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IMPROVED PERFORMANCE OF WI-FI BASED COMMUNICATION WITH MULTIPLE SENSORS THROUGH COLLABORATION BETWEEN THE WEBSERIAL REMOTE SERIAL MONITOR AND ESP-NOW PROTOCOL

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Abstract: This article is a continuation of the research conducted in [Abotaleb 2023] to analyse the importance of coexistence between different wireless technologies in the instrumentation field. The WebSerial based laboratory stand described in [Abotaleb 2023] showed a limited range of WiFi communication due to decreased Received Signal Strength Indicator (RSSI) levels at points not located at a straight Line of Sight (LOS) from the host controller. The ESP32 controller is the backbone of such a stand, administrating both serial and Wi-Fi communication to send the collected data from multiple sensors to the host controller. In order to increase the range of wireless communication, the WiFi based ESP-NOW protocol will be presented as an alternative to performing such a task from the perspective of possible future application in maritime engineering.

Keywords: ESP-NOW, RSSI, WebSerial, Wi-Fi.

1. INTRODUCTION

The rapidly increasing popularity of wireless technology in the instrumentation field means additional requirements for ensuring reliable as well as secure data transmission from multiple sensors with the appropriate, accepted range of wireless communication. One of these requirements is the principle of coexistence between different wireless technologies or even different wireless protocols, which is an important factor to analyse. A laboratory stand dedicated to this purpose was described in the previous article. The basic feature of this laboratory stand was its dependency on performing data transmission operations from multiple sensors through simultaneous WiFi based wireless communication (generated by the ESP32 controller as an access point) with the host controller and serial communication with the arduino controller, to which the simulated sensors are connected. As was indicated in the future work section in the previous article, limited RSSI levels were detected at very short distances from the host controller due to physical indoor obstructions such as concrete walls or metallic objects. This can be considered a major drawback in an instrumentation system based on partially or fully wireless data transmission, as the main purpose of transmitting data wirelessly is to save the cost of cabling and its accessories such as cable trays and junction boxes which extend for very long distances all over the plant.

Accordingly, in order to overcome such a drawback, this article will discuss the possibility of using the ESP32 controller through coexistence between two wireless protocols in order to increase the maximum possible range of WiFi based wireless communication on a specific site. The first protocol is the WebSerial remote serial monitor which was discussed in detail in the previous article and [Randomnerdtutorials 2021; Sharma 2021; Techtutorialsx 2022], while the second one is the ESP-NOW protocol.

In order to provide a full description of the problem of the limited range of WiFi based wireless communication, the first section of the article will discuss the relation between the distance from the host controller to the ESP32 access point on specific indoor or outdoor sites and the RSSI levels at different locations on these sites. It is veey important to indicate this relation during the planning phase for any wireless instrumentation system for locations with low RSSI levels to be identified in order to consider installing repeaters or switches at such locations.

The second section of the article will provide a basic description of the ESP-NOW protocol and its uses related to the subject of the article as well as the available literature. The third section of the article will introduce two possible configurations for using the ESP-NOW protocol as an alternative to increasing the range of ESP32 WiFi based wireless data transmission from multiple sensors in an instrumentation system.

The first configuration is based on two ESP32 controllers. The first controller performs wired serial/WiFi ESP-NOW communication tasks, while the second controller performs WiFi ESP-NOW/WiFi WebSerial communication tasks. The second configuration is an upgraded version of the first configuration. It is based on using multiple ESP32 controllers to perform the role of switches between the two ESP32 controllers described in the first configuration at locations where low levels of RSSI are expected. For the sake of simplicity, this article will consider using only one ESP32 controller as a switch. The fourth section of the article will describe the relation between the improved range of WiFi communication resulting from using the ESP-NOW protocol in conjunction with the WebSerial remote serial monitor and possible future uses in the maritime engineering field, particularly on commercial ships.

2. PROBLEM IDENTIFICATION

As discussed in the previous article authenticated WiFi based wireless data transmission from multiple sensors was provided through cooperation between the Arduino mega 2560 controller and ESP32 controller. The simulated multiple sensors were connected to the Arduino controller as analogue inputs, and the measurements from these sensors were sent through serial communication to the ESP32 controller, which in turn sent the measured data to the host controller using the WebSerial remote serial monitor. The maximum range obtained from this configuration, which guaranteed successful communication, was almost 12 meters with an RSSI level of almost -70 dbm detected at the host controller (Fig. 1-a). It is important to consider the fact that the host controller was located inside a room and the laboratory stand was located outside the room. This configuration was not selected randomly. It was selected for a reason, and even for a very good reason, as most of the host controllers in any industrial plant are located inside a control room, while the sensors and the wireless module sending the measurements from these sensors are placed in the plant outside the control room, separated by a wall or a group of walls from the host controller.

In order to characterise the relation between RSSI levels and the distance from the host controller to the ESP32 access point included in the laboratory stand at specific indoor as well as outdoor sites, five sites will be considered.

The indoor sites are located at the Faculty of electrical engineering at Gdynia Maritime University, while the outdoor sites are located at the neighbourhood of the university building:

1) Straight corridor (indoor site, length: 75 meters) (Fig. 1-a).
2) Straight corridor (indoor site, length: 50 meters) (Fig. 1-a).
3) Straight long passage (outdoor site, length: 180 meters) (Fig. 1-b).
4) Parking site, shopping stores and fuel station (outdoor site) (Fig. 1-c).
5) Straight corridor at the upper floor starting from the location of the host controller (indoor site, length: 50 meters) (Fig. 1-d).

Due to the fluctuations detected in RSSI levels at the 1st and 2nd sites, at the slightest movement, each of the illustrated RSSI values at figure 2-a indicates the average measured RSSI level at a specific point. The explanation for such unstable RSSI values detected at the indoor site is the increased level of reflections that the radio waves will experience insuch an enclosed space, from the walls, the objects included on the site and even the human traffic.

Equation (1) was derived from the average RSSI readings obtained with respect to the distance between the host controller only at the 1st site, using the Matlab curve fitting tool. The RSSI measurements at the second site were used to verify if this equation was applicable or not. At any indoor sight, deriving such an equation will be very helpful during the planning phase for a wireless instrumentation network, especially if that site includes similar sections such as rooms, corridors, halls with similar dimensions and structural features. For this reason, the RSSI readings at the second site were used as an experimental verification for such a planning technique. Equation (2) was derived from the RSSI readings taken in the third outdoor site (Fig. 2-b).

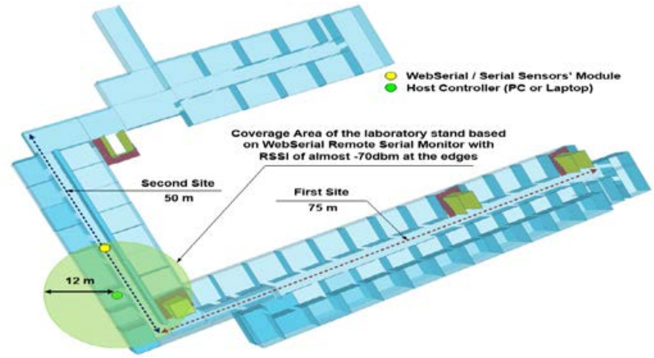
Generally, to guarantee successful WiFi communication, the recommended RSSI level should be no less than – 60 dbm [Abotaleb et al. 2022]. Consequently, based on the results obtained from equations (1) and (2), the RSSI level of – 60 dbm corresponds to a distance (from the host controller to the ESP32 unit) of 20 or 40 metres for indoor and outdoor applications respectively (Fig. 2-c). Despite the fact that both equations are characterising the relation between RSSI and distance at the specific mentioned locations, general guidelines and recommendations can be drawn from both equations, related to the use of the ESP32 controller as an independent WiFi access point.

Accordingly, 20 and 40 metres are the maximum recommended distances between ESP32 WiFi access point and the host controller at a straight LOS without obstacles for indoor and outdoor applications respectively. RSSI values measured at the fourth site were taken to indicate some assumed points that were intended to be covered in an assumed wireless WiFi instrumentation network based on the ESP32 controller, and were not covered due to the low RSSI levels at these points. Like the fourth site, the fifth site is another example of an area assumed to be covered by only one ESP32 controller, communicating with the host controller using the WebSerial remote serial monitor. It is located on the next floor from the host controller.

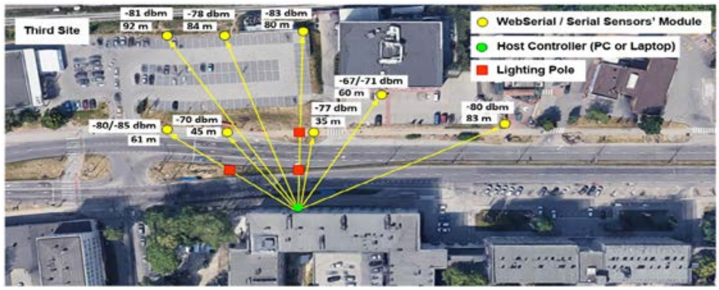
$$\mathrm{RSSI_{indoor}}\ (\mathrm{dbm}) = k_{i1}d^4 + k_{i2}d^3 + k_{i3}d^2 + k_{i4}\,d + k_{i5} \tag{1}$$

$$\mathrm{RSSI_{outdoor}}\ (\mathrm{dbm}) = k_{o1}d^3 + k_{o2}d^2 + k_{o3}d + k_{o4} \tag{2}$$

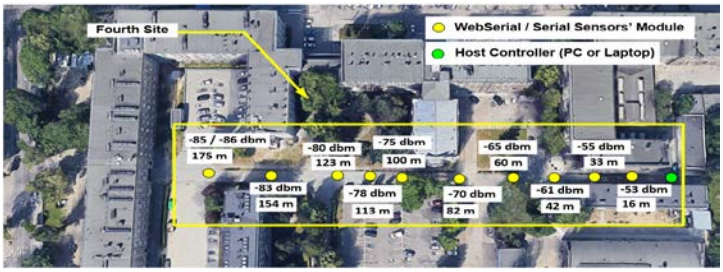
Where k_{i1} = 9.95e-06 dbm/m^4,k_{i2} = -0.001587 dbm/m^3, k_{i3} = 0.0894 dbm/m^2, k_{i4} = -2.282 dbm/m, k_{i5} = -38.76 dbm
k_{o1} = -5.9e-06 dbm/m^3, k_{o2} = 0.002781 dbm/m^2, k_{o3} = -0.5587 dbm/m, k_{o4}= -41.23 dbm and d is the distance from the host controller to the sensors module in metres.



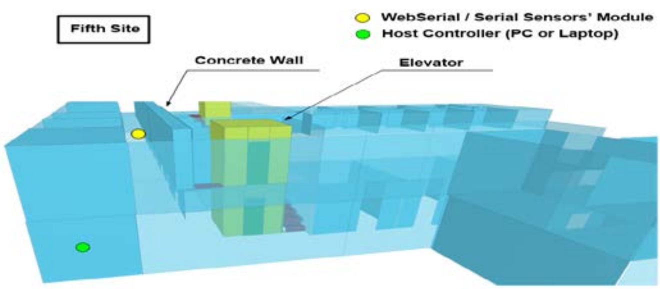
(a) Limited range of WebSerial based Laboratory stand, 1st and 2nd sites used to derive and verify equation(1)



(b) RSSI measured at points deflected from LOS (3rd site)

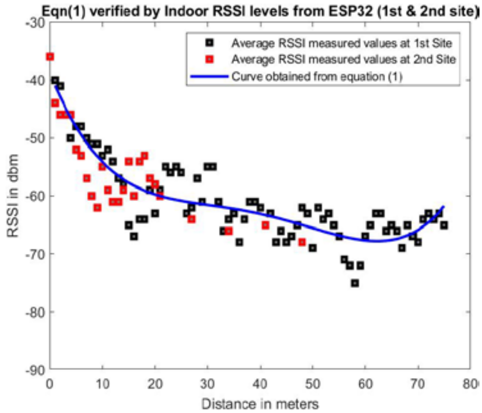


(c) RSSI measured at points on the straight LOS (4th site)

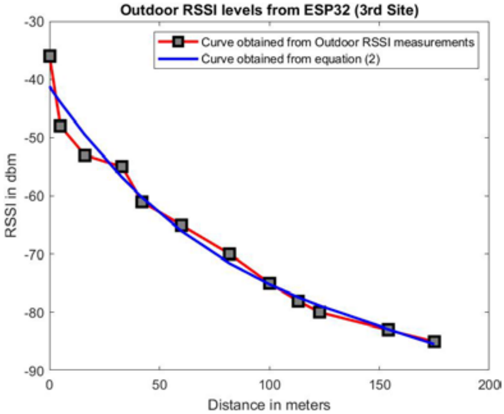


(d) Fifth site

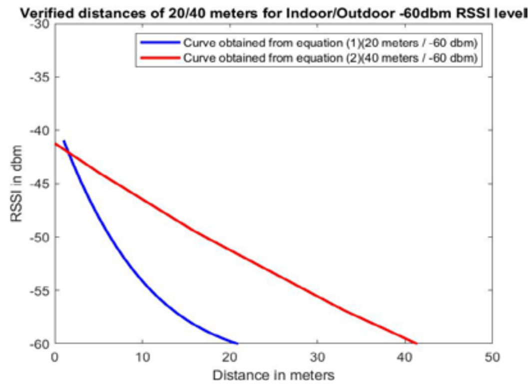
Fig. 1. Five indoor/outdoor sites used for experimental analysis of ESP32 WiFi range



(a)



(b)



(c)

Fig. 2. Curves obtained from RSSI measurement with respect to distance at 1st, 2nd and 3rd sites and curves obtained from equations (1) and (2)

3. ESP-NOW PROTOCOL

ESP-NOW is a WiFi wireless communication protocol developed by Espressif to perform wireless low power and quick communication tasks based on transmitting messages with a maximum size of 250 bytes between ESP32 and ESP8266 units but only in the knowledge of their MAC addresses. The ESP-NOW protocol also enables encrypted data transaction in order to increase the security level of wireless communication. Counter Mode with the Cipher Block Chaining Message Authentication Code Protocol (CCMP) is used by ESP-NOW to execute encrypted data transaction. The CCMP protocol is mainly based on using a Primary Master Key (PMK) and several Local Master Keys (LMK) for the purpose of identifying the devices permitted for communication. The AES 128 algorithm is used to set up both master keys [Randomnerdtutorials January 2020b; Espressif Systems 2023].

In this article, the ESP-NOW WiFi wireless communication tasks executed will be based on unencrypted data transaction; the ESP-NOW protocol can be used in too many setups [Randomnerdtutorials January 2020a; Randomnerdtutorials April 2020a,b]:

- single master and multiple slaves (one to many);
- single slave and multiple masters (many to one);
- simplex, half duplex or full duplex communication.

The exact final nature of wireless communication in an ESP32 unit can only be defined by the technique adopted when such a unit is being programmed. Arduino IDE as well as Micropython are two environments used to program the ESP32 controller. In this article, the Arduino IDE environment was used to program the ESP32 controller. During experimental programming trials and according to the programming techniques proposed in the previous article, it wemerged that it was not advisable to perform simultaneous two-way communication (full duplex) between more than two ESP32 units as this would probably lead to a program crash. In this article, to solve the problem of limited range in the ESP32 WebSerial WiFi based wireless instrumentation network, two configurations will be proposed for the fourth section.

In the first configuration, the ESP32 unit near the host controller will perform ESP-NOW/WebSerial WiFi based communication. As suggested in [Randomnerdtutorials May 2020; Carrasco 2021], the following considerations should be taken into account when performing this type of communication:

- using WiFi mode as an access point and independent station *WiFi.mode(WIFI_AP_STA)*;
- considering a possible change of the WiFi Communication channel.

The programming functions used to establish successful ESP-NOW WiFi communication were thoroughly described in [Randomnerdtutorials January 2020b; Espressif Systems 2023]. In this article, two specific functions will be briefly described due to their particular importance in conjunction with the subject of this article. The first function is *esp_now_send()*, and is dedicated to sending data by using the ESP-NOW protocol. This function requires three parameters, which are the MAC address of the ESP32 receiver unit, a pointer to the variable holding the data to be sent and the length of this data. This function returns so many responses. However the most important of these is *ESP_OK*, which indicates that the data sent has been successfully delivered to the receiving unit. The second function is *esp_now_register_send_cb*, and registers a callback function triggered upon sending data from the ESP32 unit using ESP-NOW. This callback function detects the status of the enumeration *esp_now_send_status_t*.

If the status of that enumerator was *ESP_NOW_SEND_SUCCESS*, it means that data has been delivered successfully to the receiver. However if its status was *ESP_NOW_SEND_FAIL*, it means that data was not successfully delivered to the the receiver. Consequently, based on using such functions, it cis clear that the ESP-NOW protocol provides its own authentication technique for data transmission without the need for using additional programming as was used with WebSerial remote serial monitor building the laboratory stand in the previous article.

4. PROPOSED SOLUTION

In light of theresults obtained from the second section and on the basis on the brief description presented in the third section for ESP-NOW protocol, this section will introduce the proposed solution for overcoming the problem of the limited range of ESP32 WiFi based wireless communication when only one ESP32 controller is used to communicate with the host controller using the WebSerial remote serial monitor.

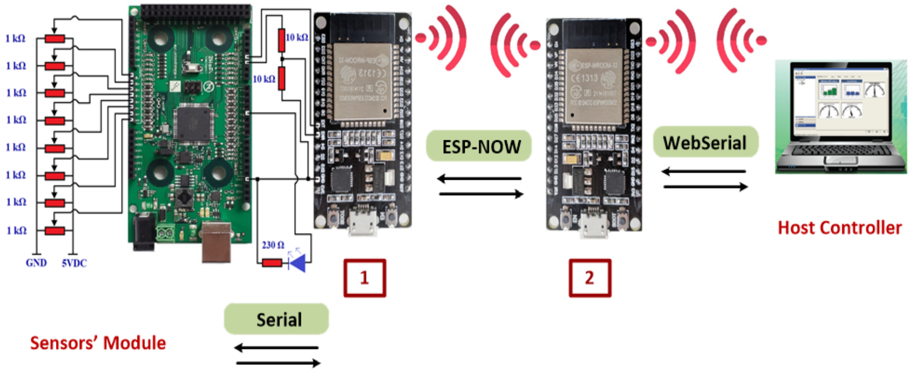
The proposed solution is based on two configurations. The first configuration (Fig. 3-a) is based on only two ESP32 controllers. The first controller (located at sensors' module) will collect the data measured by the sensors through serial communication with the Arduino controller and send it wirelessly using the ESP-NOW protocol to the second controller. The second controller (located near host controller) will serve as an independent WiFi station, communicating with the first controller to collect the data measured using the ESP-NOW protocol and sending the data collected to the host controller using the WebSerial remote serial monitor. Both controllers should be located on the same straight LOS, otherwise a communication failure is highly likely to occur. Accordingly, indoor structural changes such as stairs, corners, doors and others make the first configuration less than convenient for indoor applications.

The second configuration (Fig. 3-b) is an upgraded version of the first configuration, in which additional ESP32 unit/units will be added to the network to perform as switches at points where communication failure is expected due to low RSSI values detected during the planning phase. For the sake of simplicity, this article will discuss adding only one ESP32 switch. It will execute ESP-NOW based on many to one (messages from other ESP32 units to the ESP32 switch) and one to many (messages from the ESP32 switch to the other ESP32 units) communication tasks at the same time.

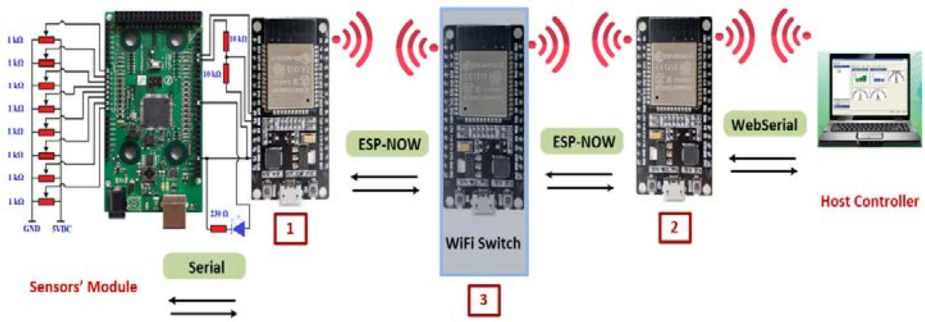
In order to ensure stable reliable communication in this case, the ESP32 switch will be programmed to differentiate between both types of communication with break time intervals, which means that the ESP32 switch will perform two-way half duplex communication. Both configurations can be applied on the five previously described sites in the second section in order to increase the range or the area covered by the wireless ESP32 wireless WiFi network.

In this article, the second configuration will be applied at these sites for the following reasons:

- it provides a longer range as well as wider coverage for WiFi communication in a specific area;
- it enables more ESP32 units to be added, which will perform as switches in the designated area with a very simple program uploaded to these units, without the need for conducting major changes at the program uploaded to both ESP32 units, communicating with the sensors or with the host controller;
- adding more ESP32 units to the network increases reliability due to the increased number of possible links for information transaction between the sensors' module and the host controller;
- adopting the second configuration gives the user the opportunity to expand the wireless instrumentation network by upgrading the task assigned to the ESP32 units, performing as switches, to perform as routers collecting measurement data from additional newly installed sensors modules located close to it.

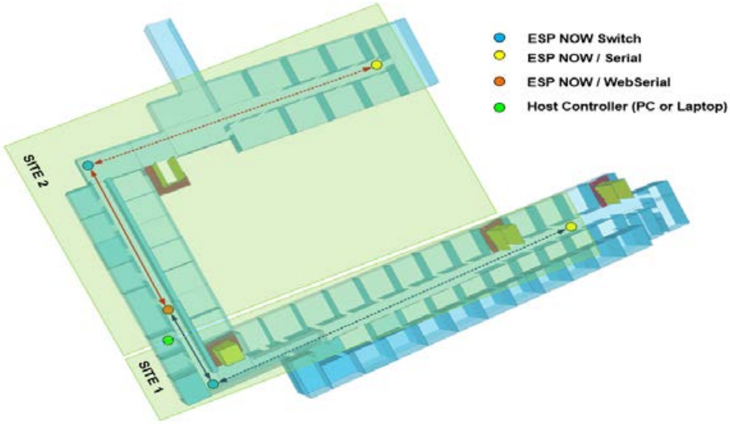


(a) 1st Proposed Configuration

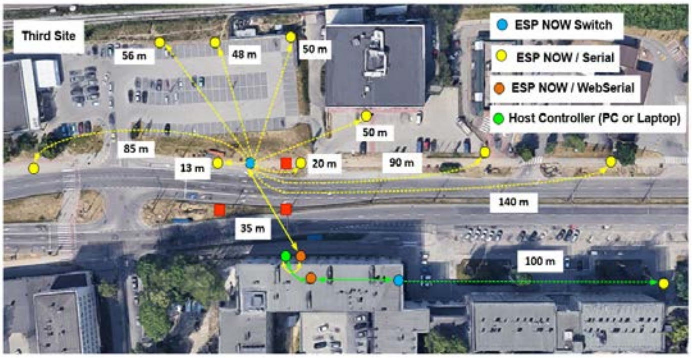


(b) 2nd Proposed Configuration

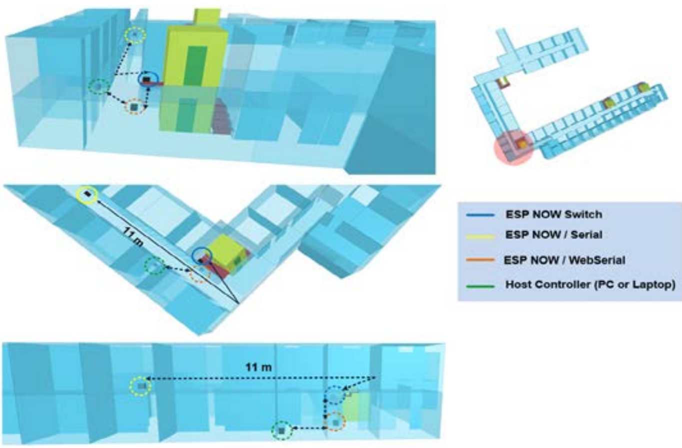
Fig. 3. Proposed solution to increase the range and coverage area of ESP32 WiFi based network. Numbers 1,2 and 3 refer to ESP32 units at sensors' module, host controller and in the middle (performing as a switch) respectively



(a) 1st and 2nd Indoor Sites



(b) 3rd Outdoor Site



(c) 5th Indoor Site

Fig. 4. Increased range and coverage area of ESP32 WiFi based network due to application of 2nd Configuration

Figure 4-a is an illustration showing the improvement in the network range and coverage area achieved by adopting the second configuration in the first and the second indoor sites by adding only one ESP32 unit as a ESP-NOW based switch located at the corner of the building.

Figure 4-b demonstrates the increased coverage area at the fourth outdoor site, obtained by adding only one ESP32 unit as an ESP-NOW based switch at a distance of 35 metres from the host controller, which enabled successful authenticated wireless data transaction between the sensor module and the host controller in an area containing several of obstacles (heavy human and car traffic, traction power lines and street lighting poles).

Figure 4-c illustrates how successful WiFi based wireless communication was maintained between the host controller located at a lower room and the sensors' module located on an upper floor by adding an ESP-NOW based switch half-way up the stairs.

5. DISCUSSION

Eventually, after discussing the key elements of this article by describing the problem in hand at the 2nd section, presenting a brief theoritical background for the backbone of the proposed solution (ESP-NOW protocol) at the 3rd section and demonstrating the recommended solution at the 4th section, it would be important to link the three sections together with regard to possible future applications as well as the most important conclusions. As discussed in the 2nd section, indicating the relation between RSSI levels with respect to distance is a very important factor to consider during the planning phase of any ESP32 WiFi based wireless instrumentation system.

The information collected during the planning phase gives the network designer the required knowledge to identify the locations where fortifying switches or routers will be needed. Based on the two proposed configurations discussed in the 4th section and according to the structural properties of the network site, the network designer will determine which configuration to adopt.

According to the solution illustrated manifold in the 4th section, the ESP-NOW protocol showed improved capabilities for performing successful WiFi communication tasks at distances and locations that were difficult to reach when only the WebSerial remote serial monitor was adopted in the network.

These capabilities can be manifested by performing successful wireless communication between multiple ESP32 units located at either the same vertical level (1st and 2nd sites) or at different vertical levels (4th and 5th sites) with considerable structural obstacles such as concrete walls, stairs and lifts in indoor sites or traction lines, road traffic and lighting poles on outdoor sites.

Additionally, using ESP-NOW protocol in conjunction with the WebSerial remote serial monitors in the laboratory stand described in the previous article ensure more secure authenticated data transaction using two techniques. The first technique was explained in detail in the previous article and is based on using Python to access the WebSerial remote serial monitor as a websocket generating an automated response to the measurement data transmitted from the sensors' module to the host controller. The second authentication technique is based on the built-in functions of the ESP-NOW protocol dedicated to authenticating the data sent and making sure it is delivered to the receiving unit.

If the configurations proposed in the 4th section were viewed with regard to possible applications in the field of maritime engineering, particularly on commercial ships, the second configuration will be the most advisable in areas like the engine room and accommodation area, while the first configuration will be the better solution in areas like the main deck. Generally, regardless of the structural nature of the area, the second configuration should be adopted if there are any future plans for expanding the wireless instrumentation network. In the maritime field, measurement and control systems are almost the same on most types of commercial ships, except for several systems that might be needed in a particular type of environment such as an inert gas system on tanker ships. A brief description for the most common maritime measurement and control systems was given in [Abotaleb et al. 2022]. Each of these systems has its own dedicated built-in wired sensors and transmitters supplied by the manufacturer of the system. If any of these sensors was defective or needed to be replaced for any reason, spare parts should be ordered by the ship's owners or managers from the manufacturing company for that system. For this reason and in case the ship's owners decided to adopt wireless technology for measuring data transaction on their ship, it will be very difficult to replace these sensors or transmitters based on wired technology with others based on industrial wireless technologies, such as wireless HART or ISA100.11.a. This difficulty can be manifested in two aspects, operational and economical.

The operational aspect is the possibility of fitting or mounting these wireless transmitters to the system, while the economical aspect is the expected cost for such wireless transmitters exceeding the cost of cabling. Accordingly, the ship's owners will have to consider a coexistence technique between wired and wireless technologies, otherwise they will probably overlook the idea of upgrading to wireless technology, mainly due to the previously explained economical aspect. The coexistence technique between both wired and wireless technologies will be based on collecting all data measured from all transmitters and sensors dedicated to a specific system, immediately sending them wirelessly to the host controller.

In other words, cabling will only exist between the system and its local control panel located a few metres next to it. The wireless module will be mounted at the same local control panel to collect the measured data from all transmitters to the host controller. This leads to the role of both configurations introduced in the third section (based on collaboration between the WebSerial remote serial monitor and ESP-NOW protocol) or even the configuration presented in the previous article (based only on the WebSerial remote serial monitor).

In the light of this discussion, it can be clearly observed that the coexistence between the WebSerial remote serial monitor and ESP-NOW as two WiFi based protocols dedicated to ESP32 controller can facilitate the application of the principle of coexistence between wired and wireless technologies by creating easily expandable wireless instrumentation networks. Here, it is important to differentiate between the two terms: the first (Wireless Instrumentation Networks WIN) was mentioned in the previous article, and the second is Wireless Sensors Networks WSN.

The term WIN was used in this article to describe networks based on the coexistence between wired and wireless technologies as well as the coexistence between different wireless protocols to measure process variables in an industrial plant. In this type of network, it is not a necessary to have an independent wireless sensor to measure a single variable. However, in WSN, each variable has its own independent self-powered wireless transmitter.

6. CONCLUSIONS

- Identifying the relation between RSSI levels and distance is a very important aspect of planning any wireless instrumentation network.
- In ESP32 WiFi based wireless instrumentation networks, based on measurements taken in indoor and outdoor sites, 20 and 40 metres are the maximum recommended distances between the host controller and the ESP32 unit, communicating with the host controller using the WebSerial remote serial monitor for indoor and outdoor applications respectively.
- The collaboration between WebSerial remote serial monitor and ESP-NOW WiFi based wireless protocols leads to the expanded range and area of the wireless instrumentation network.
- The first configuration proposed to use the ESP-NOW protocol in conjunction with the WebSerial remote serial monitor is based on two ESP32 units. The first of these is located as close as possible to the host controller, while the second one is located at the sensors' module. Simultaneous serial communication and ESP-NOW WiFi based wireless communication tasks are executed by the ESP32 unit located at the sensors' module, while simultaneous ESP-NOW WiFi based communication and WebSerial WiFi based communication tasks are executed by the ESP32 unit close to the host controller. This configuration is suitable for implementing wireless instrumentation networks where sensors are located at the

same LOS from the host controller, with the least possible structural obstacles and without future planning for expanding the network.

- The second configuration is an upgraded version of the first configuration based on deploying additional ESP32 units to perform as switches at locations where structural obstacles might lead to communication failure. In addition to the two ESP32 units described in the previous point, the additional ESP32 unit/units will undertake WiFi wireless communication tasks based solely on the ESP-NOW protocol. This configuration is suitable for implementing wireless instrumentation networks with larger areas and higher intensity of structural infrastructure. It is also highly recommended for networks whose future expansion is planned.
- Successful coexistence between different wireless technologies or protocols facilitates applying the principle of coexistence between wired and wireless technologies in the field of instrumentation.
- Using ESP-NOW in a wireless instrumentation network based on the laboratory stand described in the previous article leads to an increased level of authenticated data transaction as the authentication process will be conducted twice, firstly using the technique described in the previous article by the automated Python response to messages received from WebSerial and secondly using programming commands available in ESP-NOW.
- From both an operational and economical point of view, it is advisable to adopt the second configuration proposed in this article for implementing ESP32 WiFi based wireless instrumentation networks in maritime engineering applications, particularly on commercial ships. This topic will be subjected to more detailed research in the near future.

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