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Efficient Peer-to-Peer Unicasting for VANET Architectures via Enhanced Monolithic Protocols

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***Abstract*—With the advent of vehicular networks and the corresponding requirements, developers are faced with new challenges associated with fundamental protocol attributes and capabilities. In our work, we consider ESP-NOW: a connectionless WiFi communication protocol developed by Espressif and featuring short packet (up to 250 bytes) transmission. It is different from more traditional WiFi protocols, as the upper five layers of the Open Systems Interconnection (OSI) stack are simplified to a single monolithic layer. The data does not need to travel through all the OSI- or Transmission Control Protocol (TCP)-specific layers, which measurably reduces overhead, processing delay all while increasing system responsiveness. The presented work targets the considerable research gap in regards to this protocol and constitutes an attempt to dissect it and provide experimental results, which prove to be promising for highly mobile clusters. Relevant developments find great applicability in ad hoc and vehicular communications, where real-time connectivity and sufficient coverage are pivotal in supporting reliable networking. In this paper, we also investigate the usage of a modified 802.11 standard to enable long-range and low-power interfacing amongst networked vehicular nodes.**

***Index Terms*—Vehicular Ad Hoc Networks; Long Range, Real Time Communications**

I. Introduction

Vehicular communications have introduced an entire new spectrum of requirements in terms of real-time interfacing, data heterogeneity, range of connectivity and overhead minimization. This unique category of Mobile Ad-hoc Networks (MANETs), is a key enabler of future intelligent transporting and logistics systems which require the dissemination of data on inter-vehicle communication, road surveillance, traffic information, road condition, and even novel real-time machine vision applications [1] which find a constant increasing degree of applicability in vehicular communications . Efficient ad hoc networking protocols, in conjunction with novel technologies have enabled a vast spectrum of applications, including cooperative vehicular and aerial networks [2]. More specifically, cooperative aerial and terrestrial/vehicular networks can support terrestrial network coverage and capacity enhancements.

However, high node mobility, accompanied with frequent topology changes, unstable links and lack of infrastructure to facilitate coverage everywhere, are issues in hindering relevant implementations [3].

In this paper, we study a specific monolithic communication protocol, ESP-NOW, as a means of achieving real-time and next to zero-overhead communications. Various relevant challenges can be identified, with the most prominent being energy availability, mobility and path planning, the security-QoS tradeoff [4] [5], and positioning of base stations/roadside units where applicable [6]. As mentioned by P. Radoglou-Grammatikis et al. in [7], approaching networking, and more specifically security issues in an Internet of Things (IoT) context is challenging, and relevant developments need to consider application-specific constrains and metrics.

ESP-NOW is a highly efficient, acknowledgement (ACK)-less and connectionless IoT-centered communication protocol. It occupies minimal CPU and flash resources, and can work with both WiFi and Bluetooth. The data transmission mode of ESP-NOW is rather flexible, and includes unicast and multicast modes, which is a key requirement in VANETs [8]. Moreover, ESP-NOW can be used as an independent supportive module to help network configuration, debugging, firmware

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upgrades or general control of IoT devices in real time. There are numerous advantages to ESP-NOW which render it a usable choice due to its lightweight and connectionless nature:

- Quick Response: Post power-on, the networked nodes can transmit data and control other paired devices directly (i.e., without any wireless connection), and the response speed is in the order of a millisecond.
- Low-power: ESP-NOW simplifies networking by incorporating the functionality of several layers into a single one (as seen in Figure 1), which leads to easier communication process and lower power consumption.
- Backhaul connectivity: Assuming a mobile device is connected to a router, it can also establish and maintain a fast and stable ESP-NOW link to keep stable connection even in the case of a faulty router or network failures.
- Long-distance Communication: ESP-NOW supports long-distance links inherently even without modifications to antenna hardware or additions of relaying points. This makes it a great choice for vehicle-to-vehicle communications.
- Multi-node Control: Networks can support multi-hop dissemination of data and control of vehicular devices via ESP-NOW, effectively having an ESP-NOW message relayed to its end-point on-demand.

ESP-NOW boasts extremely low-latency, direct and low-power peer-to-peer communication capabilities, without the need of a router. The presented work constitutes an analysis of this novel and partly monolithic protocol, as well as an attempt to experimentally analyze its attributes and validate its functionality.

The remainder of this paper is organized as follows. Section II documents and surveys a set of existing relevant works. Section III discusses the overall structure of the ESP-NOW messages, as well as the process of initializing the link between a set of peers, the process of adding a peer, and lastly it discusses security issues. Section IV discusses our overall implementation and provides a description of the utilized system. Section V describes the experimental setup used to perform our tests, and presents the results obtained in terms of power draw. Section VI discusses the results obtained during our experiments, and provides additional insight on the achieved data exchange. Lastly, Section VII concludes the paper with some final remarks.

II. Related Work

N. Dutta in [9] targets the issue and challenge of information dissemination amongst peers in vehicular ad hoc networks. The authors of this paper, propose a distributed peer-to-peer architecture capable of accommodating information dissemination in such networks. The novelty of their work can be attributed to the consideration of the mobility and occasionally limited connectivity of the nodes in a typical vehicular network. The purpose of the proposed architecture is the design of a highly scalable scheme. The approach followed revolves around splitting the ad hoc network into distributed, unique physical zones. Then, the scheme involves using consistent hashing to map both nodes and the data itself, to unique identifiers in a distributed hash table, which in turn enables the provision of scalable look-up services.

Y. Sun et al. in [10] proposes a cross layer routing protocol which is designed to operate with Cognitive Radio (CR) Ad Hoc Networks, in line with the requirements defined in [11]. Their communication protocol exploits the passage of CR performance information from the Physical/MAC layers up to Network layer as contributing factors within the route selection algorithms. The performance of the proposed protocol is investigated via simulations and the results confirm its favorable operation within ad hoc network environments. This is quite similar to what ESP-NOW attempts to implement, but with the addition of cross-layering as a routing metric.

In [12] C. Cheng, aims to tackle the issue of achieving cooperative connectivity for vehicles as a means of sharing and retrieving information in a distributed manner to bring about a more intelligent logistical and transportation landscape, through traffic management services. The author places particular emphasis on cooperatively disseminating and retrieving data from moving vehicles and roadside units efficiently. The ultimate goal of relevant developments is enabling greater safety in the road and disseminating driver and vehicle state data [13]. The main bottleneck affecting such cooperative ad hoc systems is that commonly utilized application layer peer-to-peer protocols typically suffer from low packet delivery ratios, disproportionately long latency, and an overall bad Quality of Service (QoS). The author proposes a two-tier system that integrates VANETs and an infrastructure-based overlay; this architecture is envisaged to achieve a higher QoS, and a measurably reduced latency, accompanied by minimal overhead.

Similarly, P. L. R. Chze and K. S. Leong in [14], introduce a multi-hop routing protocol for secure ad hoc communications. The routing protocol enables the IoT devices to authenticate before forming a new network or joining an existing network, which is implemented in a fashion very similar to that of ESP-NOW. The authentication uses multi-layer parameters to enhance the security of the communication. The proposed routing protocol embeds the multi-layer parameters into the routing algorithm, thus combining the authentication and routing processes without incurring significant overheads. The multi-layer parameters include a unique User-Controllable Identification, users' pre-agreed application(s), and a list of permitted devices, thus saving resources by maintaining smaller routing information. Experimental and field tests were conducted with results showing that our secure multi-hop routing is suitable to be deployed for IoT communication.

T. N. Hoang, et al. in [15] present an indoor voice communication system based on ESP-NOW, a peer to peer network protocol powered by Espressif. The system is implemented on a System on Chip (SoC) ESP32; with such hardware and firmware, the targeted application of the network is supporting a quick response communication in short range areas including factories, hospitals or offices. In order to minimize the cost and power consumption the final product must undergo a trade off

in range but still satisfy a low latency communication.

A very interesting piece of work is presented by D. Yukhimets et a. in [16], where the authors propose a new approach to the implementation of open distributed automatic control systems, exchanging data via ESP-NOW. Due to the used data transfer protocol, it became possible to quickly and losslessly transfer data packets between computing nodes, which favorably affected the operation of the entire system as a whole. The solution proposed in the work allows the use of distributed automatic control systems (ACS) to control complex industrial objects.

Continuing, S. M. Koushik et a. in [17] present a Wireless Sensor Network (WSN) data logger system for collecting data accurately from an agricultural field. The authors engage in ESP-NOW enabled data collection to apply machine learning and prediction algorithms accurately compute the amount of fertilizer, water and other manures required for yield optimization.

Lastly, D. Eridani et al. in [18] provide rather useful comparison results of ESP-NOW, WiFi, and Bluetooth as wireless Local Area Network (LAN) protocols. These protocols have been widely implemented on IoT devices. Inconsequential use of these protocols in areas that are not appropriate according to the characteristics of the protocols will cause problems such as fast battery drain, transmission speed is too wide with small data sent, and so on. For this reason, it is important to conduct a comparative study, to obtain information on the performance comparison of each protocol. The authors compare each protocol from the point of view of point-to-point transmission using key performance indicators such as maximum range, transmission speed, latency, power consumption, and resistance to obstructions using built-in and external antennas. Experiments were done with an equivalent testing method using the same components or tools. The data obtained were used to compare each protocol using a descriptive quantitative method by presenting the data in numerical, graphical, or descriptive form. The results of this paper are expected to be used as a consideration for which protocol is suitable for its implementation by providing an overview of the advantages and disadvantages of each protocol.

III. ESP-NOW Protocol Attributes

ESP-NOW is a connectionless, monolithic communication protocol, occupying the upper three layers of the Transmission Control Protocol (TCP)/Internet Protocol (IP) stack, and the upper five layers of the Open Systems Interconnection (OSI) model correspondingly. This parallelism is visualized in Figure 1.

As expected, ESP-NOW does not use acknowledgements (ACK-less protocol) and does not perform handshake during the connection establishment. Also, it supports no retransmission in case of error or packet loss. If information is lost, it cannot be recovered. In other words, this protocol is (like the UDP) unreliable yet incredibly fast and with minimal control overhead. It is possible, however, to implement application-level reliability, as the link is fully bidirectional.

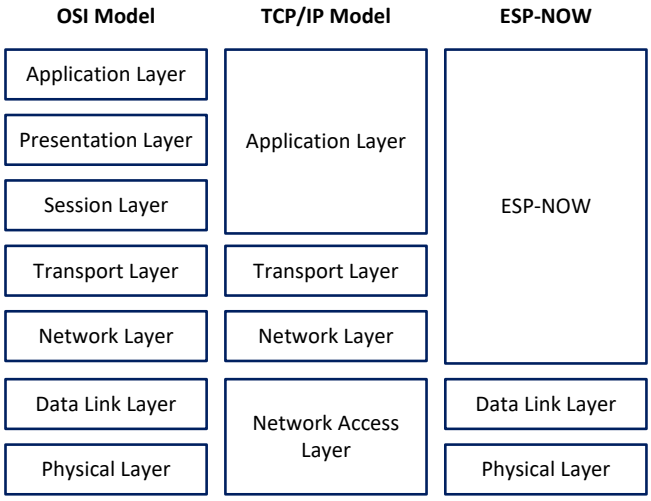


Fig. 1: ESP-NOW Protocol Stack

ESP-NOW requires in the form of an ID is the MAC address of the peer unit(s). As a result, the header of each package is very small in relation to the payload, as shown in the analysis of the ESP-Now package.

The ESP-NOW protocol adopts a ”flat” hierarchy which, among other things, structurally simplifies it and allows full duplex communication to be implemented easily. In an ESP-NOW link, there is no master-slave relationship between the communicating entities, which is the case with many IoT-specific protocols. Instead there is a two-way peer-to-peer relationship. ESP-NOW does not require a WiFi network connection. The peers communicate directly with each other without the need for an intermediate router - something that further reduces latency and overhead in the communication flow. Note however, that an initial ”match” of the units is required, after which the remaining peer-to-peer connection is established and no handshake is required. The default - basic bitrate of ESP-NOW is 1Mbps.

The ESP-Now communication protocol provides the following services in the wireless connection process:

- Encrypted and unencrypted unicast communication
- Full duplex communication
- Selective encryption for each communicating device
- Up to 250 bytes of load per datagram
- Update the application layer on the sending status (success / failure) via a callback function
- Connectionless, unreliable peer-to-peer communication

The ESP-Now protocol comes with some limitations:

- No broadcast support
- Support for up to 10 encrypted peers in ”Station Mode”. However, multiple unencrypted peers (up to 20) are supported.
- The payload datagram can not exceed 250 bytes.
- ESP WiFi connectivity cannot be used at the same time as the 2.4GHz antenna is used for sending / receiving

ESP-NOW messages.

Below is the structure of the packages sent as defined in the ESP-Now API. The recipient receives the packet at the physical level, which delivers the encapsulated data to the higher-layer services.

A. Message Structure

A condition that must be met for the successful export of data from the received datagram is that the structure of each message must be exactly the same. Although it seems somewhat obvious, every name, and type of variable, along with every variable itself, must be defined in the same way for both the sender and the recipient of each message. Otherwise, the recipient will not be able to decode the messages correctly and information will be lost or received/decrypted/decapsulated incorrectly. For the use-case presented in this paper, the message structure is defined as follows:

Due to its partly monolithic nature, each ESP-NOW datagram contains only a small number of fields. Table I provides information regarding the structure of an ESP-NOW datagram.

The `MAC header` is somewhat different from the standard one, as the `FromDS` and `ToDS` bits of `FrameControl` field are set to 0; furthermore, the first address field is set to the one corresponding to the destination address, the second address field is set to the source address, and the third address field is set to broadcast address (0xff:0xff:0xff:0xff:0xff:0xff).

The `Category Code` field is set to value 127 by Espressif, and it indicates the category of the package creator.

The `Organization Identifier` contains a unique identifier (`0x18fe34`), which is the first three bytes of the MAC address range allocated to Espressif.

The `Random Value` field contains 4 bytes of dummy data which is used to prevents replay attacks.

The `Payload` field is occupied by the payload of each corresponding message.

Lastly, the `FCS` field contains a checksum for the datagram.

Table II describes the payload structure for ESP-NOW.

The `Element ID` field is set to value 221 by Espressif, and it indicates the type of payload.

The `Length` field contains the total length of the Organization Identifier, Type, Version and the Body.

The `Organization Identifier` contains the same value as mentioned previously.

The `Type` field is set to value 4 indicating ESP-NOW from the list of Espressif-specific protocols.

The `Version` field contains the value of the current version of ESP-NOW.

Lastly, the `Body` field contains the actual payload data, in our case the vehicular telemetry.

B. Initialization

Initialization of the ESP-Now protocol is required before establishing a connection between the communicating units. This is done by calling the `esp_now_init ()` function.

As the re-transmission of information via ESP-Now requires the activation of the WiFi antenna of each ESP, the corresponding function must be initialized first. Correspondingly, WiFi should only be turned off after communication has been completed and `esp_now_deinit ()` has been called. When the de-initialization function is called, all information about the link of the communicating units is deleted.

C. Peer Addition

After initialization and before any information exchange occurs, peer must be added. At this stage, they ”see” each other for the first time and make a reconnaissance handshake (thus occurs only once). The function responsible for this is `esp_now_add_peer ()`. It is required to know the MAC address of the peer with whom there will be communication. In order to find out this address, the `WiFi.macAddress ()` function of the `ESP8266WiFi.h` library included in the ESP core can be used. The MAC address is used as a peer addition metric for the ESP-NOW protocol using the following command (note that the MAC address shown below is only an example input): `uint8_t broadcastAddress[]=0xFF,...,0xFF`. This is in inherent limitation of this monolithic protocol: nodes can only communicate with peers whose MAC addresses are already known.

D. Security

ESP-NOW is not focused on safety but on speed. However, some security services are provided by encrypting the transmitted packets if this is desired and the necessary settings are made by the unit developer. According to the ”Security” section in Espressif ESP-NOW API, the CCMP (Counter-mode CBC-MAC Protocol) method is used. The units have a primary master key (PMK) which is used to encrypt local master keys (LMK) based on the AES-128 (Advanced Encryption Standard) standard. This feature is enabled by calling the `esp_now_set_pmk ()` function.

Three Rijndael branch cryptography are selected, block size 128 bits each. AES-128 is implemented through four key steps:

1) Key expansion: Acquisition of Rijndael keys
2) Round key addition: Each byte of information is subject to a logical XOR operation with the resulting key.
3) Loop:
   - Substitute bytes: Each resulting byte is replaced by another according to a pre-agreed two-dimensional table.
   - Shift rows: The last three rows of the table are rotated.
   - Mix columns: Linear mix of four bytes of each column.
   - Round key addition: Each byte of information is subject to a logical XOR operation with the resulting key, as in step 2.

The pre-agreed keys are exchanged between the ESPs at the peer addition stage. The key is set with `esp_err_t esp_now_set_pmk (const uint8_t * pmk);`

Unless the developer sets his own PMK, the field is filled with a default value. An excellent hardware addition to a PMK encrypted system is an external (dec) encryption device

TABLE I: ESP-NOW frame

MAC Header	Category Code	Organization Identifier	Random Values	Payload	FCS
24 bytes	1 byte	3 bytes	4 bytes	7∼255 bytes	4 bytes

TABLE II: ESP-NOW payload

Element ID	Length	Organization Identifier	Type	Version	Body
1 byte	1 byte	3 bytes	1 byte	1 byte	0∼250 bytes

implemented with digital logic gates or even FPGAs since the complexity of the key (hence the security) offsets the cost. Data encryption was not considered necessary for the implementation of this work. Also, in applications with large peers volumes, the use of encryption as mentioned, significantly reduces the number of peers. If the application does not need to be encrypted, it is recommended that the key be left at its default value.

IV. ESP-NOW Implementation

For the implementation of our experiment, data from a flex sensor and an MPU6050 accelerometer were used as transmission test metrics. The core idea is to emulate the transmission of telemetry and sensor measurements in intra-vehicle links. This subsection analyzes the entire process of data extraction for all used message types. We designed two ESP32-based boards to facilitate experimentation using the two modes under comparison. The designs we utilized have been extensively documented in our previous work in [19]. Figures 2a and 2b demonstrate the two setups utilized to concurrently obtain measurements.

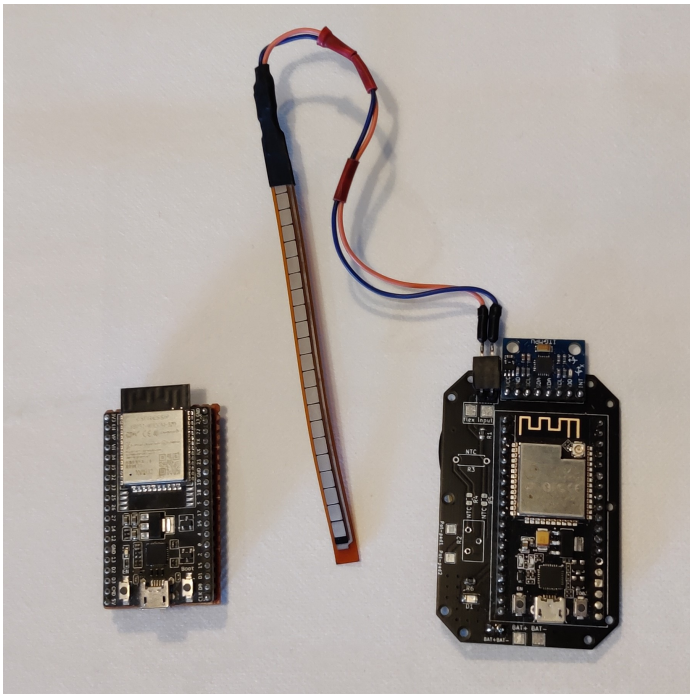
Regarding the flex sensor, data is received as an analog value from the internal ADC. The two following commands are used to read the ADC values using the default 12-bit resolution. This corresponds to a total of number of values equal to $2^{12} = 4096$.

We chose to use a flex sensor and a gyroscope for generating data payload, as in both cases, data integrity and timely delivery are of utmost importance. Moreover, generating data and telemetry using real-life mechanical manipulation of components and/or physical node attributes is highly realistic in the case of vehicular communications.

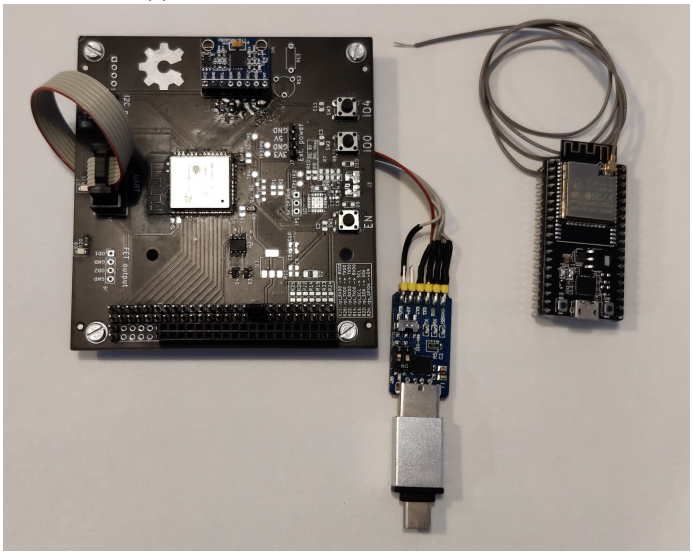
Regarding the MPU6050 gyroscope, values are extracted using the built-in functions included in the `MPU6050.h` library. The library uses quarternions for the angular parameters generated by the MPU6050 Digital Motion Processor (DMP) to avoid the Gimbal Lock effect.

However, because quadratic values have no immediate practical value for the ESP-NOW communication test application, the `mpu.dmpGetEuler (euler, & q)` function is used, which converts values to Euler angles measured in radians. Gravity vectors, yaw, pitch, roll and acceleration can then be calculated.

Finally, the conversions are made from radians to degrees, which are now usable and ready for further processing and transmission. The following is a more detailed analysis of the most important parts of the code, where the accelerometer data



(a) Testbed for nominal WiFi modulation



(b) Testbed for LR WiFi modulation

Fig. 2: The experimental setup utilized in the context of this research, implementing two versions of ESP-NOW based on different WiFi modes.

is harvested and then outputted for plotting and debugging. Algorithm 1 showcases how a transmitting node obtains and prepares its data for encapsulation, and eventually transmission of its telemetry data. Correspondingly, Algorithm 2 demonstrates the high-level process of generating a global message structure, and using it to receive data.

Algorithm 1 Obtaining Tx Data

if $fifoBuffer \leftarrow full$ **then**
    $quatern \leftarrow mpu.GetQuaternion$
    $euler \leftarrow mpu.GetEuler$
    $grav \leftarrow mpu.GetGravity$
    $ypr \leftarrow mpu.GetYawPitchRoll(gravity)$
    $accel \leftarrow mpu.GetAccel$
    $laccel \leftarrow mpu.dmpGetLinearAccel(gravity)$
end if
Roll $= ypr[0] * 180/\pi$
Pitch $= ypr[1] * 180/\pi$
Yaw $= ypr[2] * 180/\pi$
acRoll $= laccel[0] * 180/\pi$
acPitch $= laccel[1] * 180/\pi$
acYaw $= laccel[2] * 180/\pi$
fdat $= read(FlexSens)$

Algorithm 2 Generating Message Structure

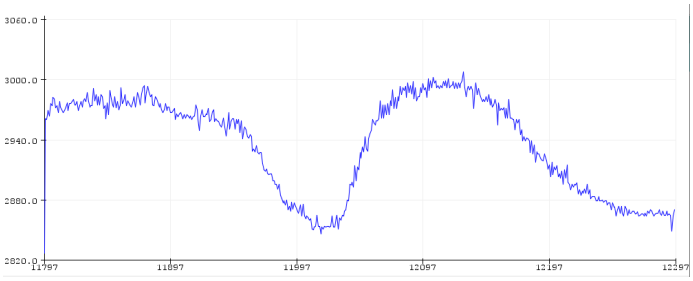
$messageStruct \leftarrow [Roll, Pitch, Yaw, acRoll, acPitch, acYaw, fdat]$
if $DataReception$ **then**
    $RxHandler \leftarrow RxData$
    Roll.RxData $= messageStruct[1]$
    Pitch.RxData $= messageStruct[2]$
    Yaw.RxData $= messageStruct[3]$
    acRoll.RxData $= messageStruct[4]$
    acPitch.RxData $= messageStruct[5]$
    acYaw.RxData $= messageStruct[6]$
    fdat.RxData $= messageStruct[7]$
end if

V. Experimental Results

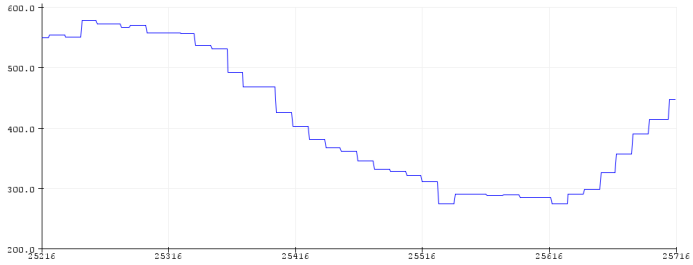
Table III demonstrates the experimental parameters used to benchmark the two combinations: ESP-NOW under the 802.11b and 802.11LR modes respectively.

TABLE III: Experimental Parameters

Experimental Parameters	**Test #1**	**Test #2**
Relative Node Velocity	8 m/s	8 m/s
Communication Protocol	ESP-NOW	ESP-NOW
WiFi Standard	802.11b	802.11LR
Frequency	2.4 GHz	2.4 GHz
Max. Datarate	2 Mbps	0.25 Mbps
Max. Tx Power (100 meters)	2.5 W	2 W
Max. Rx Power (100 meters)	0.28 W	0.2 W



(a) Transmitted Data



(b) Received Data

Fig. 3: Transmission and reception of telemetry data over ESP-NOW in 802.11 LR mode using mobile nodes.

After defining the message structure, initializing and adding the peers, the units are ready to exchange data. The variables to be sent are encapsulated in transport level packages with the MAC addresses of the respective units as the sender and recipient address. The data is sent by calling the `esp_now_send ()` function. In addition to this function, `esp_now_register_send_cb` is used which provides feedback on the sending status. Specifically, it returns `ESP_NOW_SEND_SUCCESS` or `ESP_NOW_SEND_FAIL` in case of success or failure respectively. This information can be used if application-level reliability is desired. In any case, even if no type of reliability is implemented, this feedback is used as follows: each packet is sent after the `esp_now_register_send_cb` function feedback for the previous outgoing packet has been received. This is done to avoid congestion on the recipient. Note, however: the confirmation provided by this function is a confirmation of a successful shipment and not a delivery.

The measured values in both cases followed an almost linear incremental increase, with usage of the WiFi LR mode managed to achieve a 25% reduction in energy expenditure, at the expense however of data-rates. In Figures 3a and 3b, we can observe the degree of quantization for a signal transmitted and received over ESP-NOW in 802.11 LR mode. Given the fact that absolute synchronization of the two modules' captures was not possible, the later signal is a sub-component of the first one and not a one-to-one map. One can observe however, that while the initial signal (prior to transmission) is sampled appropriately, the received signal indicated a measurable deterioration. Signal deterioration can be attributed to packet losses introduced by mobility and free-space losses. The authors in [20] identify a similar issue affecting LoRaWAN links, and

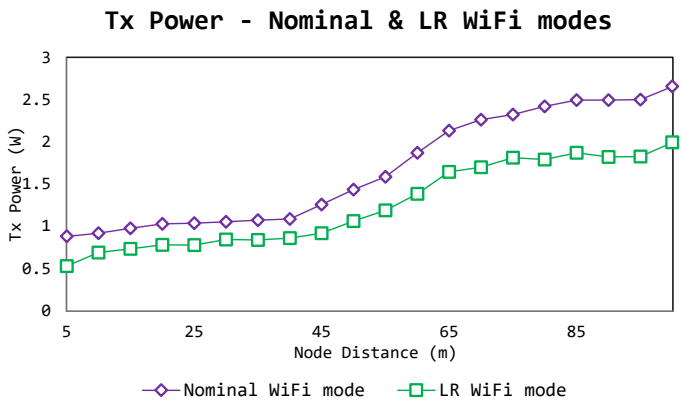


Fig. 4: Comparison of Nominal and LR WiFi modes: Power Consumption

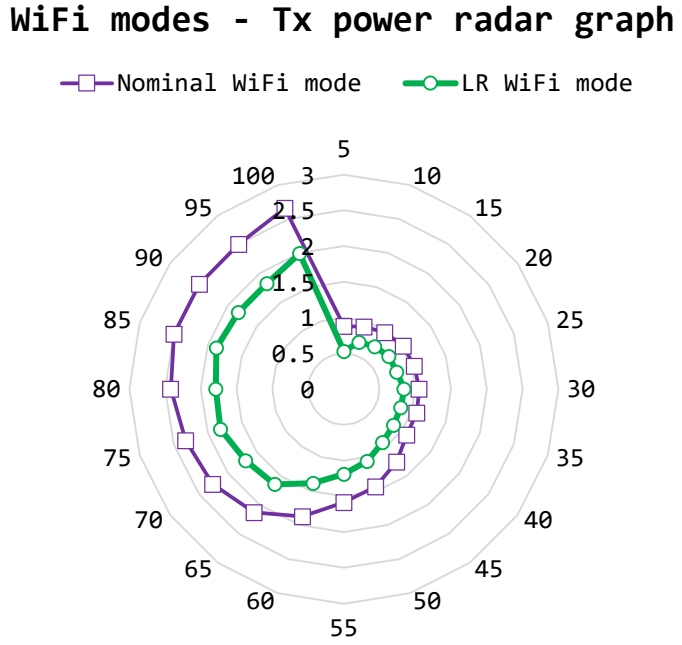


Fig. 5: Comparison of Nominal and LR WiFi modes: Power Consumption - Radar graph

propose a MAC-layer mechanism to tackle it.

The experiment conducted in the context of the presented work validated that dropping the channel bit-rate has tangible effects on energy expenditure, and thus battery lifetime, where applicable. It has to be noted however, that while the bit-rate was dropped by 50%, energy consumption only dropped by 25% (having averaged out all the obtained data from both experiments), peeking at a 28% decrease. Figures 4 and 5 illustrate the decrease in power consumption in a quantitative manner.

As this is a connectionless protocol, the sender has no way of knowing if a package has been delivered to its destination.

As mentioned, the ESP-NOW protocol supports P2P communication and therefore the concept of master-slave relationship does not exist. However, for the sake of simplicity, we will refer to the sender's unit as master and the recipient's unit as slave respectively. On the receiver's side, the same process is applied, in "reverse" to decapsulate the data from incoming ESP-NOW packets.

VI. Discussion

Two distinct scenarios were considered, one for the nominal WiFi implementation of ESP-NOW and one for the Long Range/Low Rate (LR) implementation, which is a patented custom mode that can achieve a line of sight (LoS) range of approximately 1km using the basic on-board antenna of the ESP32, which is an impressive feat in and of itself.

For the first scenario involving usage of the ESP-NOW protocol over a normal wireless medium, the nominal (full bit-rate) WiFi mode was considered. The power consumption required for the successful establishment of links between the two networked nodes increases almost linearly with distance.

For the second scenario involving the LR medium (implementing the proprietary 802.11LR standard by Espressif) a half bit-rate WiFi mode was considered. Support for the proprietary 802.11 LR mode in the ESP-IDF officially began in 2016. Enabling this mode can be done via a simple function call, with no further modifications to the code being necessary: `esp_wifi_set_protocol(WIFI_IF_STA, WIFI_PROTOCOL_LR)`.

It is worth mentioning that 802.11 LR mainly alters data-rate. Furthermore, this mode uses a different modulation, which is not compatible with any other standard WiFi device - this limits the typology of inter-connected devices, and thus achievable network heterogeneity.

The unique combination of modulation, data-rate and the monolithic nature of the applied ESP-NOW protocol managed to increase reception sensitivity by a factor of approximately 200% compared to the nominal 802.11b mode.

It is interesting to note that, while one would expect a "Long-Range" mode to have direct effects on transmission power (if modifying PHY-layer attributes is applicable), it appears that Espressif's 802.11 LR mode does not apply any such Tx power increase. On the contrary, this mode appears to reduce the energy required to transmit the same data over the same distance, effectively maxing out the antenna power draw at a greater distance than in the baseline case.

It can be deducted that irrespective of the custom 802.11 LR mode, the monolithic ESP-NOW protocol is suited for local/small-scale and peer-aware ad hoc networks: while it supports real-time connectivity, it requires prior knowledge of peer devices' MAC addresses in order to perform the initial handshake and the subsequent peer addition described in Subsection III-C. Ideally, this mode-protocol combination would significantly benefit from the use of a backhaul low-proximity connection for the exchange of MAC addresses with local nodes (e.g., vehicles, roadside units, base stations etc.).

Another possible enhancement enabling scalability under this protocol is the use of neighbor-awareness implementing tables, using MAC addresses and Received Signal Strength

Indication (RSSI). Said tables shall be updated periodically, removing vehicles/roadside units upon exceeding a distance/RSSI threshold, and adding them in a dynamic manner upon entering a node's communication range. Lastly as discussed in Section III, an inherent limitation of ESP-NOW the number of unencrypted peers. By resorting to smart forwarding schemes, this issue can be avoided on a network scale - at the expense however of fair resource allocation.

VII. Conclusions

In this work, we have tested the proprietary 802.11LR mode in conjunction with ESP-NOW, and discussed its usability in the context of VANETs. Usage of lower bit-rates can be an effective way to minimize power expenditure. Nevertheless, due to the subsequent drop in data-rate, resorting to LR mode by default can not be considered a highly advantageous design approach. Using this protocol-mode combination appears to be a good practice in applications where high data-rates are not as pivotal as communication range or battery-life extension.

Vehicular sensory equipment and various ad hoc IoT devices using ESP-NOW, or any other real-time communication protocol, can strongly consider reverting to the LR WiFi mode for energy-saving modes in an on-demand manner. Future developments may be directed towards implementing more efficient transmission scheduling for the monolithic ESP-NOW protocol. Efficient scheduling can exponentially decrease energy draw in ad hoc communications, and increase similarly responsiveness [21]. Concluding, a set of potential enhancements for the monolithic protocol under investigation is investigated and proposed.

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