td>CAM</td>
<td>99.81%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>28.39%</td>
<td>ReceivedDTIMs off &amp; Inappropriate wakeup</td>
<td>25 ms</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Max Perf.</td>
<td>CAM</td>
<td>99.62%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Low PS</td>
<td>A-PSM</td>
<td>72.73%</td>
<td>ReceivedDTIMs off &amp; Early sleep</td>
<td>130 ms</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
<td>CAM</td>
<td>98.99%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>26.00%</td>
<td>ReceivedDTIMs off</td>
<td>130 ms</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Max Perf.</td>
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<td>99.86%</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
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<td>Low PS</td>
<td>A-PSM</td>
<td>97.53%</td>
<td>None</td>
<td>392 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
<td>CAM</td>
<td>99.93%</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>43.03%</td>
<td>ReceivedDTIMs off</td>
<td>392 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Max Perf.</td>
<td>CAM</td>
<td>99.74%</td>
<td>None</td>
<td>391 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Low PS</td>
<td>A-PSM</td>
<td>96.57%</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
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<td>99.75%</td>
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</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>47.93%</td>
<td>ReceivedDTIMs off &amp; Early sleep</td>
<td>392 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Max Perf.</td>
<td>CAM</td>
<td>99.89%</td>
<td>None</td>
<td>391 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Low PS</td>
<td>A-PSM</td>
<td>97.45%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
<td>CAM</td>
<td>99.99%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>24.03%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Max Perf.</td>
<td>CAM</td>
<td>99.89%</td>
<td>None</td>
<td>391 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Low PS</td>
<td>A-PSM</td>
<td>47.93%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
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<td>N/A</td>
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<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>25.07%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
</tbody>
</table>

1. ReceiveDTIMs off

2. Early sleep

3. Inappropriate wakeup

Fig. 2. Undesired functions of STAs.

Many chipsets, namely, IWL5300, IWL6235, AR9380, and AR9462, show this undesired function in Max PS or Low PS. The PDR of each chipset varies according to how often DTIM beacon is skipped. This undesired function is also reported in previous studies [6, 7].

**Early sleep**: In IEEE 802.11 standard, AP can continuously send buffered multicast packets to STA in PSM beyond one beacon interval. In **Early sleep** case [6], STA only receives multicast packets during one beacon interval and goes to doze state. We extend the concept of **Early sleep** to include that STA even goes to doze state within one beacon interval before the end of multicast transmission. **Early sleep** causes significant packet losses because STA receives multicast packets only for a short period of time. BCM94313HMGB, IWL5300, and IWL6235 show this undesired function in Max PS or Low PS.

**Inappropriate wakeup**: As mentioned above, STA with the A-PSM mechanism sends a unicast null frame to notify AP of its power management mode change. In **Inappropriate wakeup** case, STA switches to AM from PSM for unidentified reason and goes back to PSM. Because AP sends multicast packets, the STA must continue to remain in awake state, but it falls in doze state after going back to PSM. Accordingly, the STA cannot help but miss the remaining multicast packets, and **Inappropriate wakeup** results in packet losses. IWL5300 shows this undesired function in Max PS and Low PS.

**C. A-PSM behavior of off-the-shelf chipsets**

**Tail time**: To investigate how long each chipset remains in AM, we observe tail time, which is the inactivity timer timeout until STA in AM switches to PSM if there is no packet. In this experiment, AP sends only one unicast packet to STA. We learn the tail time by measuring the gap between the unicast packet transmission time and the null frame transmission time. Table I presents the measured tail time. We observe that tail time depends on chipset types and power management options. Measured tail time varies from 25 ms to 392 ms. A chipset with shorter tail time stays in AM for a shorter time and

saver [15], and hence, we can easily imagine that multicast services do not work well in real environments.

**B. Undesired Functions**

The undesired functions of STAs are categorized into three cases as shown in Fig. 2. We describe the details of the three undesired functions in the following.

**ReceiveDTIMs off**: In IEEE 802.11 standard, each STA has a parameter, called **ReceiveDTIMs**. When **ReceiveDTIMs** is true, a STA in PSM must go to awake state every DTIM interval to receive all DTIM beacons. However, when **ReceiveDTIMs** is false, a STA in PSM does not need to go to awake state every DTIM interval. Even though the STA can save more energy by skipping DTIM beacons, it has no choice but to lose multicast frames transmitted after the skipped DTIM beacons.

<table>
<thead>
<tr>
<th>Chipset</th>
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<td>Early sleep</td>
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<td>Med PS</td>
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<td>A-PSM</td>
<td>47.93%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>Med PS</td>
<td>CAM</td>
<td>99.99%</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>High PS</td>
<td>A-PSM</td>
<td>25.07%</td>
<td>Early sleep</td>
<td>203 ms</td>
<td>O</td>
</tr>
</tbody>
</table>
quickly switches to PSM, and hence, the chipset tends to show undesired functions more often.

Renewal-by-multicast: To investigate whether each chipset can continuously remain in AM during multicast service, we observe renewal-by-multicast property, which is whether a chipset renews its inactivity timer upon the reception of a multicast packet. In this experiment, AP sends one unicast packet to the STA before sending multicast packets. If STA continuously remains in AM until the end of the multicast packet transmission, the chipset in STA is considered to have renewal-by-multicast property. Table I presents whether the chipset has renewal-by-multicast property or not (O/X). Renewal-by-multicast property varies by chipset types, but it is independent of power management options. Intel chipsets (IWL5300 and IWL6235) have renewal-by-multicast property while Qualcomm Atheros chipsets (AR9380 and AR9462) and Broadcom chipset (BCM94313HMGB) do not. Given that the video multicast requires large bandwidth, if a chipset with renewal-by-multicast goes to AM once, we do not need to be concerned about the chipset’s undesired functions. However, additional effort is required for chipsets without renewal-by-multicast because they switches to PSM independent of multicast packet reception.

D. Summary of Measurement Study

We observe three undesired functions of STAs with off-the-shelf WLAN chipsets, which result in multicast packet losses. All the tested chipsets show undesired functions in Max PS or Low PS even though they work normally in other power management options. The packet loss ratio reaches up to 75.96%, which makes it impossible to provide satisfactory video multicast service even if the previous efforts to enhance the reliability of multicast [2–4] are applied. Therefore, it is necessary to resolve these undesired functions. Every tested chipset implements A-PSM mechanism, but detailed implementation varies by chipset types and power management options. We design the proposed scheme by considering the different A-PSM properties of each chipset.

IV. ACT-AP: Proposed Scheme

In this section, we first present the design philosophy of ACT-AP. Next, we provide the detailed design of ACT-AP, which is a practical AP-side solution to avoid multicast packet losses caused by undesired functions in power management operation of STA.

A. Design philosophy

We aim at developing a practical solution with the following requirements. First, our proposed scheme should be practical, i.e., it should require no modification or configuration of STAs because it is practically impossible to modify or configure a tremendous number of pre-deployed STAs. Second, our proposed scheme should resolve the aforementioned undesired functions without knowledge of power management option or the type of chipset in STAs. Third, our proposed scheme should achieve the goal via software upgrade of AP. Fourth, our proposed scheme focuses on increasing PDR even if more energy is consumed at STA, since the observed PDRs from measurements are too low to support multicast video streaming. Finally, our proposed scheme should incur minimal overheads in terms of power consumption and wireless resource usage.

B. ACTivator-AP (ACT-AP)

1) Overall architecture: Fig. 3 describes the overall architecture of ACT-AP, which consists of five components: 1) Packet Inspector, 2) Mode Change Detector, 3) ACT-packet Generator, 4) Multicast Buffer, and 5) ACT-packet Interval Controller. Packet Inspector identifies multicast receivers using IGMP message and detects start of multicast service. Mode Change Detector keeps track of the change of power management mode of each STA. ACT-packet Generator creates and transmits tiny unicast packets, called ACT-packets, which make STA continue to operate in AM during multicast service. If any STA operates in PSM, multicast packets from upper layers are buffered in Multicast Buffer until all STAs go to AM. Using the information from Packet Inspector and Mode Change Detector, ACT-packet Interval Controller determines the interval for transmission of ACT-packets.

2) Packet Inspector: To distinguish which STA needs to receive multicast packets, ACT-AP utilizes IGMP messages. IGMP defines two messages, namely, JOIN and LEAVE. JOIN (LEAVE) message indicates that the STA joins (leaves) a multicast group. If ACT-AP captures a JOIN message from a STA, ACT-AP registers the STA and sends ACT-packets to the STA upon the start of multicast service. On the other hand, if ACT-AP captures a LEAVE message from a STA, ACT-AP deregisters the STA because the STA need not receive multicast packets any longer. ACT-AP can also use other control or manual messages instead of IGMP messages to distinguish STAs if such messages are known in advance.

In addition, Packet Inspector detects the start and stop of multicast service. When multicast service starts, ACT-AP begins transmitting multicast packets as well as ACT-packets to the registered STAs. On the other hand, when multicast service is finished, ACT-AP operates as a legacy AP.

3) Mode Change Detector: As mentioned above, STA informs AP of its power management mode change using PM bit. From PM bit in a received frame, Mode Change Detector recognizes power management mode change of each STA, and notifies other components of the change.

2For example, if video source rate is 2 Mb/s and the payload size of each packet is 1,328 bytes, the packet interval is 5.312 ms, which is small enough to continuously renew the inactivity timer.

3Manual setup for power management option is not practical because it is too cumbersome for each individual user to manually change the option whenever starting or stopping multicast applications. On the other hand, a solution using modification in application software, such as video player, requires software update in every user’s device, and hence, this solution cannot support other widely-used software.
4) ACT-packet Generator: ACT-AP generates and transmits ACT-packets, unicast packets with very short payload (1 byte), to the registered STAs. With the A-PSM mechanism, STAs switch from PSM to AM in order to receive ACT-packets. If AP continues to transmit ACT-packets, the packets renew the inactivity timer, thus enabling STAs in AM to stay constantly in AM. To avoid delayed transmission of ACT-packets caused by multicast transmission, ACT-packets need to have high priority over multicast packets, and hence, the access category of enhanced distributed channel access (EDCA) [5] for ACT-packets is set to voice (AC_VO).

5) Multicast Buffer: Multicast packets are transmitted only when every STA operates in AM for the following two reasons: 1) STA in PSM can miss a lot of multicast packets, and 2) after DTIM beacons, AP should not transmit any unicast packets before the end of buffered multicast packet transmission, which might allow STA in AM to switch back to the PSM due to a large delay of ACT-packet transmission.

Before being transmitted, multicast packets are buffered in Multicast Buffer until every STA switches to AM by receiving an ACT-packet. Even if it is necessary, this approach incurs possible delay of multicast transmission, as discussed in Section V.

6) ACT-packet Interval Controller: ACT-AP needs to determine the ACT-packet interval properly by considering WLAN chipsets’ tail time. Specifically, if the ACT-packet interval is too short, it results in waste of precious wireless resource. On the other hand, STA goes back to PSM if ACT-packet interval is longer than STA’s tail time. To determine a proper ACT-packet interval, we propose an ACT-packet interval adaptation algorithm, which adapts ACT-packet interval per STA basis. In Section III, we observe that A-PSM behavior varies by chipset types and power management options of STA, and hence, ACT-AP determines ACT-packet interval for each STA. The flow chart of ACT-packet interval adaptation algorithm for each STA is shown in Fig. 4.

When a multicast service begins, the algorithm initializes ACT-packet interval \( T \) and interval threshold \( T_{\text{thre}} \) to \( T_{\text{min}} \) and \( T_{\text{max}} \), respectively, where \( T_{\text{min}} \) \((T_{\text{max}}) \) is minimum (maximum) ACT-packet interval. Because minimum and maximum values among measured tail time are, respectively, 25 ms and 392 ms, \( T_{\text{min}} \) and \( T_{\text{max}} \) are set to 20 ms and 400 ms, respectively. ACT-AP conservatively selects initial ACT-packet interval since ACT-AP has no information about STA. During a multicast service, the interval is adapted by the algorithm.

To switch STAs’ power management mode from PSM to AM, ACT-AP initially sends ACT-packets to STAs. To make a STA remain in AM continuously, ACT-AP sends an ACT-packet to the STA with interval \( T \). ACT-AP adopts an additive increase and multiplicative decrease (AIMD)-based algorithm to determine proper ACT-packet interval. Note that the STA’s tail time can be changed by power management options of STA during multicast service, and hence, ACT-AP needs to determine ACT-packet interval adaptively. If the STA does not return to PSM during \( T \), ACT-AP judges that \( T \) is smaller than the STA’s tail time, and hence, ACT-AP increases the interval by \( \epsilon \), which is set to 4 ms for implementation convenience.\(^4\) Otherwise, ACT-AP judges that \( T \) is larger than the STA’s tail time, and hence, ACT-AP interval is cut in half. By increasing ACT-packet interval, ACT-AP can reduce overhead due to ACT-packets. However, if ACT-AP excessively increases ACT-packet interval, STA returns to PSM, thus increasing the latency. To give more weight to avoiding the latency increase, ACT-AP adopts the AIMD-based algorithm.

When the power management mode change occurs, ACT-AP records the current ACT-packet interval, and sets the ACT-packet interval threshold to this value such that ACT-packet interval cannot be larger than the ACT-packet interval threshold afterward to prevent further changes of power management mode. Therefore, the ACT-AP interval converges into the largest interval with which the STA remains in AM by receiving ACT-packets.

Some chipsets with a specific power management option do not need transmission of ACT-packets. Specifically, if the power management mechanism of a chipset is CAM, ACT-AP

\(^4\)We implement ACT-AP using default Linux kernel timer whose time resolution is 4 ms.
AP does not need to send \textit{ACT-packets}. Additionally, if the power management mechanism of a chipset is A-PSM with \textit{renewal-by-multicast} property, a single transmission of \textit{ACT-packet}, which makes STA go to AM, is enough as long as the interval of multicast packets is shorter than the \textit{tail time}. Therefore, to reduce such unnecessary transmission of \textit{ACT-packets}, ACT-AP stops sending \textit{ACT-packets} when the \textit{ACT-packet} interval reaches the maximum \textit{ACT-packet} interval.

With the \textit{ACT-packet} interval adaptation algorithm, ACT-AP provides reliable multicast delivery with little overhead, regardless of the power management options or the chipset type of STA.

V. Performance Evaluation

In this section, we comparatively evaluate the performance of ACT-AP via both numerical analysis and prototype-based measurements. Performance metrics include PDR, fractional airtime, power consumption, and latency, which are the key parameters for satisfactory video multicast service.

A. Analysis Result

To demonstrate the practicality of ACT-AP, we first conduct a simple numerical analysis of airtime consumption.\footnote{We skip the actual equations due to space limitation, but the analysis is rather straightforward since there is only a single transmitter, i.e., AP, without contention.} Fig. 5 presents the analysis result. We assess the fractional airtime (i.e., the ratio of channel busy time over total observation time) of the following schemes: legacy multicast, legacy unicast, and multicast with ACT-AP. In our analysis, AP transmits multicast or unicast packets to multiple STAs with no channel error. The traffic rate is 2 Mb/s, where the payload size of each packet is set to 1,328 bytes. The PHY rate of multicast packets is fixed at 6 Mb/s, while PHY rate of unicast packets (including \textit{ACT-packets}) are varied from 6 to 54 Mb/s. Note that, in this analysis, we consider the worst case where \textit{ACT-packet} is transmitted to every STA at the minimum interval (20 ms). In practice, we expect that actual fractional airtime of ACT-AP will be smaller than the analysis result since \textit{ACT-packet Interval Controller} adaptively determines \textit{ACT-packet} interval according to \textit{tail time} of each STA.

In the legacy multicast case, the fractional airtime is not changed as the number of receivers increases. However, legacy multicast cannot support reliable multicast service due to packet losses caused by the undesired functions of STA as described in Section III-B. In the legacy unicast case, we need not be concerned about the undesired functions since STA goes to AM in order to receive unicast packets. However, legacy unicast consumes airtime in proportion to the number of receivers, and hence, it is not suitable to support multiple receivers at the same time. ACT-AP requires more fractional airtime than legacy multicast case, but it can avoid multicast packet losses caused by the undesired functions. Compared with the legacy unicast schemes, ACT-AP can support much more receivers, i.e., more than fifty receivers, which should be enough for typical indoor environments.

B. Measurement Results

Now, we evaluate the performance of ACT-AP via measurements in a real classroom environment shown in Fig. 6.

\textbf{Measurement setup:} The numbered black circles, a red laptop, and a blue laptop represent STAs, AP, and sniffer of the packets on the air, respectively. The AP and the nine STAs constitute a WLAN using channel 1 (2.412 GHz). Similar to Section III, Samsung Ativ Pro (XQ700T1C-F53) with AR9462 chipset is configured as AP with Ubuntu 14.04 by using HostApd. AP streams a video clip (1280x720 resolution, MPEG-4 codec, 2 Mb/s, 54 s) to STAs via multicast. We implement ACT-AP by modifying the latest ath9k device driver, `backport 4.2.1 [16].`

We use Dell inspiron 14 3421 (STA 4) and LG XNote A515 laptops (all other STAs) after replacing their factory-installed WLAN chipset with one of the above chipsets shown in Table II. We conduct experiments with three power management configurations of STAs, namely, best, worst, and typical configuration. Table II shows the STA's power management options with respect to three configurations.

A laptop with Airpcap Nx \cite{12} capturing packets on the air is deployed. We capture and analyze packets at the AP, STAs,

\begin{table}[h]
\centering
\caption{WLAN chipsets and power management configurations}
\begin{tabular}{|c|c|c|c|}
\hline
STA & Chipset & Configurations  \\
\hline
1 & AR9462 & Max Perf. & Max PS & Max PS \\
2 & IWL5300 & Max Perf. & Max PS & Low PS \\
3 & AR9380 & Max Perf. & Max PS & Max Perf. \\
4 & IWL3235 & Max Perf. & Max PS & Low PS \\
5 & BCM94313HMGB & Max Perf. & Max PS & Low PS \\
6 & AR9380 & Max Perf. & Max PS & Med PS \\
7 & IWL5300 & Max Perf. & Max PS & Med PS \\
8 & IWL6235 & Max Perf. & Max PS & Max PS \\
9 & AR9380 & Max Perf. & Max PS & Max Perf. \\
\hline
\end{tabular}
\end{table}
and on the air to measure PDR, fractional airtime, and latency between AP and STA. To measure power consumption, STA 4 is only supplied using charging cable after detaching battery. We then measure the current through the cable using NI USB-6210 [17] and ACS712T-20A [18]. ACS712T-20A converts the current into a proportional voltage, which is measured by NI USB-6210, and then, the current is also obtained by an inverse operation. By multiplying measured current and voltage rating on power supply, we obtain the power consumption in STA. The measurement is repeated five times.

Reliability of multicast service: Fig. 7 shows the average PDR during multicast service. In the best configuration case, STA’s power management mechanism is CAM, and hence, STA receives most multicast packets transmitted from legacy AP. In contrast, in the worst configuration case, STA’s power management mechanism is A-PSM, thus showing undesired functions. Accordingly, a significant number of multicast packets are lost. In the typical configuration case, PDR of multicast packets depends on power management options of STA; STAs in Med PS and Max Perf. successfully receive most multicast packets, but STAs in Low PS and Max PS lose multicast packets considerably. ACT-AP significantly increases PDR from 30.99% to 97.91% (216% improvement) in the worst configuration by eliminating the problems caused by the undesired functions. The remaining mild losses (up to 9.18%) can be recovered by existing reliability enhancement schemes, e.g., FEC.

Wireless resource consumption: Fig. 8 presents average fractional airtime during multicast service. Due to ACT-packets, ACT-AP consumes slightly more wireless resource than legacy multicast in all configurations. However, thanks to the ACT-packet interval adaptation algorithm, ACT-AP requires little extra airtime (up to 0.47%), which is tiny cost for the significant improvement of PDR.

Power consumption: Fig. 9 shows average power consumption of STA 4 during multicast service. In Table II, power management mechanism of STA 4 in best, typical, and worst configuration is set to Max Perf., Low PS, and Max PS, respectively. As mentioned above, with undesired functions, STA experiences multicast packet losses, because STA remains in or goes to doze state instead of receiving multicast packets. In the case of legacy AP, the power consumption of STA in the worst configuration is less than that of STA in the typical configuration. That is because STA in the worst configuration drops more multicast packets by staying in doze state much longer than that in the typical configuration. Likewise, compared to the typical configuration, STA in the best configuration consumes more energy with legacy AP since STA in the best configuration remains in awake state by receiving most multicast packets successfully.

ACT-AP makes STA operate in AM, and hence, STA with ACT-AP does not go to doze state in all configurations. In the best configuration, power consumption of legacy AP and that of ACT-AP are almost the same because STA does not go to doze state for both cases. On the other hand, in the worst and typical configurations, STA with ACT-AP consumes more energy compared to STA with legacy AP because STA with ACT-AP does not go to doze state. ACT-AP consumes more energy (up to 0.69 W), but it is tiny cost for the significant improvement of PDR.

If the legacy scheme employed the ideal PSM without undesired functions, more power consumption for receiving packets would be measured, and hence, the gap in power consumption would be even smaller. Note that compared to total power consumption of STA with ACT-AP (about 9.38 W), the difference in power consumption between ACT-
AP and legacy AP is quite small. That is because WLAN chipset is not a major power-consuming component in laptop with many power-hungry components including large screen and high performance CPU.

**Latency:** Fig. 10 shows empirical CDF of the difference $L_d$ in AP-to-STA latency between legacy AP and ACT-AP:

$$L_d = (t_{tx}^{\text{legacy}} - t_{rx}^{\text{legacy}}) - (t_{tx}^{\text{act-ap}} - t_{rx}^{\text{act-ap}}),$$

where $t_{tx}^{\text{legacy}}$, $t_{rx}^{\text{legacy}}$, $t_{tx}^{\text{act-ap}}$, and $t_{rx}^{\text{act-ap}}$ denote multicast packet transmission time with legacy AP, reception time with legacy AP, transmission time with ACT-AP, and reception time with ACT-AP, respectively. Transmission and reception time are measured when a multicast packet to be transmitted enters the WLAN interface of AP and when the multicast packet is received from the WLAN interface of STA, respectively.

Since AP and STA are not synchronized with each other, the difference between transmission and reception times is the sum of AP-to-STA latency and time offset between AP and STA. To eliminate the common time offset, we consider only the differences in AP-to-STA latency between legacy AP and ACT-AP. Note that a positive (negative) value of $L_d$ indicates that latency of ACT-AP is smaller (larger) than that of legacy AP, and hence, ACT-AP delivers multicast packets earlier (later) than legacy AP.

As mentioned above, ACT-AP transmits multicast packets only when all the STAs running in AM, which incurs an additional delay for making the STAs in PSM switch to AM. In the best configuration, $L_d$ is almost zero, and ACT-AP does not affect latency in multicast transmission because STAs operate in AM with both legacy AP and ACT-AP. In the worst configuration, $L_d$ is negative for about 23% due to the aforementioned extra delay of ACT-AP, while $L_d$ is positive for about 77% because ACT-AP eliminates delay induced by the DTIM-based power save delivery for STAs in PSM. In the typical configuration, $L_d$ is mostly positive, meaning that ACT-AP improves latency by disabling PSM.

**VI. RELATED WORK**

The authors of [6] report three undesired functions of power-saving STAs, namely, 1) Early sleep, which indicates that a STA in AM returns to PSM after one beacon interval, 2) ReceiveDTIMs off, which is also addressed in our paper, and 3) Always in AM, which indicates that a STA does not return to PSM. Always in AM does not incur multicast packet losses, which is not considered as undesired function in our paper. Although they made a first measurement study on multicast delivery to power-saving STAs, their report misses the operation of devices from two main WiFi chipset vendors, i.e., Qualcomm Atheros and Broadcom. Moreover, they just report undesired functions only without proposing any solution. In addition to the STA side problems, undesired functions of the commercial APs are also reported in [6], which are all fixed in ACT-AP.

In [7], from measurement study, the authors present ReceiveDTIMs off and CPU overflow as the causes of multicast packet losses. CPU overflow indicates that STA’s CPU cannot handle interrupt from WLAN chipset when CPU is overloaded, and hence, received multicast packets are discarded. However, CPU overflow occurs when the rate of multicast packets is over 9,000 pps (packets per second). Note that 9,000 pps is enough to support video streaming 6 so that CPU overflow is not considered in our paper. Moreover, [7] does not propose any practical solution either.

The authors of [8] firstly propose A-PSM to support delay-sensitive applications. In [9, 10], the authors improve A-PSM in order to save energy further. However, these previous studies lack the consideration on multicast packet losses due to undesired functions of power-saving STAs.

**VII. CONCLUDING REMARKS**

From our extensive measurement, we verify severe multicast packet losses in off-the-shelf chipsets configured to use PSM. To resolve the problem, we develop ACT-AP that prevents STA from operating in PSM. From extensive evaluation with prototype implementation in off-the-shelf chipset, we demonstrate that ACT-AP can significantly enhance multicast delivery to STA with little additional overhead. In this work, we have focused on off-the-shelf chipsets implemented in laptops, and we plan to evaluate the performance of ACT-AP with various smartphones in the future.

**ACKNOWLEDGMENT**

This work was supported by the National Research Foundation of Korea (NRF) grant funded by Korea government (MSIP) (NRF-2015R1A2A2A01006750).

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6 For example, if the multicast packet size is 1,328 bytes, 9,000 pps is equivalent to 95.616 Mb/s.