A Novel Energy-conscious Access Point (eAP) System with Cross-layer Design in Wi-Fi Networks for Reliable IoT Services

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This work was partly supported by Institute of Information communications Technology Planning Evaluation (IITP) grant funded by the Korea government (No. 2018-0-00691, Development of Autonomous Collaborative Swarm Intelligence Technologies for Disposable IoT Devices, 50%) and Institute of Information communications Technology Planning Evaluation (IITP) grant funded by the Korea government (No. 2020-0-00833, A study of 5G based intelligent IoT Trust Enabler, 50%)

ABSTRACT This paper proposes a novel energy-conscious access point (eAP) system with cross-layer design to increase the energy efficiency of IoT devices in IEEE 802.11 Wi-Fi networks for reliable IoT services. The proposed eAP system controls the energy resources of IoT devices to extend the lifetime of the IoT device. For this purpose, we develop a new eAP system that considers a cross-layer design with a prompt TCP ACK transmit function, a caching-and-retransmit IoT data function, and a multiple IoT data aggregate function to improve the energy efficiency of the IoT device. In addition, the proposed eAP system has a device energy management module that precisely controls operating parameters, such as the transmission period of IoT packets, the delivery of traffic indication message (DTIM) value of IoT devices, and the transmitting power of IoT devices. These features extend the lifetime of the battery-powered IoT devices while satisfying service requirements for reliable IoT services. The long listening time of TCP ACK messages in receive mode (Rx) results in the high energy consumption of IoT devices due to the large round trip time. The proposed eAP system reduces the reception time of TCP ACK messages in the IoT device, using the prompt TCP ACK transmit function in the eAP. This reduces the long Rx mode time for TCP ACK reception, and increases the short sleep mode time, which results in increase of the energy efficiency of the IoT device. In the energy-saving analyses, we formulate an energy consumption model for the IoT device, and determine the energy-saving gain when the IoT device uses the eAP system model, compared to a legacy AP system model. Our performance evaluation results verify that the proposed eAP system achieves a maximum improvement in energy efficiency of approximately 88%, and 8.4 times improvement in the expected lifetime of the IoT device, compared to the legacy AP system model.

INDEX TERMS Energy consumption of IoT devices, energy-conscious AP, cross-layer design, energy-saving, Wi-Fi networks, reliable IoT services

I. INTRODUCTION

Wi-Fi is the most common global wireless access technology, and the robust Wi-Fi infrastructure can be used anywhere in the world for high-speed data transmission. Wi-Fi network protocols have primarily focused on optimizing bandwidth, transmission distance, and transmission rate, but recently, there has been an increasing interest in technologies that reduce energy consumption through protocols, such as IEEE 802.11ax. [1], [2]. In particular, as IoT services using Wi-Fi networks continue to expand, increasing the energy efficiency of IoT devices in Wi-Fi networks has become one of the field’s key issues [3]. Among these efforts, reducing the energy consumption of battery-powered IoT devices is increasingly essential for reliable wireless IoT services in indoor environments such as hospitals [4], [5]. As battery-powered IoT devices increase in the indoor Wi-Fi network,
it is considered as the most important problem to increase the energy efficiency of IoT devices by utilizing network protocols and hardware aspects ultimately.

Typically, a wireless access point (AP) relays data between a wired network and wireless devices, allowing wireless devices to access the Internet. Wireless APs are connected to routers using Ethernet cables and are primarily used by medium and large organizations, where organizations typically have multiple APs to cover the entire building. Wireless APs are managed by a single router and, which is one of the main reasons why larger organizations use wireless APs instead of Wi-Fi routers. Until now, wireless APs have had simple functions such as relays operating at the bottom layers (Physical, MAC, Network). However, these days even tiny sensor devices work beyond the bottom layers (Transport, Application), so wireless APs need to get smarter with more functions using information obtained from cross-layer, even if they are a little more complex. For example, hospitals already have multiple wireless APs installed, and these APs are simply wireless devices that only relay wireless data transmission within the hospital. However, if the wireless AP utilizes some information obtained from other layers and adds some functions, APs can control numerous stations or IoT devices connected to the AP to save energy or achieve reliable data transmission. Therefore, we consider how to save energy for IoT devices by developing a smarter AP system model with cross-layer design for the Wi-Fi networks in an indoor environment such as a hospital.

Most hospitals currently use medical devices called patient monitors, which monitor and collect patients’ biometric information using multiple sensors attached to the patient’s body, connected with wired cables. These legacy patient monitors are very inconvenient for both patients and medical staff. First, it is very inconvenient for patients to move while attached to several cables connected to the patient monitor. In addition, the nurse’s visit at night to obtain the patient’s biometric information from the patient monitors interferes with the patient’s comfortable sleep. Second, it is very inconvenient for medical staff to manually record and manage every patients’ biometric information from numerous patient monitors. Moreover, it is difficult to collect sufficient data to accurately check the patient’s condition, because the biometric information on the patient monitor is only collected intermittently by the nurse. There is also a risk of missing or incorrect records when relying on manual records.

Battery-powered IoT devices can conveniently serve as a cordless patient monitoring system for both patients and medical staff. Some wireless patient monitoring systems using IoT devices have recently been researched and utilized in academic institutions, and actual devices have been developed to improve real-time health monitoring IoT services [6]–[8]. Recently, Chungnam national university in Sejong, South Korea, built a smart hospital using a cordless disposable patch-type IoT sensor that can measure a patient’s electrocardiogram [9].

However, a cordless patient monitoring system raises two important technical concerns: the energy-saving of the battery-powered IoT devices, and the reliability of biometric information transmission.

The energy-saving of battery-powered IoT devices is the most important technical issue to be solved in order to provide convenient services using cordless patient monitoring IoT devices. If this issue is not solved, it would require frequent battery replacement due to the short operating lifetime of battery-powered IoT devices. Therefore, it is essential to significantly improve the energy efficiency of IoT devices.

Secondly, the reliable transmission of biometric information must also be ensured to provide reliable health monitoring IoT services for patients. Patient biometric information includes critical personal medical information, which requires high reliability, and this information must be delivered to medical staff promptly without data loss or contamination. An agreement method which confirms messages are "sent" and "arrived" to each other can ensure reliable transmission between the sender and the receiver. The TCP (transmission control protocol) protocol with the ACK (acknowledgement) message to ensure the reception of sending data is a common and global protocol for reliable transmission. Therefore, transmitting measured data using the TCP protocol by IoT devices can be the most suitable solution to ensure the reliable transmission of biometric information for IoT services.

Fig. 1 shows an example of a reliable and energy-efficient IoT service using Wi-Fi networks in a hospital to provide real-time health monitoring. First, several battery-powered IoT sensors are attached to the patient to measure the patient’s biometric information (heart rate, electrocardiogram, body temperature, oxygen saturation, etc.). Then, the data sensed by the IoT device is transmitted to our proposed energy-conscious AP (eAP) and forwarded to the application server to be recorded and analyzed. The eAP uses information or energy-saving models from other layers to transmit control messages to manage the operating parameters of IoT devices, such as the transmission period of the IoT packets, the delivery of traffic indication message (DTIM) values, and the transmitting power of the IoT devices for energy-saving.

These three operating parameters are the main components that affect the energy consumption of IoT devices [10], [11]. In addition to these three operating parameters, the eAP can also control the IoT devices by adding another operating parameters, such as the transmission burst size.

The proposed device energy management module in the eAP optimizes the operating parameters of the IoT devices according to each patient’s level. The patient’s levels are divided into three levels according to the patient’s conditions, and the energy management of the IoT devices varies depending on the patient’s levels. Typically, hospitals or health care institutions classify patients in three or four levels to increase controllability and patient management [12], [13]. For example, for mild patients (level 1 patients), the energy efficiency of the IoT devices can be improved by setting a large transmission period for IoT packets, a large DTIM value, and a small transmitting power value. On the other
An example of a reliable and energy-efficient IoT service using Wi-Fi networks in a hospital for real-time health monitoring.

hand, for severe and critical patients (level 2 and 3 patients), a smaller IoT packet transmission period, smaller DTIM value, and larger transmitting power can be set. Even though the energy efficiency of the IoT devices for these levels is slightly lower than that for mild patients, the exact condition of the patient can be delivered more frequently to medical staff. In addition, the patient’s biometric information, recorded and analyzed in the application server, is transmitted to the display at the nurse desk in real-time so that the nurse can monitor the patient’s condition, schedule appropriate treatment, and call a doctor as needed.

The DTIM value (also called "the DTIM interval value") controls the beacon reception time of the IoT device, which allows a sleep mode for multiple beacons. Increasing the DTIM value helps save energy because listening to each beacon message consumes a lot of receiving power and generally occupies a large portion of the average energy consumption of the IoT device. The longer the DTIM value is, the higher the energy-saving effect is. However, the high DTIM value has a tradeoff relationship with the high latency of downlink packets, because an IoT device in sleep mode cannot receive the downlink packets.

The IoT device transmits a signal with a transmitting power at or above a certain level which the receiver AP can decode, considering the influence of noise and interference in the wireless channels. In general, Wi-Fi data rate (speed) depends on modulation and coding schemes, and an signal-to-interference-plus-noise ratio (SINR) value of a certain level or higher is required for fast modulation/coding. Similar to increasing transmitting power, increasing the target SINR value may increase the Wi-Fi data rate (speed) because fast modulation/coding combinations are available.

The main contributions of this paper are as follows:

- This paper proposes a novel energy-conscious AP (eAP) system model with cross-layer design in Wi-Fi networks to increase the energy efficiency of IoT devices. The proposed eAP system model aims to increase the lifetime of battery-powered IoT devices for reliable IoT services.

- To achieve this, we designed a new functional architecture for the eAP system model considering the cross-layer design. We defined a new device energy management module in the eAP, which optimally controls the operating parameters, such as the transmission period of IoT packets, the DTIM values, and the transmitting power of the IoT devices to increase the energy efficiency of IoT devices.

- To the best of our knowledge, combining the transport-layer three functions; the prompt TCP ACK transmit function, the caching-and-retransmit IoT data function, and the multiple IoT data aggregation function; with the bottom-layer functions of an AP as a cross-layer design is the first attempt for the energy saving of IoT devices.

- Through extensive simulations, the proposed eAP system model exhibited notable improvements in the energy efficiency of IoT devices in terms of energy-saving gains, the expected lifetime of the IoT devices, and round-trip delay. Specifically, the proposed eAP system model achieved a maximum improvement in the energy efficiency of approximately 88%, and an 8.4 times im-
provement in the expected lifetime of a patient level 3 IoT device, which communicated frequently with the eAP (the transmission period of IoT packets = 0.9 s, the DTIM value = 3), respectively, compared to the legacy AP system model.

In summary, we propose the energy-conscious AP system with cross-layer design to increase the energy efficiency of IoT devices. In particular, since the eAP sends ACK to IoT devices directly without receiving ACK from the server, the prompt TCP ACK transmit function and the caching-and-retransmit IoT data function of the eAP must be considered together in order to handle packet losses. The aggregation function is also considered to compensate for the eAP energy burden and improve network performance by reducing the number of packet transmissions. The proposed eAP system controls the transmission period of IoT packets, the DTIM value, and the transmitting power of IoT devices according to the application layer model considering the physical layer.

The rest of the paper is organized as follows. Section II briefly explains the background and reviews related works. Section III explains the proposed energy-conscious AP system model with functional architecture and the newly defined eAP functions for improving the energy efficiency of IoT devices. In Section IV, we analyze the energy consumption of the IoT devices using numerical analyses. Section V details the performance evaluation of IoT devices with the proposed eAP system. Finally, conclusions are drawn in Section VI.

II. RELATED WORKS

Energy-saving methods used in IoT devices over Wi-Fi networks have a similar principle: Adjust the power-save mode according to the service situation. The adaptive power-saving mode in IoT devices focuses on maintaining the lowest power consumption mode as much as possible while meeting service requirements. In addition, there have been studies to reduce the number of retransmissions and to control link management. In Wi-Fi networks, access points typically broadcast a beacon frame every 100 ms to announce the presence of a wireless LAN. It contains information about the network and synchronizes members of the service set. The energy consumed by IoT devices for beacon reception accounts for a considerable portion of the total energy. There have been various studies on how to effectively reduce the energy consumed to receive these beacons. In [14], the authors proposed an adaptive beacon listening protocol that dynamically determined the beacon listening interval of a mobile station based on the PDF (probability density function) of the estimated round trip time. They reduced the number of beacon receptions while satisfying the required average delay. In [15], the DTIM value was used to reduce the beacon reception energy. The higher the DTIM was, the longer the IoT device went into sleep mode for multiple beacons, which potentially saved more energy. However, this was accompanied by high latency in the downlink packets. In [16], the target wake time (TWT) scheme was used for energy-saving in IEEE 802.11ah when data transmission was infrequent. The TWT function is useful for IoT devices that communicate infrequently, but it has a heavy overhead to establish an agreed wake-up schedule between AP and IoT devices. In [17], the authors modeled and analyzed the performance of IEEE 802.11ah restricted access window (RAW) and TWT function. RAW is a channel access protocol that uses station grouping to increase energy efficiency and reduce contention and collisions. The authors showed that RAW has better energy efficient performance in many stations (more than 1250 stations) or high traffic scenarios, while RAW is not suitable for critical latency applications or low traffic scenarios. And the evaluation also showed that the TWT function is effective in energy saving when the transmission period is at least 5 minutes. In [18], the authors proposed an appropriate scheduling algorithm for uplink multi-user based on TWT function to dramatically reduce collisions in IEEE 802.11ax to maximize throughput and reduce energy consumption. In [19], the authors reviewed several approaches based on TWT and wake-up radio (WUR) to reduce sensor energy consumption in the Wi-Fi network and evaluated their efficiency. The WUR mechanism uses a separate trigger frame to wake up the IEEE 802.11ax transceiver chipset to significantly reduce the energy consumption of IoT devices when traffic is sparse in IEEE 802.11ba. In [20], the authors presented an 802.11ba-based WUR receiver that is fully integrated within an IEEE 802.11a/b/g/n/ac Wi-Fi transceiver. The WUR receiver, which consumes very tiny energy, operates when the Wi-Fi system is in sleep mode and turns on the Wi-Fi radio upon receiving an 802.11ba-based wake-up packet. In [21], the authors reported that increasing listen interval to reduce beacon reception wake-up instances may negatively impact energy efficiency because it requires maintaining an association overhead in IEEE 802.11 IoT systems using empirical evaluation. In [22], the authors proposed a Wi-Fi AP that prioritized packets according to the power status of the IoT device to reduce the duty cycle. The duty cycle represents the ratio of activation (awake) time during a cycle in an IoT station. Therefore, reducing the duty cycle also reduces the energy consumption of the IoT station. The proposed AP used the IoT queue allocation algorithm for high priorities, using the remaining tail time of the IoT packet (permissible delay time of each packet before expiration). However, the proposed AP needs more dedicated queues for IoT traffic and only focuses on downlink scheduling. Moreover, the proposed AP is not suitable for services that are insensitive to delay, such as thermostat services. In [23], the portion of energy consumed for the TCP ACK message reception of measured data transmission by an IoT device was almost 17% for a temperature sensor. Furthermore, this portion of energy consumed by the IoT device for TCP ACK reception can be increased to more than 17% in the event of frequent data transmission, such as a heart rate sensor for sensitive services.

In addition, there have also been several studies that consider cross-layer interactions to increase the throughput and
energy efficiency of endpoint devices. In [24], the authors proposed a cross-layered quick UDP internet connection (C-QUIC) handover migration scheme that considers dynamic network conditions such as SINR to increase throughput and reduce power consumption in mobile networks. C-QUIC performs early migration using predictive SINR-based handover modeling using channel score and estimated smoothed round trip time (RTT) parameter. However, they focused on increasing throughput through early handover migration in heterogeneous networks, rather than saving energy on devices. In [25], the authors presented an xNode platform to increase the download rate of variable applications using xNodes, which are logical entities between the core network and the endpoint devices. The xNode has real-time network information (e.g., available link capacity, round trip time, etc.) and controls the endpoint devices using the proposed scheduler and appropriate settings of TCP initial congestion window size to increase the download rate. In [26], the authors presented a cross-layer approach for TCP uplink flows in mmWave networks to solve high packet losses and TCP timer timeout retransmission problems under non-line of sight conditions (NLOS). The author used information gathered from multiple layers of user equipment (UE), such as round-trip time, SINR, and available resource, to obtain an optimal congestion widow value, which minimized queuing delays without compromising throughput. In [27], the authors proposed an adaptive orthogonal frequency division multiplexing (OFDM) time slot configuration algorithm depending on the amount of user data enqueued at the base station to increase download rate compared to the fixed size slot configuration in 5G networks. The proposed algorithm starts with a short slot for delay quality after connection establishment, and switches slot configuration from a short slot to a long slot according to the buffered data and RTT of the base station to increase download throughput.

In summary, the related works for energy-saving of IoT devices have studied how to effectively reduce the operating times that consume high energy in IoT devices [14]–[22]. In particular, they focused on reducing the transmission time of IoT packets and the reception time of beacon packets, which consume a lot of energy in IoT devices. However, research to reduce the energy consumed for TCP ACK reception of IoT packets is insufficient. Also, research on cross-layer interaction AP to reduce energy consumption of IoT devices is insufficient in Wi-Fi networks. They mainly focused on increasing the throughput and download rate by using information from the cross-layer [24]–[27]. However, there are insufficient studies to reduce the energy consumption of endpoint devices using cross-layer designs in Wi-Fi networks. Therefore, our study focuses on efficiently reducing the energy consumed for TCP ACK reception and retransmission in IoT devices using a novel eAP system with cross-layer design. The proposed eAP system presented in the next section can be a solution to this problem.

III. ENERGY-CONSCIOUS AP (eAP) SYSTEM MODEL
In this section, we propose an IEEE 802.11 eAP system model for reliable and energy-efficient IoT services. First, we present the functional architecture of the proposed eAP system considering cross-layer design. The eAP system adopts a modular architecture that can be implemented through software updates to legacy AP systems. Secondly, we present a novel method to increase the energy efficiency of IoT devices in Wi-Fi networks by reducing the receiving time of TCP ACK using the prompt TCP ACK transmit function in the eAP.

A. FUNCTIONAL ARCHITECTURE
Fig. 2 shows the functional architecture of the proposed eAP system model with cross-layer design. The proposed eAP has a device energy management module, local cache, and three newly defined transport layer functions; a prompt TCP ACK transmit function, a caching-and-retransmit IoT data function, and a multiple IoT data aggregate function.

The device energy management module optimally controls the operating parameters of IoT devices, such as the transmission period of IoT packets, the DTIM value, and the transmitting power of IoT devices. The control messages are delivered to the IoT devices via the message queuing telemetry transport (MQTT) protocol. MQTT is a lightweight application-layer protocol that transports messages between devices based on the publish/subscribe (pub/sub) model. This protocol usually runs over the TCP/IP protocol and requires a message broker called the MQTT broker. The control message published by the device energy management module in the eAP is delivered to the IoT device using the MQTT broker, and the IoT device subscribes the control message for energy management using the MQTT. On the other hand, the measured biometric data published by the IoT device is delivered to the eAP using the MQTT, and the eAP subscribes the measured data of the IoT device using the MQTT broker. The local cache in the eAP temporarily stores the measured data of the IoT device for forwarding to the application server.

The three new transport layer functions are defined in the eAP to save energy in the IoT system. Firstly, the prompt TCP ACK transmit function is to transmit its own TCP ACK to the IoT device as soon as the eAP receives the uplink packet from the IoT device. The legacy AP receives the TCP ACK from the TCP server and forwards it to the IoT device, which requires the IoT device to stay awake for a long time in receive (Rx) mode to receive the TCP ACK. However, the eAP transmits promptly its own TCP ACK to the IoT device without waiting for a TCP ACK from the TCP server, which enables the IoT device to awake for a short time in Rx mode. This new function allows the IoT device to reduce energy consumption by reducing the Rx mode time and increasing the sleep mode time.

Secondly, the caching-and-retransmit IoT data function is to retransmit cached IoT data to the TCP server when the eAP does not receive TCP ACK from the TCP server within
the set time called TCP timer timeout. The eAP temporarily stores the measured data from the IoT device in the local cache. This retransmission occurs when the TCP ACK message does not arrive within the TCP timer timeout due to network congestion or other reasons. When the TCP timer timeout occurs, the eAP can undertake the retransmission burden of the IoT device by retransmitting stored data in the cache to the TCP server without a retransmission request to the IoT device. With this new function, the IoT device does not have the retransmission burden and can stay in sleep mode and save energy when the TCP timer timeout occurs.

Thirdly, the multiple IoT data aggregate function is to assemble IoT packets from multiple IoT devices into some bursts. Most of the measured IoT data transmitted from multiple IoT devices to APs are delivered via small size data packets compared to a TCP maximum segment size (1460 bytes). Whenever the AP receives data from the IoT device and sends data to the application server, there are many short-length packets and ACKs between the AP and the application server, which generates unnecessary and heavy traffic load. With this new aggregate function, the eAP collects data received from multiple IoT devices for a particular duration, then makes some bursts and sends them to the application server to reduce network traffic between the eAP and the application server. In addition, decrease in the number of transmissions reduces the transmission energy consumption of the eAP.

The application server for IoT services can be located remotely or locally. The application server receives the measured data from the IoT devices by subscribing to the MQTT broker and records them in the database. Then, the stored data is analyzed in the application server and delivered to the medical staff to monitor the patient’s condition in real-time.

The IoT devices have multiple bio-sensors that are battery-powered. The measured data are saved in memory during the transmission period, and published by the application MQTT protocol. For reliable transmission, the measured IoT data is delivered by TCP protocol. The energy management in the IoT devices receives a control message from the eAP and optimally controls operating parameters of the IoT device, such as the transmission period of the IoT packets, the DTIM value, and the transmitting power.

These functional architectures can be easily constructed and implemented using just software updates without adding other equipment to the legacy 802.11 Wi-Fi network system.

B. REDUCING TCP ACK RECEPTION TIME

We consider an uplink (UL) data transmission of the TCP protocol for reliable transmission. We also only consider the data transmission model between an AP and IoT devices, not the transmission model between IoT devices. Fig. 3 shows a comparison between the legacy and proposed procedure in 802.11 Wi-Fi networks.

In the legacy procedure, the AP receives measured data from the IoT devices and delivers it to the TCP server. After the network response time, the AP receives a TCP ACK message from the TCP server and forwards it to the IoT devices. Meanwhile, after sending measured data in TCP packets, the IoT device switches to Rx mode to receive ACK and stays in Rx mode until receiving a TCP ACK message from the TCP server via the AP. However, the waiting time to receive a TCP ACK message in the Rx mode is long, due to the network response time between the AP and the TCP server. The network response time is caused by processing
measured data from the IoT devices. After that, the following beacon message, as shown in Fig. 4. The IoT device has a short sleep time before receiving the long awake time required to receive a TCP ACK message, because of the TCP server. The TCP ACK frame size is \(54\) bytes which contains \(6\) bytes of TCP/IP header, \(6\) bytes of source MAC, \(6\) bytes of destination MAC, and \(2\) bytes of frame type. Also, Wi-Fi ACK with TCP ACK contains \(54\) bytes of TCP ACK and \(30\) bytes of Wi-Fi MAC header, so the Wi-Fi ACK frame size is \(84\) bytes in our system model. The SIFS (short inter-frame space) is \(10\, \mu s\) and \(16\, \mu s\) in IEEE 802.11n (2.4GHz) and IEEE 802.11ac/ax, respectively. The processing time for TCP ACK frame generation is from \(2\, \mu s\) to \(100\, \mu s\) [28]. In general, the packet generation time depends on the network equipment such as CPU, the network traffic loads, and etc.

The proposed \(e\)AP system optimally controls the operating parameters of IoT devices while satisfying QoS requirements of health monitoring IoT services. Mild patients can tolerate infrequent and delayed transmission of biometric data compared to critical patients. For example, for mild patients (level 1 patients), the energy efficiency of the IoT devices can be improved by determining a large transmission period for IoT packets, a large DTIM value, and larger transmitting power can be set. Even though the energy efficiency of the IoT devices for these levels is lower than that for mild patients, the exact condition of the patient can be delivered more frequently to medical staff. There is a tradeoff relationship between frequent data transmission and improvement the energy efficiency of IoT devices. Therefore, finding optimal operating parameters of IoT devices while satisfying QoS requirements of health monitoring IoT services can improve the energy efficiency of IoT devices.

**C. CONTROLLING OPERATING PARAMETERS OF IoT DEVICES**

Some patients require frequent biometric data transmission for timely and appropriate treatment, while some patients do not need frequent biometric data transmission. Since each patient’s health status is different, appropriate controlling operating parameter values of IoT devices are needed according to the patient’s condition to increase the energy efficiency of IoT device. As mentioned in the application case study of the introduction, we divided all patients into three patient levels based on the health condition to provide real-time health monitoring IoT services. Mild patients can tolerate infrequent and delayed transmission of biometric data compared to critical patients. For example, for mild patients (level 1 patients), the energy efficiency of the IoT devices can be improved by setting a large transmission period for IoT packets, a large DTIM value, and a small transmitting power value. On the other hand, for severe and critical patients (level 2 and 3 patients), a smaller IoT packet transmission period, smaller DTIM value, and larger transmitting power can be set. Even though the energy efficiency of the IoT devices for these levels is lower than that for mild patients, the exact condition of the patient can be delivered more frequently to medical staff. There is a tradeoff relationship between frequent data transmission and improvement the energy efficiency of IoT devices. Therefore, finding optimal operating parameters of IoT devices while satisfying QoS requirements of health monitoring IoT services can improve the energy efficiency of IoT devices.

**FIGURE 3.** A Comparison of the legacy and the proposed procedures

| IoT Device | 802.11 legacy AP | TCP Server |
|------------|-----------------|------------|
| Sleep      | Wireless (Wi-Fi)| TCP ACK    |
| Awake (for receiving TCP ACK) | beacon | beacon |
| Sleep      | beacon | beacon |
| Sleep      | beacon | beacon |
| Listen     | beacon | beacon |
| Sleep      | beacon | beacon |
| Listen     | beacon | beacon |
| (a) The legacy AP system procedure |

| IoT Device | 802.11 eAP | TCP Server |
|------------|------------|------------|
| Sleep      | Wireless (Wi-Fi) | TCP ACK |
| Awake      | beacon | beacon |
| Sleep      | beacon | beacon |
| Sleep      | beacon | beacon |
| Listen     | beacon | beacon |
| Sleep      | beacon | beacon |
| Listen     | beacon | beacon |
| Reducing TCP ACK reception time | Caching and aggregation of received IoT data |
| Increasing sleep time | Aggregated Data |
| (b) The proposed \(e\)AP system procedure |

generation time is less than \(10\, \mu s\). However, when the TCP ACK generation time is longer than the SIFS, the procedure may be changed to transmit the Wi-Fi ACK first, and then transmit the TCP ACK using random channel access. The IoT device can receive the TCP ACK message from the \(e\)AP within a shorter time because the TCP ACK message does not have a round trip time between the \(e\)AP and the TCP server.

As such, the \(e\)AP reduces the waiting time for the IoT device to receive the TCP ACK message, as shown in Fig. 3b, compared to the legacy procedure in Fig. 3a. The IoT device that receives the TCP ACK message with a short listening time switches to transmit (Tx) mode to send the L2 ACK message to the \(e\)AP and then switches to sleep mode until the next beacon reception. Fig. 5 shows the increased sleep time of an IoT device before receiving the following beacon message, compared to the legacy procedure in Fig. 4.

If the \(e\)AP does not receive a TCP ACK from the TCP server within a certain period of time (TCP timer timeout interval), the measured data cached by the \(e\)AP is retransmitted on behalf of the IoT device. In addition, the \(e\)AP aggregates data received from multiple IoT devices, makes them into some bursts, and sends them to the TCP server. That is, the \(e\)AP serves as a virtual TCP server for the IoT devices, and serves as a virtual client for the TCP server.
of IoT packets, the DTIM value, and the transmitting power of IoT devices, according to the patient’s level. Now we formulate the optimization problem to increase the energy efficiency of IoT devices.

IV. ENERGY CONSUMPTION ANALYSIS

In this section, we analyze the energy consumption of the IoT device using the proposed eAP system model. We firstly find the optimal transmit power of the IoT device in an indoor environment where noise and interference exist. Secondly, we analyze the operating time for each mode of the IoT device to calculate the energy consumption of the IoT device. Finally, we determine the energy-saving gain when using the eAP system model.

We assumed an IEEE 802.11ax network system, which is the latest standard for Wi-Fi networks. We also assumed a service scenario in which IoT packets are transmitted periodically and frequently with short transmission period (e.g., wireless patient’s health monitoring service). We considered the DTIM scheme as an energy saving method for IoT devices by reducing the number of beacon receptions in 802.11 networks. As mentioned earlier, high DTIM values help to reduce the energy consumed to receive beacons, but it increases the latency of downlink IoT packets. Therefore, it is important to use an appropriate DTIM value based on the context of the application layer. Also, we added the case of using the TWT scheme instead of the DTIM scheme in the eAP. The TWT scheme is an energy saving mechanism of 802.11ax for IoT devices with long transmission cycles. The TWT scheme is usually used for long periodic transmissions, such as tens of seconds, minutes, and days. However, the cons of the TWT scheme are lack of timeliness and long downlink delay because the IoT device cannot receive downlink data during the next promised trigger reception in sleep mode. Timeliness and short downlink delay are essential for delivering reliable healthcare service. For example, timeliness and short downlink delay are important factors for changing the uplink transmission period due to a sudden change in a patient’s condition or for quickly delivering an appropriate treatment order from a doctor. Therefore, the TWT scheme is less appropriate for frequent frame exchange scenarios that have a short period of transmission, such as the health monitoring service. Nevertheless, as the TWT scheme can reduce further energy consumption for beacon reception compared to the DTIM scheme, we added the TWT scheme as an optional use case in the eAP. In addition, since the energy consumption for the initial TCP connection procedure, which is a one-time procedure, is negligible among the total energy consumption of the IoT device, the initial TCP connection establishment procedure is not considered in the IoT energy consumption analysis. The initial setup time of TWT agreements between IoT devices and APs is also not considered in the IoT energy consumption analysis. This is because the initial TWT agreements can be set up in an implicit mode that does not require repetition of the TWT setup frames. Also, we only assumed a transmission scenario between AP and IoT devices, not between IoT devices.

A. OPTIMAL TRANSMIT POWER OF THE IoT DEVICE

In the proposed eAP system model with cross-layer design, we assume that the IoT device can change the transmitting power according to the channel condition for guaranteeing...
variable QoS requirements [29]. The following formula development is required to calculate the optimal transmitting power of the IoT device.

The signal-to-interference-plus-noise ratio (SINR) at the eAP is given by,

\[ \gamma = \frac{P_R}{P_I + P_N}, \]

where \( \gamma \) is the SINR seen by the eAP, \( P_R \) is the received power at the eAP, \( P_I \) is the measured interference power at the eAP, and \( P_N \) is the measured noise power at the eAP. Usually, interference power \( P_I \) and noise power \( P_N \) are measured together at the AP as \( P_I + P_N \). We assume the value of \( P_I + P_N = -90 \) dBm which is a suitable value in an indoor wireless environment. The received power at the eAP, \( P_R \) can be calculated by,

\[ P_R = L \cdot P_{TX}, \]

where \( L \) is the total loss factor between the IoT device and the eAP, \( P_{TX} \) is the transmit power of the IoT device. The loss factor can be modeled, for example, by using the distance path-loss model with a fading component, i.e., \( L = L_0 d^{-a} h \) [30], where \( L_0 \) is a constant depending on the transmission frequency and the antenna gains. Also, \( d \) is the distance between transmitter and receiver, \( a \) is the path-loss exponent, and \( h \) is a random variable representing the channel fading [30], [31].

The energy consumed by the IoT device to transmit a specific length message is given by,

\[ E_{TX} = (\mu P_{TX} + P_O) \cdot T_m, \]

where \( \mu \) is the conversion factor of a power amplifier from electric power to RF power, \( P_{TX} \) is the transmit power of the IoT device, \( P_O \) is the electronic power consumption overhead incurred in the communication module to encode a message, and \( T_m \) is the shortest time for transmitting a fixed-length message [31]. Using Shannon’s information capacity theorem \( C = W \log_2(1 + SNR) \), the transmitting time of a fixed-length message is given by,

\[ T_m = \frac{N_m}{B \log_2(1 + \gamma)}, \]

where \( N_m \) is a fixed message length, \( B \) is the bandwidth of the channel, and \( \gamma \) is the SINR. By substituting the above relationships, the energy consumption of the IoT device in the transmitting mode is given by [31],

\[ E_{TX} = \frac{h \mu L (P_I + P_N) \gamma + P_O}{B \log_2(1 + \gamma)} N_m. \]

From the above relation, all parameters except \( \gamma \) are related to channel limitations and hardware. However, we note that the target SINR \( \gamma \) is a free variable that the system can control by adjusting the transmit power of the IoT device.

We also consider the retransmission probability due to transmission errors to calculate the transmitting energy consumed by the IoT device. The retransmission probability \( p_e \) is given by,

\[ p_e = p_c + p_t, \]

where \( p_c \) is the probability of packet collision, and \( p_t \) is the probability of wireless link fail between the IoT device and

FIGURE 5. Power consumption of the IoT device in the e-AP system model with DTIM scheme
the AP. The packet collision probability $p_c$ can be approximated by below [32],
\[ p_c = 1 - \left(1 - \frac{1}{W} \right)^{W-1}, \]
where,
\[ W_{\text{backoff}} = (1 - p) W + p(1 - p) W^2 + ... + p^m (1 - p) W^{m+1} + p^{m+1} W^{2m} = \frac{1 - p - p(2p)^m}{1 - 2p}, \]  
(7)
where $W$ is the minimum window size, $n$ is the number of IoT devices, $W_{\text{backoff}}$ is the overall average backoff window size, $p$ is the packet collision probability of each transmission, $m$ is the maximum recursive times that increase $W$, and $2^{m}W$ is the maximum window size. This approximation of packet collision probability, $p_c$, is based on the assumption that each packet collides with constant and independent probability $p$, and it is also independent of the channel status.

From [33], [34], the probability of packet collision, $p_c$, can be approximated by,
\[ p_c \approx \frac{1}{2} \left(1 + \frac{4}{g} \sqrt{1 + \left(\frac{4}{g}\right)^2} \right), \text{ where } g = \frac{W}{n - 1}. \]  
(8)

By applying the above retransmission probability, $p_c$, the energy consumption of the IoT device considering the retransmission probability in the transmitting mode is given by,
\[ E_{TX} = \left(\frac{P_R}{L} + P_0\right) T_m = \left[\frac{\mu L}{(P_t + P_N)\gamma + P_0}\right] N_m(1 + p_c) \text{Blog}_2(1 + \gamma) = \left[\frac{\mu L \text{Blog}_2(1 + \gamma)}{d^{-a_h}}(P_t + P_N)\gamma + P_0\right] \text{Blog}_2(1 + \gamma) = A_1 \gamma + A_2 \text{Blog}_2(1 + \gamma), \]
where,
\[ A_1 = \frac{\mu L \text{Blog}_2(1 + \gamma)}{d^{-a_h}}(P_t + P_N), \]
\[ A_2 = \frac{N_m(1 + p_c)P_0}{B}. \]  
(9)

We can obtain the optimal transmit power of the IoT device considering the retransmission probability in the transmitting mode as below,
\[ P_{T_{TX}} = \arg \min_{P_{TX}} [E_{TX}] = \text{Solution of } \left[\frac{d}{dP_{TX}} \log_2(1 + \gamma) = 0\right], \]  
(10)
when using the Lambert-W function, that is, $W[z]e^{W[z]} = z$, we can substitute the optimal transmit power of the IoT device as below,
\[ P_{T_{TX}}^* = \frac{P_t + P_N}{L} \left[\exp \left(1 + W \left[\frac{A_2/A_1 - 1}{e}\right]\right) - 1\right] = \frac{P_t + P_N}{L} \gamma^*. \]  
(11)
Accordingly, the target SINR $\gamma^*$ at the minimum bound is given by,
\[ \gamma^* = \exp \left(1 + W \left[\frac{A_2/A_1 - 1}{e}\right]\right) - 1. \]  
(12)

B. ENERGY CONSUMPTION OF THE IoT DEVICE

In the proposed eAP system model, a cycle is defined as a period between the start time of the IoT data transmission and the start time of the subsequent IoT data transmission, as shown in Fig. 5. The time for each operating mode in the IoT device in a cycle can be obtained using the above equations. In this section, we analyze the time for each operation mode in a cycle and the energy consumption of the IoT device when using the DTIM scheme and the TWT scheme.

The Tx mode time of the IoT device considering the retransmission probability in a cycle, $T_{tx}$, is given by,
\[ T_{tx} = (1 + p_c)T_{data} + t_{L2ack} \]
\[ = \left(1 + p_c\right)\frac{N_{data}}{\text{Blog}_2(1 + \gamma)} + \frac{N_{L2ack}}{\text{Blog}_2(1 + \gamma)}, \]  
(13)
where $T_{data}$ is the time taken to transmit the measured data from the IoT device, $t_{L2ack}$ is the transmitting time of the L2 ACK message from the IoT device, $N_{data}$ is the length of transmitting data, and $N_{L2ack}$ is the length of the L2 ACK message.

In the DTIM scheme, the Rx mode time of the IoT device in a cycle consists of several beacon reception times and a TCP ACK reception time. This is because we assumed only the data transmission scenario between the IoT devices and the AP, not between the IoT devices. The TCP ACK reception time can be reduced using the proposed eAP system. According to [23], the portion of energy consumed for the TCP ACK reception time is about 17 percent in a 60-second transmission cycle for a temperature sensor. Other bio-sensors, such as heartbeat, electrocardiogram and blood pressure sensors, require more frequent transmission of measured data, so the portion of energy consumed for TCP ACK reception time is greater than that for the temperature sensor. This is because more frequent data transmission requires more frequent TCP ACK reception. The Rx mode time of the IoT device in a cycle, $T_{rx}$, is given by,
\[ T_{rx} = \left(\frac{I_{period}}{n_{dtim}}, t_{beacon} + t_{ack} \right) \text{(DTIM)}, \]
\[ t_{tri} + t_{ack} \text{(TWT)}, \]  
(14)
where $I_{period}$ is the period for transmission data, $n_{dtim}$ is the DTIM value, $I_{beacon}$ is the beacon interval that is broadcast by the AP (typically 100 ms), $t_{beacon}$ is the reception time.
of one beacon message, $t_{bea}$ is the reception time of one trigger frame, and $t_{ack}$ is the reception time of one TCP ACK message.

Each Rx mode time of the IoT device in a cycle that uses the legacy AP system and the eAP system is given by,

$$ T_{rx}^A = \left\{ \begin{array}{ll} t_{bea} + t_{ack} + t_{trans} + t_{lack} + t_{TWT} \quad & (DTIM) \\ t_{bea} + t_{ack} + t_{trans} + t_{lack} \quad & (TWT) \end{array} \right. $$

$$ T_{rx}^{eA} = \left\{ \begin{array}{ll} t_{bea} + t_{ack} + t_{TWT} \quad & (DTIM) \\ t_{bea} + t_{ack} + t_{TWT} \quad & (TWT) \end{array} \right. $$

(15)

where $T_{rx}^A$ is the receiving time of the IoT device that uses the legacy AP, $T_{rx}^{eA}$ is the receiving time of the IoT device that uses the proposed eAP, $t_{trans}$ is the RTT between the IoT device and the TCP server via the legacy AP, and $t_{lack}$ is the RX mode time of the IoT device in a cycle, which is the total wake-up mode time of the IoT device in a cycle,

and $t_{trans}$ is the RTT between the IoT device and the TCP server via the legacy AP, and $t_{lack}$ is the RX mode time of the IoT device in a cycle, which is the total wake-up mode time of the IoT device in a cycle.

The total transient mode time of the IoT device in a cycle, $T_{trans}$, is given by,

$$ T_{trans} = \left\{ \begin{array}{ll} \left(2 + \frac{t_{period}}{n_{dtim}} - 1 \right) + t_{trans} \quad & (DTIM) \\ (2 + \beta) \cdot t_{trans} \quad & (TWT) \end{array} \right. $$

(16)

where the left part of the above equation, $2 \left(1 - \frac{t_{period}}{n_{dtim}}\right)$, is the transition time for beacon receptions when using the DTIM scheme, and the right part, $\beta \cdot t_{trans}$, is the transition time for trigger receptions, TCP ACK reception, and L2 ACK transmission. The $t_{trans}$ is one transition time, and $\alpha$ (the transient number for data transmission, TCP ACK reception, and L2 ACK transmission) is 7 in our system model assumption, as shown in Fig.5. In the TWT scheme, $2 \cdot t_{trans}$ is the transition time for trigger reception, and $\alpha \cdot t_{trans}$ is the transition time for data transmission, TCP ACK reception, and L2 ACK transmission, and $\beta$ (the transient number for data transmission, TCP ACK reception, and L2 ACK transmission) is 3 in our system model assumption, as shown in Fig.6.

The total sleep mode time of the IoT device in a cycle can be obtained by subtracting the Tx mode time, the Rx mode time, and total transient mode time from a cycle. The total sleep mode time of the IoT device in a cycle, $T_{sleep}$, is given by,

$$ T_{sleep}^A = T_{period} - T_{tx} - T_{rx}^A - T_{trans} $$

$$ T_{sleep}^{eA} = T_{period} - T_{tx} - T_{rx}^{eA} - T_{trans} $$

(17)

where $T_{sleep}^A$ is the total sleep mode time of an IoT device that uses the legacy AP, and $T_{sleep}^{eA}$ is the total sleep mode time of an IoT device that uses the proposed eAP.

Using the above equations, the energy consumption of the IoT device during a cycle in the legacy AP system with the
DTIM scheme, $E_{cycle}^{AP,D}$, which is given by,

$$
E_{cycle}^{AP,D} = P_{tx}^{static} \cdot T_{tx} + P_{rx} \cdot T_{TAP}^{rx} + P_{sleep} \cdot T_{TAP}^{sleep} + P_{trans} \cdot T_{trans}
$$

$$
+ P_{rx} \left( \frac{I_{period}}{n_{dim} \cdot I_{beacon}} \cdot t_{beacon} + t_{IoT+server} \right)
$$

$$
+ P_{sleep} \left( I_{period} - T_{tx} - T_{TAP}^{rx} - T_{trans} \right) + P_{trans} \left[ 2 \left( \frac{I_{period}}{n_{dim} \cdot I_{beacon}} - 1 \right) + a \right] \cdot t_{trans},
$$

(18a)

where $P_{tx}^{static}$ is the static transmitting power of the IoT device, which has a fixed value, $P_{rx}$ is the operational power of the Rx mode, $P_{sleep}$ is the operational power of the sleep mode, and $P_{trans}$ is the operational power of the transition mode.

The energy consumption of the IoT device during a cycle in the legacy AP system with the TWT scheme, $E_{cycle}^{AP,T}$, which is given by,

$$
E_{cycle}^{AP,T} = P_{tx}^{static} \cdot T_{tx} + P_{rx} \cdot T_{TAP}^{rx} + P_{sleep} \cdot T_{TAP}^{sleep} + P_{trans} \cdot T_{trans}
$$

$$
= P_{tx}^{static} \left[ \frac{(1 + p_{c})N_{data}}{Blog2(1 + \gamma)} + \frac{N_{L2ack}}{Blog2(1 + \gamma)} \right]
$$

$$
+ P_{rx} \left( \frac{I_{period}}{n_{dim} \cdot I_{beacon}} \cdot t_{beacon} + t_{IoT+server} \right)
$$

$$
+ P_{sleep} \left( I_{period} - T_{tx} - T_{TAP}^{rx} - T_{trans} \right) + P_{trans} \left[ (2 + \beta) \cdot t_{trans} \right],
$$

(18b)

We can also obtain the energy consumption of the IoT device during a cycle with the proposed eAP system with the DTIM scheme, $E_{cycle}^{AP,D}$, which is given by,

$$
E_{cycle}^{AP,D} = P_{tx}^{adaptive} \cdot T_{tx} + P_{rx} \cdot T_{TAP}^{rx} + P_{sleep} \cdot T_{TAP}^{sleep} + P_{trans} \cdot T_{trans}
$$

$$
= P_{tx}^{adaptive} \left[ \frac{(1 + p_{c})N_{data}}{Blog2(1 + \gamma)} + \frac{N_{L2ack}}{Blog2(1 + \gamma)} \right]
$$

$$
+ P_{rx} \left( \frac{I_{period}}{n_{dim} \cdot I_{beacon}} \cdot t_{beacon} + t_{IoT+eAP} \right)
$$

$$
+ P_{sleep} \left( I_{period} - T_{tx} - T_{TAP}^{rx} - T_{trans} \right) + P_{trans} \left[ (2 + \beta) \cdot t_{trans} \right],
$$

(19a)

where $P_{tx}^{adaptive}$ is the adaptive transmitting power of the IoT device which has a flexible value controlled by the target SINR $\gamma^*$. The energy consumption of the IoT device during a cycle with the proposed eAP system with the TWT scheme, $E_{cycle}^{AP,T}$, which is given by,

$$
E_{cycle}^{AP,T} = P_{tx}^{adaptive} \cdot T_{tx} + P_{rx} \cdot T_{TAP}^{rx} + P_{sleep} \cdot T_{TAP}^{sleep} + P_{trans} \cdot T_{trans}
$$

$$
= \frac{P_{tx}^{adaptive} + P_{N}}{L} \left[ \frac{(1 + p_{c})N_{data}}{Blog2(1 + \gamma)} + \frac{N_{L2ack}}{Blog2(1 + \gamma)} \right]
$$

$$
+ P_{rx} \left( \frac{I_{period}}{n_{dim} \cdot I_{beacon}} \cdot t_{beacon} + t_{IoT+eAP} \right)
$$

$$
+ P_{sleep} \left( I_{period} - T_{tx} - T_{TAP}^{rx} - T_{trans} \right) + P_{trans} \left[ (2 + \beta) \cdot t_{trans} \right].
$$

(19b)

Using the above equations, the energy consumption of the IoT device during 1 second in the legacy AP system, $E_{IoT}^{AP}$, and the energy consumption of the IoT device during 1 second in the proposed AP system, $E_{IoT}^{eAP}$, are given by,

$$
E_{IoT}^{AP} = \begin{cases} 
E_{cycle}^{AP,T} & \text{(DTIM)} \\
E_{cycle}^{AP,D} & \text{(TWT)}
\end{cases}
$$

(20)

C. ENERGY-SAVING GAIN BY eAP

The energy-saving gain ($G$) using the proposed eAP system model can be defined as,

$$
G \triangleq \frac{E_{IoT}^{eAP} - E_{IoT}^{AP}}{E_{IoT}^{eAP}},
$$

(21)

where $E_{IoT}^{eAP}$ is the energy consumption of the IoT device using the legacy AP system model, and $E_{IoT}^{eAP}$ is the energy consumption of the IoT device using the proposed eAP system model. The energy-saving gain, $G$, using the proposed eAP consists of two components, $G_1$, and $G_2$. Firstly, $G_1$ is obtained energy-saving gain mainly from the prompt TCP ACK transmit function in the proposed eAP system model, and this $G_1$ is defined as below based on equation (20),

$$
G_1 \triangleq \frac{E_{IoT}^{eAP} - E_{IoT}^{AP}}{E_{IoT}^{eAP}},
$$

(22)

where $G_1$ is obtained by decreasing the Rx mode time and increasing the sleep mode time of the IoT device using the prompt TCP ACK transmit function in the eAP system model.

Secondly, $G_2$ is obtained by transferring the retransmission burden of the TCP timer timeout to the eAP using the caching IoT data retransmit function in the eAP system model. Thus, an IoT device using the eAP system has no retransmission burden due to the TCP timer timeout, and only has a retransmission burden for wireless link failures between the IoT device and the eAP. When the TCP timer timeout occurs, the eAP retransmits the cached IoT measured data to the TCP server without requesting retransmission to the IoT device. $G_2$ is obtained by the caching IoT data retransmit...
function in the eAP, and this $G_2$ is defined as below based on equation (20),

$$G_2 = \frac{(1 + p_{timeout}) E_{IoT}^{eAP} - E_{IoT}^{eAP}}{(1 + p_{timeout}) E_{IoT}^{eAP}},$$  

(23)

where $p_{timeout}$ is the probability of TCP timer timeout caused by network congestion or missing data. The probability of TCP timer timeout is affected by the number of TCP connections, buffer capacity, TCP timer timeout value, packet loss probability, etc. In general, when the number of TCP connections is 100, the probability of the TCP timer timeout occurring is almost 2% to 5% empirically. Using equations (22) and (23), the total energy-saving gain by the proposed eAP system, $G_{total}$, is given by,

$$G_{total} = G_1 \cup G_2 \cong G_{1/2}$$

$$= \frac{(1 + p_{timeout}) E_{IoT}^{eAP} - E_{IoT}^{eAP}}{(1 + p_{timeout}) E_{IoT}^{eAP}}$$

$$= \frac{E_{IoT}^{eAP} - \frac{1}{(1 + p_{timeout})} \cdot E_{IoT}^{eAP}}{E_{IoT}^{eAP}},$$  

(24)

where $G_{1/2}$ is the combined gain obtained from the prompt TCP ACK transmit function and the caching-and-retransmit function in the eAP system model. $G_1$ and $G_2$ are not mutually exclusive because they have an intersection between $G_1$ and $G_2$. Therefore, we should consider the combined gain with $G_1$ and $G_2$ based on equation (21) by considering the TCP timer timeout probability for the calculation of $G_{total}$.

We do not consider the gain from the multiple IoT data aggregate function in the eAP. Because they are related to the energy-saving of eAPs, not the energy-saving of IoT devices. In addition, the gain from the optimal operating parameters of IoT devices according to the patient’s level by the eAP is considered by the value, $E_{IoT}^{eAP}$ in equation (22), which is the energy consumption of the IoT device using the eAP. Therefore, the total energy-saving gain for the patient’s level depends on the value of the operating parameters of IoT devices.

V. PERFORMANCE EVALUATION

A. PARAMETERS FOR ANALYSIS AND SIMULATION

In this section, we present a performance evaluation of the proposed eAP system model compared with the legacy AP system model. We develop a WLAN simulator using Python for the proposed eAP system and the legacy AP system. Specifically, we consider a wireless health monitoring IoT service for patients in a hospital as a case study.

We assume that 10 IoT devices communicate on an AP, and each IoT device generates 64 bytes of data every second at a constant bit rate (CBR), and that the IoT device has no mobility. The AP coverage radius is 20 m and the location of the IoT device is random. The generated traffic is buffered and forwarded to a TCP payload of up to 1460 bytes with a 40-byte TCP/IP header, a 30-byte IEEE 802.11 MAC header, and a 6-byte PHY header in an IoT packet. The IoT packets are transmitted to the AP in a 2.4 GHz channel band of the IEEE 802.11ax network with static or adaptive transmitting power. It is also assumed that the measured power of noise and interference is $-90$ dBm in the AP [31]. As a channel fading model, we use a "Rician fading model", which has both non-line-of-sight (NLOS) and line of sight (LOS) paths, commonly used in indoor environments [35]. The transmission period of IoT packets ranged from 0.9 seconds to 60 seconds, and 0.9 seconds indicates a multiple of the DTIM of 300 ms, which is a default value of DTIM [36], as shown in Fig. 4 and Fig. 5. The DTIM value ranged from 1 to 10, and the target SINR ranged from 30 dBm to 40 dBm, which are commonly used in the empirical fields of IEEE 802.11 networks [37]. We also added simulation results for the energy consumption of IoT devices using the TWT scheme as an optional case. The contention window size ranged from 16 (slot times) to 256 (slot times), and the default value was 64 (slot times). The contention window size doubles when a collision of transmission data occurs. The number of IoT devices on an AP ranged from 1 to 30, and we assumed the default value was 10 on an AP. It was also assumed that there were a total of 100 APs in a hospital building. We also assumed the TCP ACK frame generation time in the eAP is less than 10 $\mu$s. We considered saturated network scenarios in our system model by considering background traffic such as Wi-Fi traffic from smartphones, laptops, tablets, and etc.

It was assumed that a patient level 1 (mild) sensor has 60 seconds of transmission period for IoT packets, 10 for the

| Parameters | Value |
|------------|-------|
| Contention window size | 64 (slot time) |
| Number of the IoT device on a AP | 10 IoT devices |
| Number of APs | 100 APs |
| AP coverage radius | 20 m |
| SINR on AP | 40 dB |
| Target SINR | 30 dB |
| Total loss factor | 76.53 dB |
| Link fail | 10% |
| Network response time | 30 ms |
| Bandwidth | 160 kHz |
| Sensed data size for each measurement | 64 bytes |
| Measurement interval | 1 s |
| Beacon interval | 100 ms |
| Transition time | 0.1 ms |
| Processing time | Each 1 ms |
| Slot time | 0.009 ms |
| Transmit mode power of the IoT device Static: | 450 mW, Adaptive: 45 mW |
| Receive mode power of the IoT device | 150 mW |
| Sleep mode power of the IoT device | 0.12 mW |
| Transition mode power of the IoT device | 3 mW |
| Power supply of the IoT device | 3 V, 120 mAh |
| Patient level 1 (mild) IoT device | (battery-powered) |
| The Tx period: | 60 s |
| The DTIM value: | 10 |
| Target SINR value: | 30 dB |
| Patient level 2 (severe) IoT device | The Tx period: 10 s, The DTIM value: 5, Target SINR value: 32 dB |
| Patient level 3 (critical) IoT device | The Tx period: 0.9 s, The DTIM value: 3, Target SINR value: 34 dB |
DTIM value, and 30 dB for the target SINR. Also, the patient level 2 (severe) sensor was assumed to have 10 seconds of transmission period for IoT packets, 5 for the DTIM value, and 32 dB for the target SINR. Finally, the patient level 3 (critical) sensor was assumed to have 0.9 seconds of transmission period for IoT packets, 3 for the DTIM value, and 34 dB for the target SINR, respectively.

The simulation results were averaged over 100 iterations. Table 1 lists the detailed parameters based on [23], [31], [38].

B. ENERGY CONSUMPTION OF THE IoT DEVICE

The IoT device accumulates the measured data in the buffer and transmits it to the AP in a variable data sized IoT packet. Due to the high data transmission rate of the Wi-Fi network, the transmission time of IoT packets is very short, and the energy consumed by the IoT device is also insignificant when transmitting IoT packets. On the other hand, when the number of transmissions increases, the energy consumption of the IoT device increases because of the increasing listening times for receptions of the TCP ACK.

Fig. 7 presents the energy consumption of the IoT device using different two AP system models with three different DTIM values according to the changes in the transmission period of the IoT packets. In both system models, the energy consumption of the IoT device decreases as the transmission period value increases. As the transmission period increases, the data size of the IoT packets transmitted at once increases, and the number of transmissions decreases within a certain period (which means that transmission occurs sparsely), so the energy consumption of the IoT device also decreases. Furthermore, when the transmission period increases, TCP ACK reception also occurs sparsely, so the effect on the energy consumption of the IoT device by using the eAP decreases, because there are relatively fewer opportunities.

Fig. 8 presents the energy consumption ratio of the IoT device using the eAP compared to the case of the IoT device using the legacy AP, according to the changes in the transmission period of IoT packets. Fig. 8 shows that the energy consumption ratio of the IoT device using the eAP increases sharply when the transmission period increases. For example, for the eAP with a DTIM value of 3, the energy consumption ratio is 8.9% (the best case), 81.8% (the worst case) when the transmission period is 0.9 seconds, and 60 seconds, respectively. That means the proposed eAP system model has a better energy-saving effect when IoT device uses a shorter transmission period.

Fig. 9 presents the energy consumption of the IoT device using different two AP system models with three different transmission period values, in terms of changes in DTIM value. In both system models, the energy consumption of the IoT device decreases as the DTIM value increases. As the DTIM value increases, the number of awakenings for beacon reception in the Rx mode of the IoT device decreases, and thus the energy consumption of the IoT device also decreases. On the other hand, as the DTIM value increases, the effect on the energy consumption of the IoT device using the eAP increases. When the DTIM value increases, the energy consumption portion for transmitting the IoT packet, receiving the TCP ACK reception, and sleep in the IoT device is more significant than the energy consumption portion for beacon reception, so the effectiveness of the eAP usage is relatively increased.

Fig. 10 presents the energy consumption ratio of the IoT device using the eAP compared to the IoT device using the legacy AP in terms of changes in DTIM value. Fig. 10 shows that the energy consumption ratio of the IoT device using the eAP decreases gradually as the DTIM value increases. For example, in the case of eAP with a transmission period of 0.9 seconds, the energy consumption ratio was 16.05% (the worst case), 6.09% (the best case) when the DTIM value was 1 and 10, respectively.

On the other hand, Fig. 8 and Fig. 10 show that the eAP system model was more affected by the changes in transmission period than DTIM values for the energy efficiency of the IoT device. Therefore, to optimize the energy consumption
of the IoT device, it is more important to find the optimal transmission period value than the optimal DTIM value.

Fig. 11 presents the energy consumption of the IoT device using different AP system models with static transmitting power and adaptive transmitting power according to the target SINR values. With static transmitting power, the IoT device transmits a fixed Tx power of a predetermined signal strength regardless of noise and interference channel conditions. Therefore, as shown in Fig. 11, the static transmitting powered IoT device using the legacy AP has a constant energy consumption value of about $6.4 \times 10^{-3}$ joules regardless of the change in value of the target SINR. On the other hand, for the IoT device with adaptive transmitting, power depends on the current channel SINR condition and the patient’s level, and the energy consumption increases as the target SINR value increases.

Fig. 12 shows the energy consumption ratio of the IoT device with the $e$AP compared to the static transmitting powered IoT device with the legacy AP, according to the target SINR value. In Fig. 12, the energy consumption ratio of the adaptive transmitting powered IoT device with the $e$AP increases gradually as the target SINR increases. For example, for the adaptive transmitting powered IoT device using $e$AP with a transmission period of 0.9 s and a DTIM value of 3, the energy consumption ratio is $11.79\%$ (the best case) $\sim 23.4\%$ (the worst case), and the energy consumption ratio is $73.48\%$ (the best case) $\sim 74.7\%$ (the worst case) when the transmission period is 60 seconds and the DTIM value is 10.

Fig. 13 presents the collision probability of transmission data according to the number of IoT devices on an AP and the contention window size. It shows that as the number of IoT devices communicating with the AP increases, and the contention window size decreases, the collision probability increases. As the collision probability increases, the probability of IoT data retransmission increases, so the energy
consumption of the IoT device also increases, but the amount is very insignificant.

In addition, the energy consumption ratio of the IoT device with the eAP system model is not significantly affected because the portion of energy consumed by retransmission is tiny, as shown in Fig. 14. It is almost 10% compared to the legacy AP system model when the transmission period is 0.9 s, and the DTIM value is 3.

C. ENERGY-SAVING GAIN AND EXPECTED LIFETIME

In the introduction section, we presented a service scenario in which the energy consumption of the IoT device varies according to the patient’s level by controlling operating parameters, such as the transmission period of the IoT packets, the DTIM value, and the transmitting power. We considered three patient levels based on the patient’s conditions; the operating parameters of the IoT sensor according to each patient’s level are shown in Table 1. We assumed that mild patients could accept delays resulting from infrequent transmission, and lower transmission power than critical patients.

Fig. 15 presents the energy consumption of the IoT device based on the patient’s level. It shows that the IoT device consumed more energy with higher patient levels because of the more frequent transmission and higher Tx power. The IoT device using the eAP system consumed only 1/3 to 1/9 the energy of the IoT device using the legacy AP system. In particular, the energy consumed by the IoT device using the proposed eAP system was reduced to 36.92%, 30.89%, and 11.90% compared to the IoT device using the legacy AP system for patient level 1, patient level 2, and patient level 3, respectively, as shown in Fig. 15 and Fig. 16b.

Assuming that 1,000 IoT devices are needed for IoT services in a hospital and the ratio of the number of patients for each level is 7:2:1, the total energy consumption of IoT devices using the eAP system is only 0.3108 joules. This is less than a quarter of the total energy consumed by the legacy AP system model, which required 1.3142 joules.

Fig. 16 presents the portion of energy consumed by the IoT device using the legacy AP system and the proposed eAP system model according to the patient’s level. In the legacy AP system, the portion of energy consumed for the TCP ACK reception is very large, that is almost 12% ∼ 80% according to the patient’s level in Fig. 16a. On the other hand, the portion of energy consumed for TCP ACK reception by the IoT device using the eAP was dramatically reduced to 1% ∼ 22% compared to the IoT device using the legacy AP system according to the patient’s level in Fig. 16b. In addition, we can see that the portion of energy consumed for the sleep mode by the IoT device using the eAP was increased compared to the IoT device using the legacy AP system, because the sleep opportunity increased due to the reduced reception time for the TCP ACK in Fig. 16b.

The energy-saving gain of the IoT device that uses the eAP system model is defined in equation (24). The higher the patient’s level, the greater the energy consumed by the
IoT device due to frequent data transmissions, and the greater the energy-saving gain by the eAP system model. The total energy-saving gain, $G_{total}$, of the IoT device according to patient’s levels is given in Table 2. $G_{total}$ is 63.81%, 69.71%, and 88.34% for patient level 1, patient level 2, and patient level 3, respectively.

Fig. 17 presents the expected lifetime of the IoT device according to the patient’s level. Assuming that the IoT device is powered by 3 V and 120 mAh batteries, the expected lifetime of the IoT device with the legacy AP system model is 566 hours, 317 hours, and 56 hours for patient level 1, patient level 2, and patient level 3, respectively. On the other hand, the expected lifetime of the IoT device with the proposed eAP system model is 1533 hours, 1028 hours, and 471 hours for patient level 1, patient level 2, and patient level 3, respectively. That means the eAP system model achieves a 2.7 times, 3.2 times, and 8.4 times improvement in the expected IoT device lifetime compared to the legacy AP system model for patient level 1, 2, and 3, respectively.

### TABLE 2. Energy-saving gain of the IoT device according to patient’s level

| Patient level | $E_{AP}$ [Joules] | $E_{eAP}$ [Joules] | $G_1$ [%] | $G_2$ [%] | $G_{total}$ [%] |
|---------------|-----------------|-----------------|--------|---------|-------------|
| Mild (1)      | $0.636 \times 10^{-3}$ | $0.235 \times 10^{-3}$ | 63.08% | 1.90% | 63.81% |
| Severe (2)    | $1.133 \times 10^{-3}$ | $0.350 \times 10^{-3}$ | 69.11% | 1.90% | 69.71% |
| Critical (3)  | $6.424 \times 10^{-3}$ | $0.764 \times 10^{-3}$ | 88.10% | 1.90% | 88.34% |

### D. ROUND-TRIP DELAY

Round-trip delay (RTD) is the elapsed time between when the IoT device transmits a data packet and receives its ACK. This time delay includes processing delay, transmission delay, and propagation delay between the two communicating endpoints. The transmission delay is a serialization delay...
FIGURE 18. Round-trip delay of the IoT packets according to the number of IoT devices on an AP

FIGURE 19. Round-trip delay of the IoT packets according to the number of IoT devices using the legacy AP

FIGURE 20. Round-trip delay of the IoT packets according to the number of IoT devices using the energy-conscious AP

FIGURE 21. Energy consumption of the IoT device according to the transmission period (including the TWT scheme)

The probability of retransmission increases. As a result, the average RTD value increases slightly.

E. EVALUATION WITH THE TWT SCHEME

As a further evaluation, we simulated the energy consumption of the IoT device using the TWT scheme instead of the DTIM scheme. The TWT scheme is less appropriate for the health monitoring service because it has shortcomings of lack of timeliness and long downlink delays. Nevertheless, the TWT scheme can reduce further the energy consumption of the IoT device compared to the DTIM scheme, because it reduces the consumed energy for beacon receptions.

Fig. 21 shows the energy consumption of the IoT device using different two AP system models with three different DTIM values and with the TWT scheme according to the changes in the transmission period of the IoT packets. The energy consumption of the IoT device with the TWT scheme shows slightly better performance compared to the DTIM
scheme, as the IoT device with the TWT scheme consumes little energy to receive triggers sparsely.

Fig. 22 shows the energy consumption of the IoT device based on the patient’s level. In Fig. 22, the energy consumption of the IoT device with the TWT scheme shows slightly better performance compared to the IoT device without the TWT scheme. This is because the IoT device with TWT scheme can save energy consumption for receiving numerous beacons. However, as mentioned earlier, the TWT scheme is less appropriate for the health monitoring service, because of the disadvantages of lack of timeliness and long downlink delays.

Fig. 23 presents the expected lifetime of the IoT device according to the patient’s level. Assuming that the IoT device is powered by 3 V and 120 mAh batteries, the expected lifetime of the IoT device with the legacy AP system model with the TWT scheme is 642 hours, 1819 hours, and 705 hours, for patient level 1, patient level 2, and patient level 3, respectively. That means the eAP system model with the TWT scheme achieves 3.5 times, 4.9 times, and 12 times improvement in the expected IoT device lifetime compared to the legacy AP system model with the TWT scheme for patient level 1, 2, and 3, respectively. Although there is a meaningful improvement compared to the absence of the TWT scheme, as mentioned earlier, the TWT scheme is less appropriate for the health monitoring service, due to the shortcomings of timeliness and downlink delay which are the essential factors to provide reliable IoT health care services. However, the eAP system with the TWT scheme can be an excellent low-energy-consumption solution for providing latency-insensitive services such as thermostat services.

VI. CONCLUSION

This work proposed a novel energy-conscious AP (eAP) system model with cross-layer design to improve the energy efficiency of IoT devices in Wi-Fi networks. The proposed eAP system model significantly reduces the energy consumed by the IoT device by reducing TCP ACK reception time. To achieve this, three newly defined functions and the device energy management module were developed with a local cache in the eAP of the IoT device. The device energy management module optimally controls operating parameters of IoT devices, such as the transmission period of IoT packets, the DTIM value, and the transmitting power of the IoT device, according to the patient’s level in real-time health monitoring IoT service scenario. Also, the optimal transmit power of the IoT device, the energy consumption of the IoT device, and the energy-saving gain with the eAP were analyzed for increasing the energy efficiency of IoT devices using a numerical method. Through extensive simulations, we found that the proposed eAP system model achieved a maximum of approximately 88% improvement in IoT device energy efficiency, and increased the expected lifetime of the IoT device by almost 8.4 times compared to the legacy AP system model. In addition, the average round-trip delay of IoT data packets was also improved by almost 90% in the eAP system model.

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