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Indoor Performance Evaluation of ESP-NOW

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***Abstract*—ESP-NOW is a connection-less communication protocol developed by the semiconductor manufacturer Espressif Systems for their in-situ low power IEEE802.11-enabled Internet of Things devices. In this paper, we conduct a number of experiments to evaluate the performance of ESP-NOW in an indoor environment. More specifically, we assess the protocol performance in terms of achieved range, packet delivery ratio, and penetration capability using commonly used off-the-shelf devices. Furthermore, we conduct a power characterization of the protocol under different operating modes and compare its power consumption to that of a typical WiFi approach. The evaluation results show that environmental factors such as reflections and obstacles heavily affect the overall performance. Nevertheless, the comparison with the WiFi approach showed an improved indoors range of 15% in terms of packet delivery ratio and more than 30% in terms of power consumption.**

***Index Terms*—Internet of Things, ESP-NOW, Performance evaluation**

I. Introduction

To better understand and optimize the physical world processes, the use of measurement, control, and monitoring systems are swiftly increasing. The development of Internet of Things (IoT) systems assists in that direction due to their autonomous way of monitoring and reporting their measurements. The paradigm of IoT can be applied in many application areas including healthcare, construction monitoring, smart homes, and smart agriculture [1]. Many IoT devices are deployed indoors where the presence of walls and other obstacles vastly worsens the quality of wireless transmissions. Hence, the development of solutions with extended range capabilities is important.

Moreover, there are many challenges related to the deployment and maintenance of a massive number of devices in an IoT network that significantly affect the accessibility and the system cost [2, 3]. In order to reduce these costs, there is a need to develop protocols that are designed with a more open and generic architecture compared to traditional wireless networks.

ESP-NOW has been proposed as a very low-cost and low-power solution for IoT devices operating at the 2.4GHz Industrial, Scientific, and Medical (ISM) spectrum. It is used in many industrial [4], smart agriculture [5], and smart home applications such as smart light systems [6]. It can also be used as a supporting and independent module for helping network debugging, configuration and firmware upgrades or overall control of IoT devices in real time [7]. The protocols allows many devices to communicate with each other using the widely available and low-cost IEEE802.11 transceivers [5].

ESP-NOW merges functionalities of several Open Systems Interconnection (OSI) layers into a single layer as it is shown in

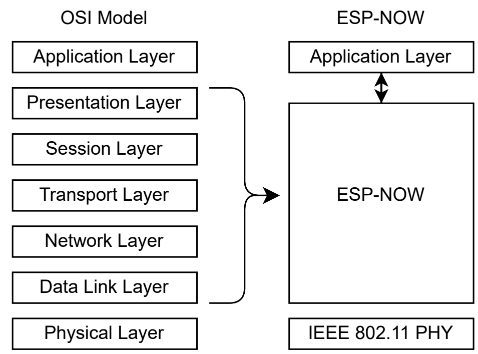


Fig. 1: The ESP-NOW protocol stack as compared to the traditional OSI model.

Fig. 1. At the physical layer, it relies on the native IEEE802.11-1999 standard [8] but also on an Espressif's Long-Range (LR) mode of operation which allows transceivers to achieve higher sensitivity at the expense of a lower data rate. Due to the improved sensitivity, a signal can travel longer distances as compared to other short- and medium-range solutions. For example, it covers a 15 times longer distance compared to Bluetooth Low Energy (BLE) [9].

At the link layer, the protocol does not require a connection to be established first between a transmitter and a receiver but everything works in an adhoc peer-to-peer manner. A Medium Access Control (MAC) address-based pairing may be required depending on the application. ESP-NOW allows direct (single-hop) and easy communication between devices equipped with Espressif (ESP) Systems-on-Chip (SoC) such as the ESP32 SoC. At the MAC layer, ESP-NOW relies on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) method of IEEE802.11. A number of re-transmissions will be performed if an acknowledgment is not received in a short amount of time after the transmission.

In this paper, we evaluate the performance of ESP-NOW under different conditions using a number of experiments conducted indoors. More specifically, we assess the performance of the protocol in terms of achieved range and packet delivery ratio at short and long distances between a transmitter and multiple receivers. We select 15 indoor positions exhibiting various signal strength values ranging from -50 to almost -100 dBm. The results are compared to a custom Transmission Control Protocol (TCP) WiFi-based protocol. Moreover, a power characterization of the protocol is conducted which gives useful insights of its underlying mechanisms as well as of the radio power consumption. Conclusions are made for each of the aforementioned experiments that might be useful for researchers and engineers in the area of Internet of Things.

In summary, the contributions of the paper are as follows:

1) The performance of ESP-NOW is evaluated using real experiments conducted in an indoor environment. Both the regular and the LR mode are evaluated.
2) A power characterization of the protocol is also conducted.
3) A comparison with the IEEE802.11n mode is made.
4) A number of evaluation tools are developed that are freely available to the research community.

II. Related Research

This section surveys some recent studies which show the higher efficiency of ESP-NOW compared to other short and medium range IoT technologies through a number of experimental comparisons.

Khanchuea et al. [10] evaluated the performance of ESP-NOW using a 5-hop low-power wireless network prototype. The authors presented a use case where a building automation system was developed for the control and management of air-conditioners and power meter units. They performed field tests to study the impact of distance and the number of hops on network metrics such as the throughput, the average round-trip time, and the jitter. They concluded that ESP-NOW is a better choice for a multi-hop building monitoring scenario compared to regular WiFi solutions.

In a similar study [11], a structural health monitoring use case is considered where a set of IoT devices are constantly monitoring and reporting their measurements in a synchronized manner. The authors conclude that ESP-NOW is more energy efficient than a TCP over WiFi solution most likely because of the increased overhead of the latter one.

Furthermore, Lablib et al. [9] worked on the performance evaluation of ESP-NOW by conducting a series of indoor and outdoor experiments. It is claimed that ESP-NOW can achieve an up to 15 times longer range compared to BLE while consuming roughly the double of power that BLE consumes. The authors also report a 15m indoor and 90m outdoor range while using ESP-NOW. Similar findings are reported in [12]. The comparison with BLE and WiFi (a/b/g mode) showed a 12 and a 2 times higher range, respectively. However, the study reports a 40% higher energy consumption compared to the other two approaches.

In the aforementioned works, it is clearly shown that other widely used approaches have lower efficiency compared to ESP-NOW in terms of achieved range, even though this comes with some more energy expenditure. However, all the previous studies consider only the regular mode of ESP-NOW which is not very different to a typical IEEE802.11-1999 modulation. The proprietary long range mode of ESP-NOW has not been evaluated. Moreover, most of the experiments are conducted outdoors while the indoor performance is not thoroughly explored. Apart from that, the MAC layer capabilities of the protocol such as the retransmission mechanism are not discussed at all.

III. The ESP-NOW protocol stack

This section briefly presents the basic functionalities of the ESP-NOW protocol stack as well as a description of the available hardware.

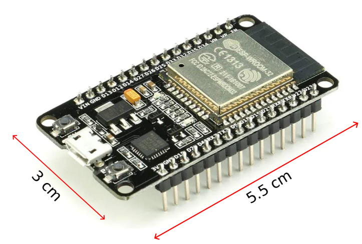


Fig. 2: The ESP32 WROOM module.

A. The ESP32 devices

ESP-NOW can theoretically run on any IoT device equipped with an IEEE802.11 transceiver. However, the long range mode of the protocol can only run on ESP32 and ESP8266 devices. ESP32 is a dual core microcontroller unit (MCU) made by Espressif Systems that integrates Bluetooth and WiFi transceivers. The manufacturer has released many different modules based on the ESP32 architecture. A typical module is the ESP32 WROOM (see Fig. 2). It consists of 4 MB flash memory, a 40 MHz crystal oscillator, an ESP32 SoC with two Tensilica Xtensa LX6 CPUs and 520 KB of RAM as well as the radio transceivers, and some passive components. ESP8266 has similar characteristics. ESP modules usually come with an integrated 2.4GHz antenna.

B. Physical, Link, MAC layer features

At the physical layer, ESP-NOW relies on the standard IEEE802.11 direct sequence spread spectrum (DSSS) modulation that is also met in the initial version of IEEE802.11. The bitrate is set to 1 Mbits per second even though a long-range (LR) version of the protocol exists and it is claimed to achieve a longer range at 250 or 500 Kbits per second. As it was mentioned earlier, the LR version employs a proprietary modulation which trades range with data rate. All devices of the network must be set up with the same settings in order to communicate over the LR mode.

At the link and MAC layer, ESP-NOW supports either one-to-many or many-to-many modes of operations. A packet forwarding mechanism is also present. Collisions are handled using the default IEEE802.11 CSMA mechanism. Furthermore, it exhibits two modes of communication; the broadcast and the unicast mode.

In *Unicast* mode, a master device (transmitter) sends an individual packet to a slave device (receiver) indicating the slave's MAC address in the corresponding frame field (see next paragraphs). It shortly expects an acknowledgment from the slave node, otherwise retransmissions occur. The number of retransmissions is by default set to 10 but up to 31 retransmissions are supported.

In *Broadcast* mode, a master device can send a packet to multiple slave devices simultaneously by indicating a full-bit MAC address in the corresponding frame field. Broadcast transmissions are not acknowledged.

ESP-NOW allows sending and receiving payloads between two devices of up to 250 bytes long via vendor-specific action frames. Vendor-specific action frames are 802.11 management-type MAC frames, that are used to achieve supervisory functions (e.g. when leaving and joining access points or wireless

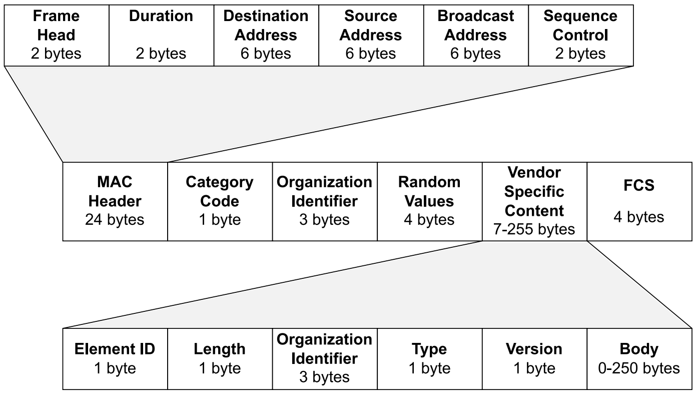


Fig. 3: The ESP-NOW packet format following the IEEE802.11 Vendor-specific action format.

TABLE I: Experiment Parameters

Parameter	Value
Experiment time	∼30min per instance
Master devices (transmitter)	1
Slave devices (receiver)	15
Terrain size	80x50 m
Device positions	see Fig. 4
Firmware version	ESP32 2.0.3
CPU clock speed	80 MHz
Radio channel	2.4 GHz IEEE802.11 Channel 1
Tx power	20 dBm
Payload	8 Bytes
Packet rate	1pkt every ∼1.1 seconds
ESP-NOW modes	Regular (1Mbps) and LR (250Kbps)
WiFi mode	IEEE802.11n
WiFi retransmissions	10

networks) according to the IEEE802.11 standard [8]. According to the currently released implementation[1], the ESP-NOW packet format is depicted in Fig. 3. It can be observed that the protocol exhibits an overhead of a total of 43 Bytes.

The payload can optionally be encrypted at the application layer using the widely used CCMP protocol. A device stores a Primary Master Key (PMK) and Local Master Keys (LMK), both 16 bytes long. LMK are encrypted using PMK with the AES-128 algorithm, and then the vendor-specific action frame is encrypted using LMK of the paired device.

IV. Performance evaluation

In this section, we describe the experimental setup, the experimental procedure, and finally we present and discuss the obtained results.

A. Setup & Procedure

The experimental setup consists of five ESP32 WROOM slave devices labelled with E1, E2, E3, E4, and E5 and a master device labelled with E0. Three sets of experiments were conducted at different slave device positions as it is described in the next bullet paragraphs. The purpose of each of these scenarios was to assess the protocol performance under different conditions such as with Line-of-Sight (LoS), without LoS, and at distant positions without LoS. The selection of the positions was made based on the received signal strength, the accessibility to certain rooms, and the manpower availability criteria. More than 100 positions were evaluated and 15 representative ones were selected.

- Experiment A: The slave devices were placed at different distances (short and long ones) away from the master device with LoS. The shortest distance was 5 meters away from the master node while the furthest distance was about 55 meters.
- Experiment B: The slave devices were placed at different distances from the master device without LoS but with many obstacles in between the two ends.
- Experiment C: The slave devices were placed at distant positions from the master device without LoS.

All of the experiment parameters are represented in the Table I. A map of the node positions for all three scenarios is shown in Fig. 4. The star node is a master device, the green circles indicate nodes with LoS which are used for experiment A, and the blue triangles are non-LoS positions with a presence of walls, doors, and other obstacles between the transmitter and the receivers. Finally, diamond-shaped positions indicate slave devices at distant positions used in experiment C.

The flow of the experiment's process can be seen in Fig. 5. Each experiment was conducted several times sending 1000 unicast packets one-by-one to each of the five slave nodes of each experiment. An adequate period of time was dedicated to retransmissions before proceeding to transmit to the next device. The average results are presented. All experiments were conducted in the same frequency channel without the presence of external interference so that the backoff algorithm of IEEE802.11 is not triggered [13].

For each of the conducted experiments, we measured the number of packets that reached the slave nodes. A packet is considered as "delivered" if it reaches the destination (slave device). If an acknowledgement transmitted by a slave device does not reach the destination (i.e., the master device), retransmissions occur. To avoid double-counting same transmitted packets, a sequence number of each unique packet is added in the payload (4 bytes) along with a timestamp (4 bytes). The Received Signal Strength (RSS) and the Packet Reception Rate (PRR) are recorded at each slave device and stored in text format in MicroSD cards. The slave devices are equipped with a MicroSD card module depicted in Fig. 6, which is connected to the node via Serial Peripheral Interface (SPI). Due to the absence of a battery charging module on ESP32-WROOM devices, a boost converter was used as a convenient way to power up the device from the USB port. This converter increases the voltage from 3.7 to 5V.

After all 1000 packets are transmitted, the results from all slave devices are collected and statistics are compiled using a number of scripts developed in Python. The software developed for conducting the experiments along with all additional tools are freely available to the research community[2].

Both versions of ESP-NOW are evaluated; the regular one (1Mbps) and the LR mode (250Kbps). ESP-NOW is compared

[1]https://github.com/espressif/esp-now

[2]https://github.com/prinnevald/esp-now-eval-tools

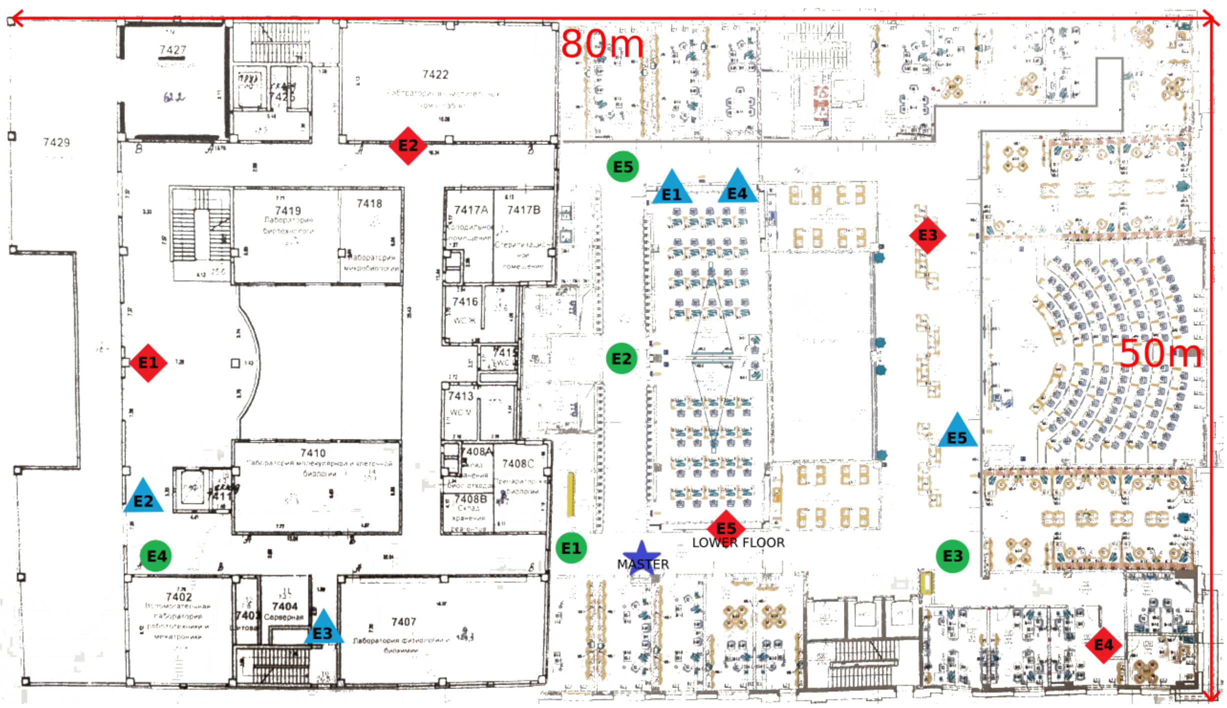


Fig. 4: Map of the floor where experiments were conducted. Master device: star, Slave devices: circles (Experiment A), triangles (Experiment B), diamonds (Experiment C).

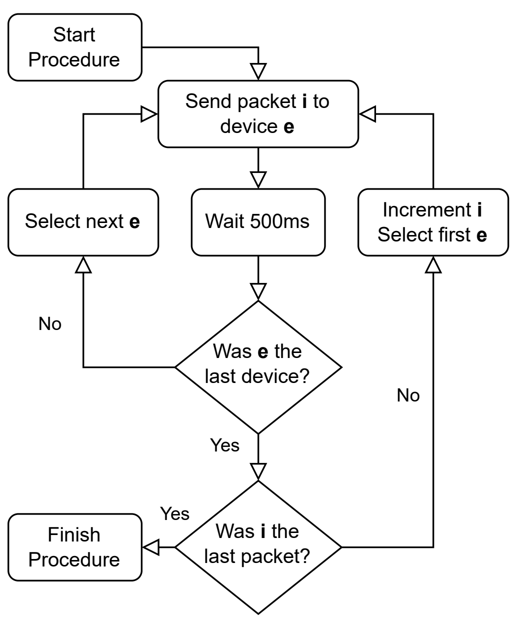


Fig. 5: The flowchart of the process followed in the experiments.

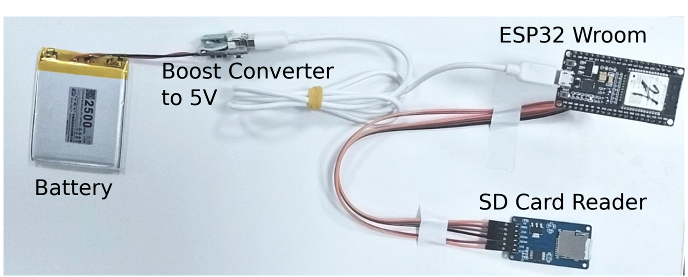


Fig. 6: The experimental setup consists of four components.

TABLE II: Experiment A: Various distances with LoS

Posi-tion	ESP-NOW			ESP-NOW LR			WiFi TCP		
	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %
E1	-58.0	0.71	100	-58.9	0.81	100	-62.3	2.31	100
E2	-72.7	0.96	100	-62.9	0.74	100	-58.4	0.8	100
E3	-88.5	1.47	99.8	-85.5	2.02	99.3	-83.2	1.55	99.3
E4	-72.2	1.35	100	-77.1	1.24	100	-86.2	1.69	96.9
E5	-83.6	1.37	99.8	-78.4	1.11	100	-81.2	1.55	99.4

to a custom WiFi TCP approach. The IEEE802.11n mode is selected because it is the most widely used mode in access points and WiFi equipment nowadays. Nevertheless, IEEE802.11n does not exhibit any considerable differences to the IEEE802.11g mode for low-cost IoT devices operating at 2.4GHz.

B. Packet Success Rate

1) Experiment A: Various distances with LoS: As it can be observed from Table II, the Packet Success Rate (PSR) is high for devices with LoS for both modes of ESP-NOW but also for WiFi. Even when the distance is long (e.g., for position E4), all approaches exhibit an acceptable performance with more than 96% of the packets delivered. The standard deviation of the received signal strength (RSS) is also very low for most of the measurements which positively contributes to the consistency of the results.

2) Experiment B: Positions without LoS: The results of Table III represent the outcome of Experiment B where non-LoS positions are evaluated. As it was expected, the devices achieve a worse performance than the previous experiment, however, the performance is still high. The PSR ranges between 93.8 to 99.9% for ESP-NOW and between 92.9 and 99.4% for WiFi. The LR mode presents on average slightly better results, however,

TABLE III: Experiment B: Mid-distance positions without LoS

Position	ESP-NOW			ESP-NOW LR			WiFi TCP		
	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %
E1	-89.0	1.48	98.2	-85.9	1.42	99	-89.7	1.6	97.3
E2	-87.6	2.07	97.1	-91.3	1.56	97.7	-70.3	1.66	99.4
E3	-90.3	1.87	99.1	-82.1	1.8	99.9	-86.4	1.49	98.5
E4	-91.2	1.4	98.9	-90.2	1.29	99.5	-90.6	1.72	96.9
E5	-89.1	1.57	93.8	-89.5	1.65	94.1	-87.4	1.72	92.9

TABLE IV: Experiment C: Extreme positions without LoS

Position	ESP-NOW			ESP-NOW LR			WiFi TCP		
	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %	RSS dBm	RSS σ	PSR %
E1	0	0	0	-93.7	1.88	1.5	0	0	0
E2	0	0	0	-96	1.41	0.2	0	0	0
E3	-90.9	1.33	94.5	-90.2	1.39	97.1	-91.6	1.4	44.6
E4	0	0	0	0	0	0	0	0	0
E5	-89.4	1.13	99.3	-92.2	1.27	99.9	0	0	0

without considerable difference to the regular mode. Moreover, the reflections on the walls positively affected the performance of all approaches (e.g., positions E1, E4).

3) Experiment C: Extreme positions without LoS: Finally, Table IV depicts the results obtained from Experiment C where all slave nodes are placed far from the transmitter without LoS. It is interesting to see that the penetration capability of ESP-NOW is higher than that of IEEE802.11n which managed to get results only from one node placed at the same floor. It was also observed that the connection-full operation of WiFi was one of the reasons for the high number of dropped packets. The LR mode achieved a slightly better performance than the regular ESP-NOW, however, the performance was highly affected by the presence of multiple obstacles. As a consequence, the signal strength presented higher fluctuations than the previous two experiments. In general, the high frequency of the signals does not help ESP-NOW to penetrate more than 2 or 3 office walls.

C. Range

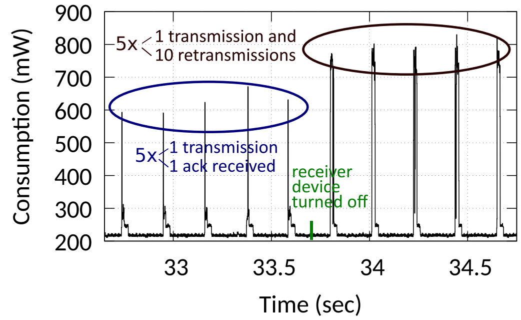
Apart from Experiments A-C, some more indoor experiments were conducted to determine the maximum efficient range of the LR mode. Two cases were evaluated; a 300m-long open-space atrium with only a few light obstacles between the two furthest points, and a narrow tube-shaped corridor with a 400m length. A transmitter and a receiver were used in these experiments following the same procedure. A number of positions were tested with a goal of 90% PSR out of 1000 transmitted packets.

The results showed that in the first case, the maximum range is close to 280 meters while in the second case the maximum achieved range was more than 330 meters. This is a clear indication that the presence of reflections and the absence of multiple obstacles critically affect the maximum range.

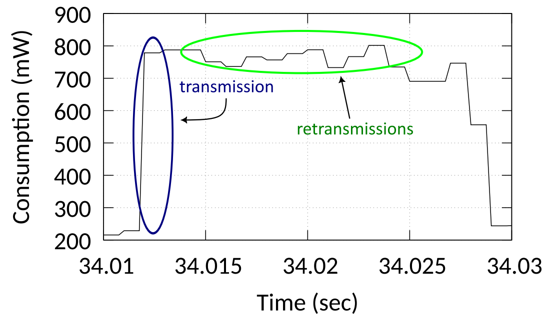
D. Power Characterization

A pair of transmitter and receiver devices was employed and put onto a power analyzer to measure the protocol power consumption and behavior. The regular mode of ESP-NOW was assessed at this phase. The effect of packet transmissions at different timings and circumstances can be seen in Fig. 7.

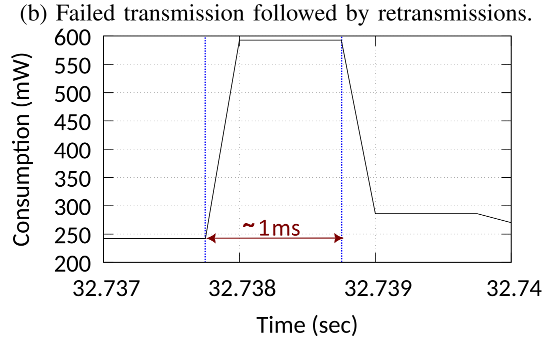
Fig. 7a depicts five successful transmissions followed by five unsuccessful ones. The transmitter was in idle mode between



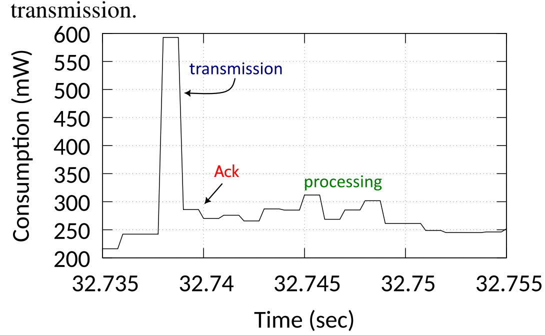
(a) Power consumption increase after turning off the receiver.



(b) Failed transmission followed by retransmissions.



(c) A zoom-in on the length of an 8-byte payload transmission.



(d) Typical transmission followed by an acknowledgement and some processing.

Fig. 7: Regular ESP-NOW power consumption profiles at the transmitter in different scenarios and timings.

successive transmissions. The power expenditure of the successful transmissions varies between 600 and 660mW. An acknowledgment is received immediately after each transmission. The receiver was intentionally turned off after five successful receptions to measure the effect of retransmissions and the extra cost of transmitting and receiving (i.e., waiting for an acknowledgement) at the same time. It can be observed that the full-duplex mode of IEEE802.11 transceivers leads to a 20% higher power consumption. Moreover, Fig. 7b illustrates that an unsuccessful transmission is followed by a long retransmission time which lasts around 12ms. Assuming that each transmission lasts around 1ms, this is enough time to fit 10 retransmissions as it is set in the protocol's specifications.

The length and the corresponding power consumption of a successful transmission is depicted in Fig. 7c. The total transmission length using an 8-byte payload (plus 43 Bytes of overhead) was measured at around 1ms. Some extra time was deserved for processing after receiving the acknowledgement as it is shown in Fig. 7d.

The experiments were repeated for the LR mode of ESP-NOW as well as for the WiFi TCP approach. The figures are omitted due to the limited size of this paper. The results of the LR mode showed a similar performance as with the regular ESP-NOW mode. On the contrary, WiFi TCP transmissions yielded constant peaks of 950mW of power. Moreover, the connection-full mode of the standard WiFi caused much higher average energy consumption compared to ESP-NOW.

V. Conclusion & Future Work

Espressif System devices have been widely used in many IoT applications due to their low cost and low power operation. This paper studied the manufacturer's proposed protocol stack for their in-situ devices, called ESP-NOW. A number of field experiments were conducted to understand and assess the protocol performance in terms of range, packet success rate, and power consumption in an indoor environment. Both the regular and the proprietary (LR) modes of ESP-NOW were tested. The results showed that ESP-NOW can achieve a slightly longer range than a typical WiFi TCP approach in presence of many obstacles. The success rate is also slightly better in mid- and long-range positions. The proprietary LR mode did not present any considerably higher performance compared to the regular ESP-NOW. Moreover, the power characterization experiments revealed a reduction in power consumption of more than 30% compared to WiFi.

In the future, we are planning to compare ESP-NOW to other technologies in the same ISM spectrum as well such as the LoRa and the IEEE802.15.4g technologies.

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