Bluetooth Low Energy (BLE) Beacon Single and Multi-Channel Scanning Delay Evaluation for Improved Home Automation User Experiences

Mohamed Ragab Mahmoud Farghaly, Yewguan Soo, Kim Chuan Lim, Feng Duan

Abstract*: The demand of improving home automation system to control the home appliance in conveniently and efficiently leads to be more concerned about what the user daily activities the way they want to control their home appliances. Since the BLE has the ability to advertise data without the need to be connected to a master (known as BLE beacon). Measuring the best response for best user experience for ESP32 beacon scanner to be used for light control is studied by make the advertisement happen at single and multi-channel and using an ESP32 as scanner with different scanning paraments (ESP32-80 and ESP32-20). The result showed that not only the number of packets on ESP32-80 and ESP32-20 increase, but also it achieve a time response that less than 100ms with 59.47% and 49.93% of received packets for ESP32-80 and ESP32-20 respectively. Advertising on single channel will not only reduce the response time (21% and 14.73% of first packet received on ESP32-80 and ESP32-20 respectively at time that less than 100ms) but also reduce the number of packets received on the ESP32-80 and ESP32-20. It is also shows the ability of using ESP32 as a beacon scanner for home automation system.

***Keywords* : home automation, BLE, beacon, user experiences.**

I. INTRODUCTION

Home Automation system has been growing popular because of the benefits, price reduction and the technology improvement [1]–[3]. BLE is one of the commonly used wireless communication interface in our daily life as it can be found in most devices such as smartphones, smart watches and etc. BLE is designed for low-power and low bandwidth applications including home automation system control.

Before any communication happen between two BLE devices, the BLE scanner (master) need to scan for BLE advertiser (slave) before any connection is established. BLE slave supports two type of modes for data exchange, normal connection mode and non-connection mode (also called BLE beacon). The former is used for data exchange between the master and slave, while the latter one is used for indication and localization system [6]–[10]. Both the connection mode and non-connection mode advertise the packet on three channels (Fig. 1) in sequence. However, BLE advertiser also has the ability to advertise this packet on single channel only. But for connection mode after the slave is successfully connected, the data exchange occurs at different sequences of channels agreed on it by both.

The advertisement of non-connection mode cannot happen fast (not less than 100ms between each advisement) [11]. Advertising for a long time will drain the battery from devices that powered up by a battery. Due to that, the best time response for best user experience for home automation system using BLE technology is an important trade off.

In this paper, the feasibility of using ESP32 that has Wi-Fi and Bluetooth Low energy (BLE) 4.2 technologies embedded on it [4], [5] is studied. The ESP32 is used as a beacon scanner for home automation system. The effect of advertising the BLE beacon packet on multi-channel and single channel will be studied in term of number of packets received successfully and the time it takes to receive the first packet to investigate the response time.

The paper is structured as follows, In Section II, a brief background about BLE and how BLE operate. Section III cover the method used to investigate the difference between multi and single channel advertisement. In Section IV the results are presented and discussed. Finally, Section V concludes the finding and future work.

II. BACKGROUND

Bluetooth had been around since 1989 and has been used in short range communication for example connecting headphone to the phone, sharing files and streaming data with other devices. But it wasn't meant for those battery powered devices that sending a periodic data. BLE was introduced in 2010 [12], [13] to expand the use of Bluetooth. It is the solution for applications that require low-power consumption and small periodic data.

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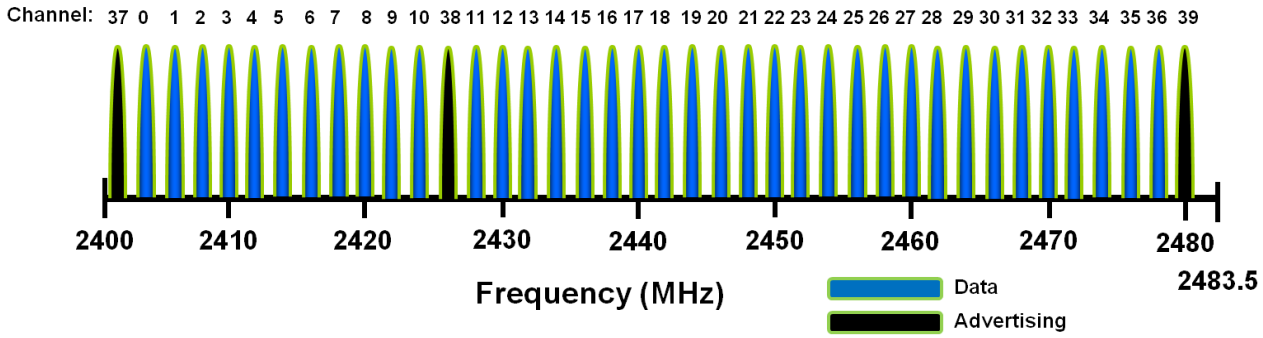

Fig. 1. BLE frequency spectrum.

The difference between BLE and classic Bluetooth is that when there is no data to be transmitted, the BLE will go to sleep. BLE operates almost the same as normal Bluetooth in data exchange and connection modes.

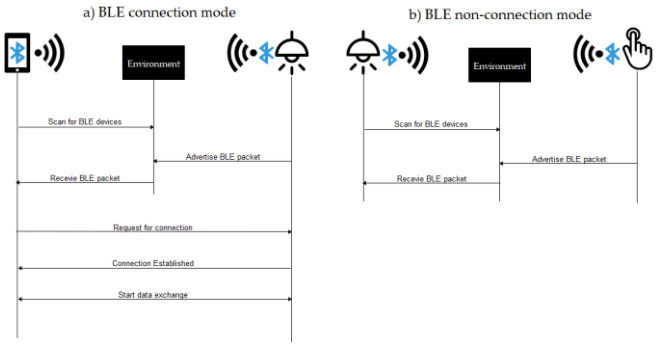

Fig. 2. overview of (a) BLE connection mode and (b) BLE non-connection mode.

For example, as shown in Fig. 2(a), when the phone wants to control the light, first the phone needs to scan for any Bluetooth devices nearby while the light is advertising. Once the phone finds the light, it will request for a connection and the light will accept the connection. Then, the control data (on, off or dim) is can be transmitted to the light. The drawback of this method is the phone can only be connected up to 7 devices at the same time. In 2010, Apple introduces a new way to use BLE without the need to connect two devices together [10] known as iBeacon. This will allow the master to receive data from unlimited number of slaves at the same time as illustrated in Fig. 2(b) where the light is triggered when the button is pressed.

Fig. 3 shows the iBeacon packet format; the master will scan for specific device with special ID called Universally Unique Identifier (UUID) that has the size of 128-bit (16 Bytes) of the 248-bit (31 Bytes) of the BLE advertisement packet. Also, in the BLE advertisement packet another 32-bit (8 bytes) for major and minor values (each one is 16-bit or 4 byte) that can differentiate between each device or send specific small data [18]. BLE Beacon can be used in different application that doesn't require any connection to the master which is suitable for applications that require to send a small data (≤24 bytes) that would also help in reducing the power consumption of the devices that powered up by batteries [19].

Fig. 4 shows an overview an example how the light is controlled with BLE beacon. BLE advertisement and scanning occur at 3 channels [20], [21]. As shown in Fig. 4(a), in advertising mode, there is an advertising interval (T_{AI}) that need to be set (for BLE beacon not less than 100ms [11]) followed by some delay (δ) (0-10ms) generated randomly and when the advertising event start, the packet is sent on the three channels in order with delay of (T_{WA}) that has to be equal or less than 10ms.

In scanning mode Fig. 4(b), the define scan window (T_{SW}) is the window where the scanner will scan (the radio is turned on) a specific channel at this time, the defined scan interval (T_{SI}) is when the scan completed and switch to another channel on the next scan window (the radio is off).

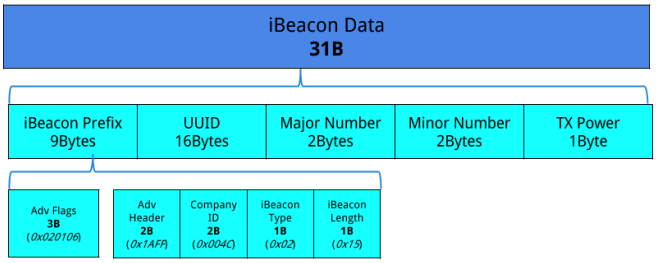

Fig. 3. overview of iBeacon packet

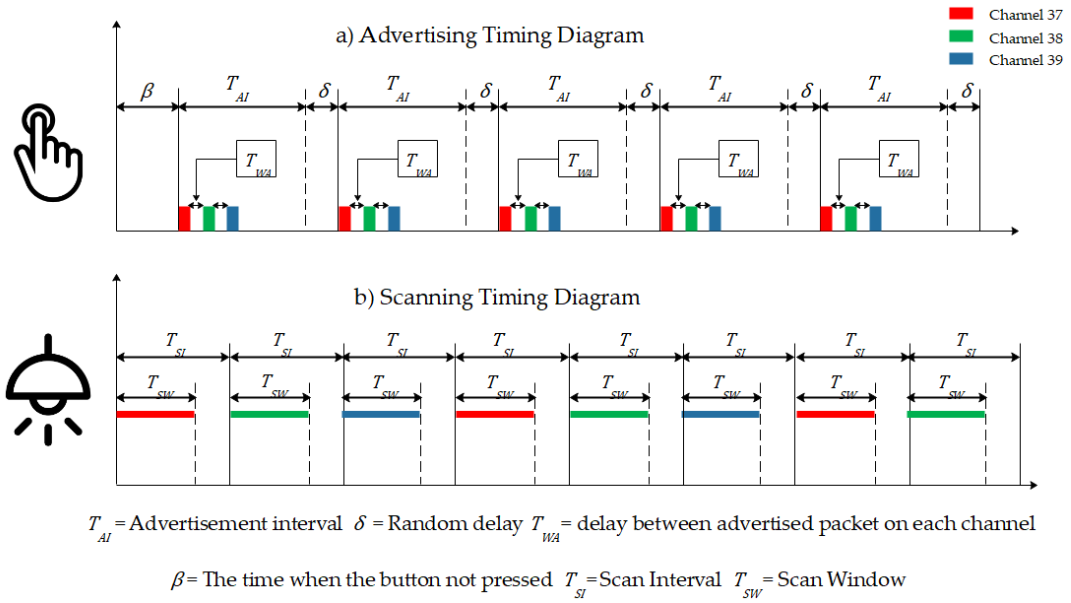

Fig. 4. BLE beacon advertising and scanning timing diagram.

III. METHODOLOGY

Four NRF51 dongles were used as sniffers. Three sniffers sniff at a particular channel and the last sniffer sniff across all channels (refer to Table-I). Two ESP32 were used as a scanner with two different settings (refer to Table-II). For the first setting, the scan window is set to 45ms and the scan interval is set to 80ms (ESP32-80). For the second setting, the scan window is set to 10ms and the scan interval is set to 20ms (ESP32-20). Fig. 5 shows an overview and timing diagram for each sniffer and scanner.

Table-I Setting for each sniffer

Sniffer	Sniffer C-37	Sniffer C-38	Sniffer C-39	Sniffer C-all
Channel	37	38	39	37-38-39

Table-II setting for each ESP32

Scanner	ESP32-80	ESP32-20
Scan Window	45	10
Scan Interval	80	20

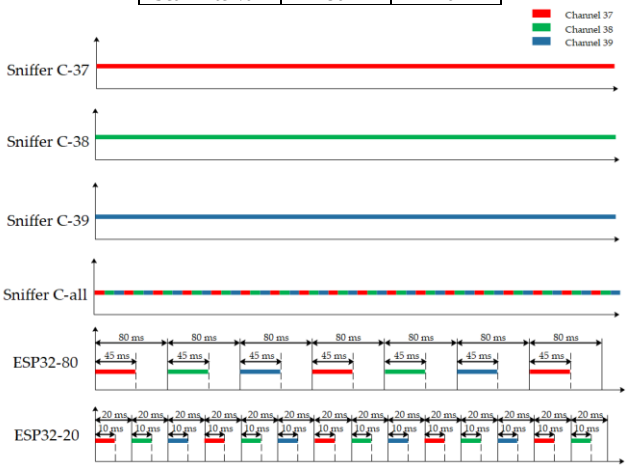

Fig. 5. timing diagram for each sniffer and scanner

A. Advertise on single and multi-channel investigation

The first investigation is to advertise the iBeacon using single channel only, the aim for this investigation is to see which sniffer would pick up most of the advertisement packets and how many packets can be received by the ESP32. Since the ESP32 is acting as a scanner that will scan the three channels, theoretically only 2 sniffers (the sniffer that sniff all channels and the sniffer that listen to that channel) and ESP32 should pick up the BLE packets. The other two sniffers that listen to different channels won`t pick it up.

Then the NRF51 is set to advertise the beacon using all channels, here we study how many packets will be received by each sniffer and ESP32, since the advertisement happen in all channels, the 4 sniffers and ESP32 should pick up advertisement packets. This investigation is repeated 10 times.

B. Investigate the time taken for the ESP32 to Receive the 1st packet

The second investigation is on how long does it take for the ESP32 to pick up the first packet? (only ESP32 used to for this investigation). To conduct this investigation, a push button mechanism is imitated by connecting pin17 from NRF51 to pin25 ESP32-80 and ESP32-20 and a signal is sent from the NRF51 to ESP32-80 and ESP32-20 before the advertisement start. By assuming that when the button is pressed, the time of the button pressed (the time of the signal) (T_b) is recorded in the ESP32 and the NRF51 start advertising the packet. The time of the received packet (T_p) is recorded, the time ESP32 takes to receive the first packet is calculated as following $T_r = T_p - T_b$.

This investigation is conducted for single and multi-channel advertisement to see whether the number of packets advertised will affect the arrival time of the first advertise packet. Since ESP32-80 and ESP32-20 scan on three channels, then advertising on the three channels should give better response (the time of the first packet arrived when advertise on multichannel is smaller than when advertise on a single channel). This investigation was conducted for one day, and the advertisement occurs every minute.

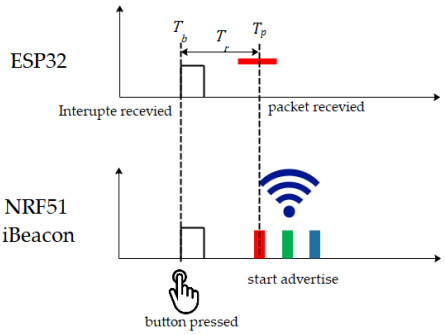

Fig. 6. timing diagram for push button connection imitation and interrupted between nrf51 and ESP32

IV. RESULTS AND DISCUSSION

A. Advertise on single and multi-channel investigation

When the BLE beacon advertises on a single channel, only the sniffer that listen to that channel can capture the packets which can be seen in Fig. 7 and Fig. 9. Sniffer C-37 and Sniffer C-39 managed to pick up all the 10 packets from all the 10 trials. Figure 8 shows that Sniffer C-38 managed to pick up most of the packets which indicate that channel 38 has interference that reduces the number of packets received. Sniffer C-all manages to pick up a small number of packets across the 10 runs, referring to Table-III the mean packets across the 10 runs when advertising on a single channel for Sniffer C-all is relatively low compared to ESP32-80 and ESP32-20 who are relatively high. Also, it is noticed that ESP32-80 is relatively higher than ESP32-20 which indicate that scanning for single channel advertisement with small scan windows and scan interval would affect the number of packets received.

Table-III Mean and stander deviation of number of packets across the 10 runs

Advertise at	Channel 37		Channel 38		Channel 39		All channels	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Sniffer C-37	10.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00
Sniffer C-38	0.00	0.00	9.30	2.21	0.00	0.00	9.30	1.06
Sniffer C-39	0.00	0.00	0.00	0.00	10.00	0.00	9.90	0.32
Sniffer C-all	0.40	0.70	0.50	0.53	1.00	1.25	27.00	1.63
ESP32-80	2.00	0.67	1.90	0.57	1.70	0.67	5.80	1.32
ESP32-20	1.40	0.52	1.90	0.99	1.30	0.95	5.30	1.89

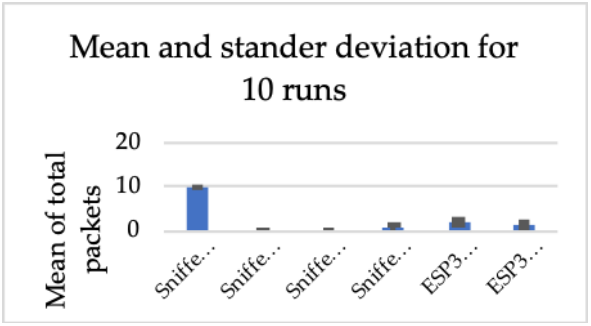

Fig. 7. Mean and Standard deviation for Advertising at Channel 37

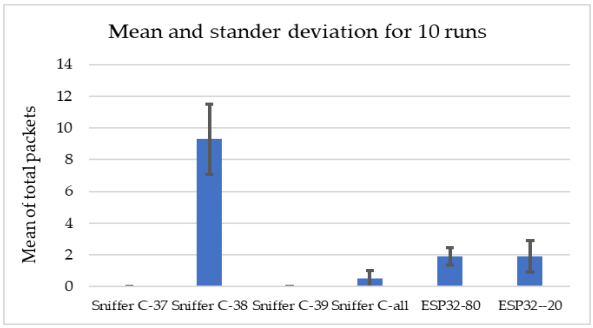

Fig. 8. Mean and Standard deviation for Advertising at Channel 38

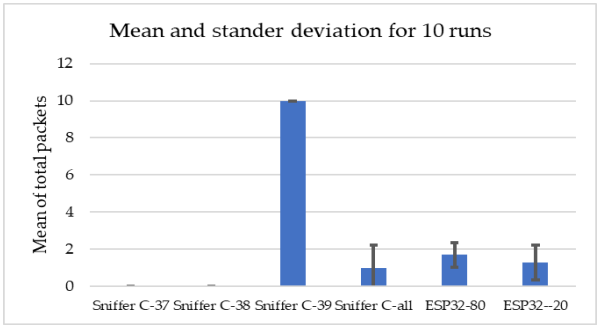

Fig. 9. Mean and Standard deviation for Advertising at Channel 39

Figure 10 shows that when advertising the beacon on multi-channel, the mean packet across the 10 runs for Sniffer C-all is relevantly the highest compared to the other sniffers and the scanners. The other sniffers do not show a constant result. Table-III shows that Sniffer C-38 and Sniffer C-39 are relatively lower than Sniffer C-37 which indicates Sniffer C-38 and Sniffer C-39 suffered from interference during the scanning. Also, Table-III shows that ESP32-80 still relatively higher than ESP32-20 which also prove that scanning too fast will affect the number of packets received.

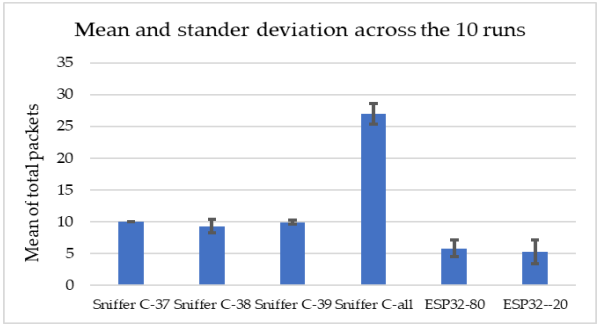

Fig 10 Mean and Standard deviation for Advertising at all Channels

B. Investigate the time taken for the ESP32 to Receive the 1st packet

Before Fig. 11(a), 11(b) and Table-IV show that when advertising on multi-channel, 59.47% of the total packet received on ESP32-80 can be picked up at a time that less than 100ms compared to ESP32-20 which 49.93% of the total packet picked up in less than 100ms. And 40% and 40.67% of packets received on ESP32-80 and ESP32-20 is between 100ms and 300ms. Also, ESP32-80 shows a

rare chance (0.40% and 0.07% of the packet received between 300ms-500ms and bigger than 500ms respectively) that it can receive the packet at a time that bigger than 300ms compared to ESP32-20 (10% and 1.47% of the packet received between 300ms-500ms and bigger than 500ms respectively). This proves that advertising on multi-channel will not only increase the number of packets on ESP32 (Section IV A) but also will improve the time it takes for the ESP32 the receive the first packet when the advertisement starts.

Fig. 11(c), Fig. 11(d) and Table-IV shows that when advertising on a single channel, almost 21% and 31.14% of the total packets received on ESP32-80 and ESP32-20 respectively is less than 200ms. Also, 31.6% and 14% of the packet is received at time that less than 100ms. 28.13% and 31.67% of the packets is received between 100ms and 300ms. 24.20% and 21.87% of the packets is between 300-500ms and 26.60% and 20.53 of the packets is received at a time bigger than 500ms for ESP32-80 and ESP32-20 respectively. Also, ESP32-20 shows that 11.13% of the packets is lost.

These results show that advertising on single channel would increase the response time since ESP32 generally scan on three channels sequentially. But ESP32-80 has better performance and that is due to, the longer it takes to scan each channel (with a scan window equal to 45ms) compared to ESP32-20 (with a scan window equal to 10ms) which made ESP32-20 suffered from some packet loss. But overall advertising on single channel would reduce the time response and would not improve the user experience compared to when the advertisement occurs in multi-channel Also prove that the response on ESP32-80 would stay most of the time less than or equal 200ms.

V. CONCLUSION

BLE beacon technology for home automation system can use to improve the user experience. As presented in the results, when ESP32 is used as a beacon scanner, the advertisement occurs on the multi-channels, it shows a good time response that less than 100ms by using the setting in ESP32-80 or ESP32-20. But when the advertisement happens on single channel the time response for both ESP32-80 and ESP32-20 become bigger than 100ms and even bigger than 500ms which it would take even a second for the ESP32 to pick up the first packet. Also, it would lead to packet loss if the scanning parameter small like in ESP32-20.

Since ESP32 also provide Wi-Fi interface that will help in connecting the home automation system to the cloud. However, due to the sharing of the antenna between the BLE and the Wi-Fi, more studies will need to be carried out to investigate the effect to the Wi-Fi when the BLE scanner is utilizing the resources. It is interested to see the effect on the scan response of the BLE beacon.

Table-IV percentages of first packet received across the time

Advertise at		Multi-channel		Single channel	
Time	Setting	ESP32-80	ESP32-20	ESP32-80	ESP32-20
<0 (packet loss)		0%	0%	0%	11.13%
<100ms		59.47%	49.93%	21%	14.73%
100-300ms		40%	40.67%	28.13%	31.67%
300-500ms		0.4%	10%	24.2%	21.87%
>500ms		0.067%	1.47%	26.6%	20.53%

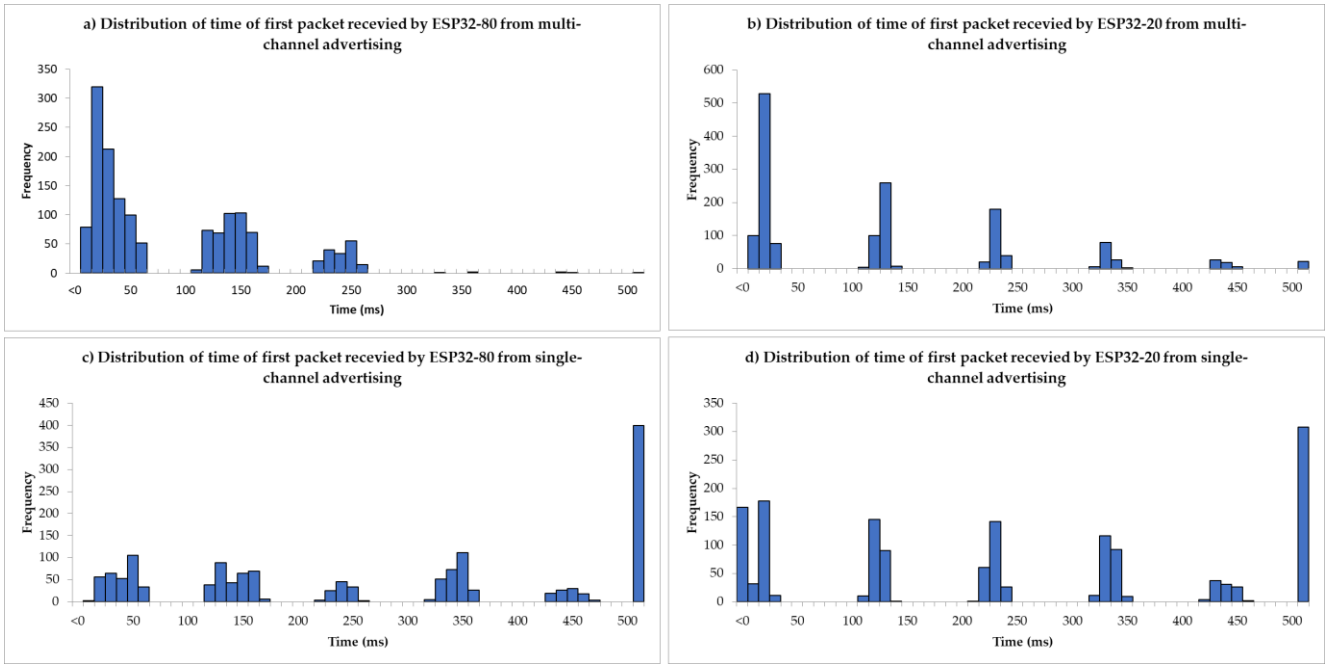

Fig. 11. Histogram for single and multi-channel advertisement for ESP32-80 and ESP32-20

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