Received January 28, 2020, accepted February 10, 2020, date of publication February 17, 2020, date of current version February 27, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2974214

When Backscatter Communication Meets Vehicular Networks: Boosting Crosswalk Awareness

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This work was supported in part by the European Regional Development Fund (FEDER), through the Competitiveness and Internationalization Operational Programme (COMPETE 2020) of the Portugal 2020 Framework, in part by the National Public (FCT) (OE) through Project MobiWise under Grant POCI-01-0145-FEDER-016426, and in part by the Project Aveiro STEAM city through Urban Innovative Actions under Grant UIA03-084. The work of Marina Jordão was supported by the Fundação para a Ciência e Tecnologia (F.C.T.) through Ph.D. Grant under Grant SFRH/BD/143204/2019.

ABSTRACT The research of safety applications in vehicular networks has been a popular research topic in an effort to reduce the number of road victims. Advances on vehicular communications are facilitating information sharing through real time communications, critical for the development of driving assistance systems. However, the communication by itself is not enough to reach the most desired target as we need to know which safety-related information should be disseminated. In this work, we bring passive sensors and backscatter communication to the vehicular network world. The idea is to increase the driver (or vehicle) awareness regarding the presence of pedestrians in a crosswalk. Passive sensors and backscatter communication technologies are used for the pedestrians' detection phase, while the vehicular network is used during the dissemination of the detection information to surrounding vehicles. The proposed solution was validated through end-to-end experimentation, with real hardware and in a real crosswalk with real pedestrians and vehicles, demonstrating its applicability.

INDEX TERMS Vulnerable road users, driver assistance systems, connected vehicles, passive sensors, energy harvesting, backscatter communication, vehicular networks, decentralized message dissemination.

I. INTRODUCTION

The Internet of Things (IoT) has been reshaping the present and the future of computer networks. A radical evolution on the capabilities of everyday objects is leading to a network of interconnected *things* that, not only collects information from the environment, but also interacts with the physical world to provide services for information transfer, analytics, applications and communications [1].

The associate editor coordinating the review of this manuscript and approving it for publication was Theofanis P. Raptis.

Recently, the integration of IoT with Intelligent Transportation Systems (ITS) has been explored, since it complements the evolution of intelligent transportation systems based on the concept of object-to-object communication [2]. ITS integrates Information and Communications Systems (ICT) with transportation engineering methods to get an improved knowledge of current and future states of the transportation system [3]. Driver assistance systems for on-road vehicles are some of the main use cases for the development of new vehicular control systems. In these systems, mobile network infrastructure is an important requirement for the management of mobility in the cities [4]. Moreover, safety vulnerable traffic participants, *i.e.* pedestrians, bicyclists, and motorcyclists, must not be neglected from these systems. Active collision protection systems with emergency braking and collision mitigation capabilities, despite the technical challenge they represent, can be considered indispensable, to truly decrease traffic-related fatalities [5], [6]. Nevertheless, the success of such services depends not only on the platform used to collect and process the accurate data from the environment, but also on the communication infrastructure. Vehicle-to-Everything (V2X) communication provides the means for communication among vehicles and between vehicles and the infrastructure, whether supported by IEEE 802.11p/WAVE (also denoted as Dedicated Short Range Communication (DSRC)) or Cellular-V2X. However, the communication over a vehicular network (VANET) imposes several challenges, most of them due to the high mobility of its elements [7].

In the IoT context, billions of connected objects are expected to be used and deployed worldwide, which makes difficult, or even impossible, to perform the maintenance of the devices' battery frequently [8]. To enable the growth of such devices, the need for sensor's batteries must be reduced or even eliminated. The challenges of the future of radio communications have a twofold evolution, being one the low power consumption and, another, the adaptability and intelligent use of the available resources. Specially designed radios should be used to reduce power consumption, and adapt to the environment in a smart and efficient way, so that the radio will use the least amount of power as possible to communicate. One possibility to reduce power significantly is to use passive sensors - which can harvest energy to operate without requiring batteries - and backscatter radios - which are very energy efficient when compared with other communication system [9], [10].

In this work, we jointly explore the potential of backscatter radios, passive sensors and vehicular communications to increase the safety of citizens, pedestrians and drivers. The use case here presented was selected from a wide range of applications that could make use of such concepts to increase the road safety. In this work a passive piezoelectric sensor, placed in the surroundings of a crosswalk, is used to harvest energy that can supply the digital control to perform backscatter communication. In the case of detecting the presence of a pedestrian the system starts a dissemination process to the vehicles driving near the crosswalk. Such system aims to increase the driver awareness with respect to the presence of pedestrians in a crosswalk, thus reducing the number of road accidents.

The main contributions of this work can be summarized as follows:

- **Sensing without energy**: we propose an analog circuit composed by a set of piezoelectric transducers that generate energy when a person steps on them, with the management block to rectify and stabilize the energy from the piezoelectric elements. Futhermore, in the same circuit and supplied by the piezoelectric elements, an oscillator is employed to feed the digital control to perform the backscatter modulation, and finally the antenna is designed for the desired impedance;
- **IoT-VANET gateway**: in order to provide the communication between the passive crosswalk sensor and the interrogator/reader, we perform a real-time LabVIEW application that generates a Continuous Wave (CW) to interrogate the sensor. Thus, through backscatter communication (PSK modulation), the information is sent back to the interrogator that detects a peak at the desired frequency and informs the RSU;
- **Decentralized alert dissemination**: we propose a decentralized dissemination scheme for safety messages where each OBU decides, in an independent manner and using only the neighboring information, who is the relaying node. Thus, the number of network nodes relaying the information is minimized, while the delivery ratio is high and the message delay is very low;
- **Real road testbed**: we propose an end-to-end vehicular safety-awareness system, from the crosswalk to the driver, exploring the potential of passive sensor and backscatter communications in a vehicular communication environment. A complete real road scenario is deployed and tested to show the efficiency of the proposed approach.

The remainder of this paper is organized as follows. Section II provides a review of existing related work. Section III presents the proposed system. It gives a brief overview of the overall framework, and then, it goes into detail for each sub-system: from the crosswalk to the road side unit, focusing on the use of passive sensors and backscatter communication; and from the road side unit to the on board units in the vehicles (and then, the driver), focusing on the dissemination of information using the vehicular network. The performance of our system is evaluated in Section IV. Finally, conclusions and future directions are discussed in Section V.

II. RELATED WORK

The proposed solution is a contribution of two topics whose related work is quite distinguishable. Therefore, and for the ease of understanding with respect to each area, we present the related work individually. We start by discussing recent works on passive sensors and backscatter communication, and then we move into the dissemination of safety information in vehicular networks. In the end, we discuss the few works that already tried to bring both topics into the scope of driver assistance systems.

Passive or battery free RFID sensors are an attractive option for Wireless Sensor Networks and RFID applications, because they do not need any maintenance requirements. This is due to the fact that passive sensors do not use a battery for power storage, since energy is harvested from several sources. Examples of these sources are solar [11], motion or vibration [12], ambient RF [13], or an RF signal generated by the RFID reader.

The main difference between passive and active wireless transceivers is the backscatter modulation [14] for the uplink. In backscatter communications, the tag reflects a radio signal transmitted by the reader, and modulates the reflection, by controlling its own reflection coefficient, and with this presenting different load values to the antenna [15]. The load modulator is usually a switching transistor that normally changes between two different impedances. By switching the antenna impedance between those two values, the tag can binary modulate the RF signal and scatter it back to the reader. An energy harvester and power management circuitry are responsible for collecting sufficient energy to power the tag and any additional sensor. The modulation schemes frequently used are Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) [16], [17], although high order modulators have been reported [18].

However, there are some applications where reader-delivered RF power is not suitable or it may not be the best option. When available, piezoelectric transducer is considered a potential choice due to its high energy density when compared with electromagnetic solutions as is the case of RF power. In [19], Lallart points an energy density of $35.4\,\mathrm{mJ\,cm^{-3}}$ for piezoelectric and $24.8\,\mathrm{mJ\,cm^{-3}}$ for electromagnetic.

Due to the reasons enumerated previously, many works have explored the material capabilities and the human walking movement to harvest energy for different applications. The work developed by Shenck Et. al. in [20] presents a self-powered, active RF tag that transmits a short-range, 12-bit wireless identification code while the bearer walks. Once the piezoelectric generates high voltage peaks, it is necessary to design Piezoelectric Vibration Energy Harvester (PVEH), in order to have a more stable source of energy. The most common circuits in linear techniques consist in full-bridge rectifier or double-voltage rectifier, with capacitive filters to suppress the ripples from the rectified output. Some experimental results show that full-bridge rectifiers have higher power efficiency than double-voltage rectifiers; however, double-voltage circuits are suitable for usage at a higher voltage range [21].

In terms of crosswalk detection, in [22] is presented a system to detect pedestrians' in crosswalks using camera images and convolutional neural networks. When the system detects a pedestrian in the crosswalk area, by analysing the camera images, a message is sent to the high-level decision maker subsystem to the car control pipeline, in order to correct the car behaviour, for autonomous cars. A pedestrian collision warning system is proposed in [23] based on sensor fusion of a monocular camera and a millimeter wave radar. To detect pedestrians, the method assumes that when objects are moving in the crosswalk area, the system evaluates as pedestrians, under certain circumstances.

The pedestrian detecting system is important, but equally important is the communication infrastructure that must efficiently disseminate the information to drivers within the relevant area. The delivery of warning messages requires fast and reliable mechanisms. The works in [24], [25] use the distance as the only metric to select which nodes are going to disseminate the message, without considering the relative position of the vehicle when compared to the crosswalk, which can induce the choice of redundant nodes. In [26] the authors consider the available bandwidth to chose the best nodes to disseminate the emergency message. The works in [27], [28] consider the existence of specific control messages to coordinate the process to choose the nodes disseminating the messages.

With respect to driver assistance system, which includes the collision prevention and avoidance mechanisms, most of the works have been focusing on the approximation between vehicles, without considering the Vulnerable Road Users [29]–[32]. The work in [33] proposed an advance model for collision avoidance that serves for pedestrians and bicyclists. It uses the "sliding force" concept to collision avoidance and it reduces the complexity of the model. The work in [34] presented a system for predicting probable vehicle to pedestrian collision, based on a communication scheme between the VANET and the LTE network's location service to retrieve position information about pedestrians. The detection algorithm runs at the RSUs, which play the role of controllers in collecting data, running the algorithm, and warning the cars. In [35] a framework uses a collision estimation algorithm, together with smartphones, to sense the surrounding events and provide alerts to drivers. This solution uses estimation and does not work with sensors to improve better precision. More recently [36] proposed a location-based urban vehicle network for IoT data transmission in the urban environment. Nevertheless, this work is proposed to perform the non-real time data gathering task, while real-time is an important requirement in vehicular safety environments.

To the best of our knowledge, so far only two research works explored the use of backscatter communication in vehicular environments, and none of them are exploring this concept to increase the safety of vulnerable road users. The work in [37] proposes a backscatter communication between two cars with the purpose of detecting the proximity between them in parking situations. In [38] backscatter technology is used for vehicular positioning purposes, complementing the information given by the GPS.

III. SYSTEM ARCHITECTURE

A. OVERVIEW

The vehicular safety system proposed in this paper aims to increase the awareness of drivers to the presence of pedestrians around a crosswalk, by means of backscatter communication and through vehicular communications. In this work relevant information is transmitted to the driver by the means of a mobile phone, however such information can be integrated in the vehicle's Advanced Driver-Assistance Systems (ADAS) or even used by autonomous vehicles without interference or awareness of the driver. The use case

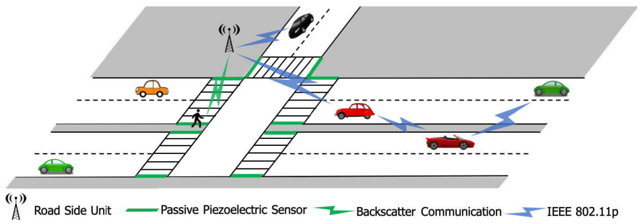

FIGURE 1. Scenario of application.

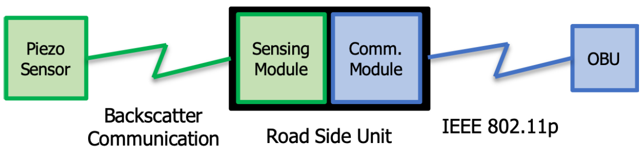

FIGURE 2. System architecture: block diagram.

scenario is depicted in Figure 1. Each crosswalk is equipped with a passive sensor that, when stepped by the pedestrian, or any other vulnerable road user, informs the Road Side Unit (RSU). It is important to notice that one RSU per intersection is enough due to the possibility of identifying which sensor is being activated (and therefore, which crosswalk).

Once the information reaches the RSU, it must be forwarded to the vehicles that have high probability of traversing the crosswalk. For that, we rely on IEEE 802.11p/WAVE communication, the vehicular communication standard, where each RSU is able to communicate with the On-Board Unit (OBU) in each vehicle. Furthermore, each OBU is also capable of communicating with other OBUs, providing a communication link between every moving element. The vehicular communication framework is based on the solution in use in the PortoLivingLab [39] platform, an urban-scale, multi-source sensing infrastructure deployed in the city of Porto, Portugal. We extend this approach for efficient dissemination of emergency messages.

The block diagram of our architecture is illustrated in Figure 2. In the next sub-sections we detail each block describing the functionalities, the mechanisms and the interfaces. We start by presenting the passive backscatter solution, focusing on the communication between the crosswalk and the RSU. Then we focus our attention in the dissemination process over the vehicular network up to the vehicles near and approaching the crosswalks.

B. FROM THE CROSSWALK TO THE RSU

The proposed architecture consists in a passive crosswalk sensor, capable of detecting when someone steps in the crosswalk, and an interrogator/reader, which allows the communication between the sensor and the RSU. The crosswalk sensor does not require any cable or battery to operate: it uses the energy generated by a human walking to perceive when someone is in the crosswalk; and by performing backscatter communication, it transmits the information to the reader.

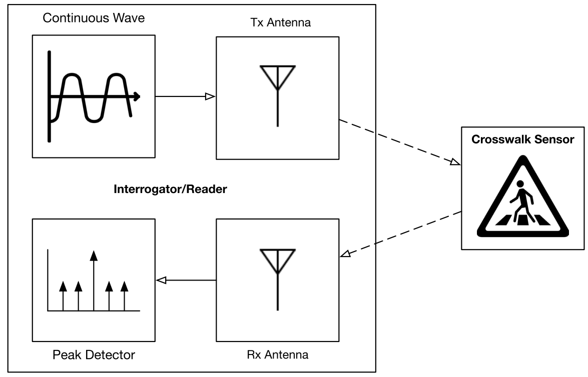

FIGURE 3. Interrogator/reader - crosswalk sensor communication.

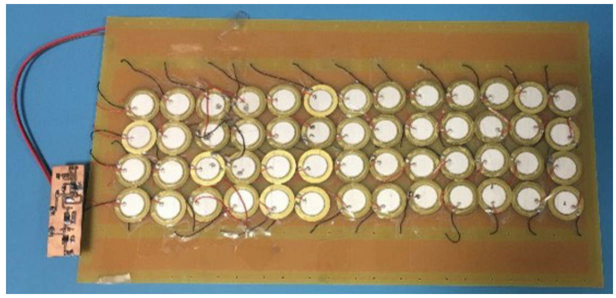

FIGURE 4. Set of piezoelectric elements.

The interrogator/reader is composed by two patch antennas, one responsible from transmitting a CW, and another to obtain the signal provided by the crosswalk sensor. The transmitter and receiver are both developed through the Vector Signal Transceiver (PXIe-5644R, from National Instruments).

In this sense, a real-time LabVIEW application was developed to continuously transmit a CW and to detect the wave reflected by the sensor. The aim of the application is to monitor the frequency range and, when the frequency peak is detected, the LabVIEW application informs the RSU that the sensor was detected. Figure 3 illustrates the interactions between each module.

The crosswalk sensor is composed by the following elements: a set of piezoelectric elements that generate energy when someone steps on them; a block of energy management that is responsible for rectifying and stabilize the energy delivered by the piezoelectric elements; a linear regulator to guarantee the required voltage; an oscillator block to feed the backscatter modulator and to consequently allow the communication; and an antenna to transmit the information.

As mentioned, the piezoelectric elements have the capability of transforming mechanical energy into electrical energy. When someone steps on the piezoelectric elements, which can be seen in Figure 4, electrical energy is generated. From the practical point of view, the whole crosswalk sensor only works when someone steps on it; all the remaining time it is in a sleep mode.

One of the most important requirements for the effectiveness of backscatter modulator is to guarantee a stable voltage

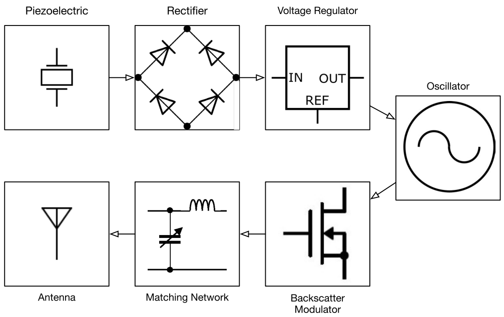

FIGURE 5. Block diagram with the elements of the crosswalk sensor.

of 0.5 V and then an oscillation to perform the communication, which is guaranteed by the regulator.

As explained, the crosswalk sensor is constantly being interrogated by the CW: when no one steps in the piezoelectric elements, the backscatter modulator absorbs the incident wave and nothing is reflected. On the opposite side, when someone steps on a set of piezoelectric elements, the oscillation is produced and the backscatter modulator switches to another state and reflects the CW with a frequency deviation equal to the produced oscillation. This reflected wave is the one that is detected by the reader.

Figure 5 shows the block diagram which illustrates the described behavior of the system. The schematic regarding the PCB which includes the rectifier, voltage regulator and oscillator blocks can be seen in Figure 6.

C. FROM THE RSU TO THE VEHICLE (AND DRIVER)

The proposed architecture between the RSU and the driver consists of a multi-hop VANET based on IEEE 802.11p/WAVE composed of RSUs that serve as entry points to the network for the crosswalk's information. OBUs serving as relays and receivers so that the information may reach the driver. This way, we will be able to expand the awareness of the drivers approaching a crosswalk, allowing them to react ahead of time, even if the crosswalk is not in line of sight.

1) THE RSU AS AN ENTRY POINT

The RSU has two main roles. It serves as an interpreter that reads the crosswalk sensor's information, and it also acts as an entry point for this information into the vehicular network, sending it to other nodes nearby. This unit uses one IEEE 802.11p/WAVE interface to communicate with the vehicular network, and another interface, through backscatter communication, to receive data from the crosswalk sensors. It is assumed that each RSU knows its GPS position.

The RSU receives the information regarding the status of several crosswalks, when associated with an intersection. The RSU will then, for each crosswalk, combine the state read from the sensor with its position. Periodically, a packet following the structure illustrated in Figure 7 is created, and its information is injected into the vehicular network by the RSU that broadcasts the packet to nearby OBUs, as illustrated in Algorithm 1.

Algorithm 1 RSU's Behaviour

```
position ← myGPSposition;
while ∞ do
    foreach crosswalk do
        state ← readcrosswalksensor;
    end
    packet ← buildPacket(state, position);
    sendBroadcast(packet);
end
```

The RSU is capable of broadcasting the information in single mode or burst mode. Since broadcast packets are not replicated by Layer 2, by replicating the information (in burst mode) we are increasing the probability of packet delivery and overcome unstable connections usually observed in vehicular environments. Both strategies will be tested and results will be discussed in Section IV.

2) FROM ONE OBU TO THE OTHER

The OBU is a network element mounted onto the vehicles equipped with one IEEE 802.11p/WAVE interface, one IEEE 802.11 (WiFi) interface and GPS. Each OBU is part of a dynamic mesh of nodes that need to communicate with each other in order to form a multi-hop vehicular network, that has the ability to disseminate information introduced in the network, by the RSUs, to every mobile node that is approaching the crosswalk. Peer communication is achieved using the IEEE 802.11p/WAVE interface, and omnidirectional antennas. Moreover, the OBU also provides an access point to any other devices inside the vehicle through WiFi. Using this interface, it is possible to provide to the end-user the information about the status of the nearby crosswalks, received through the vehicular network. Again, notice that this is only required if the vehicle does not have self-driving capabilities.

The OBU's software can be divided into three categories: Network Handling, Packet/Information Handling and Displaying Information. The software running on the OBU has an execution thread dedicated to each of these main functions. First of all, the OBU has to be able to receive packets from multiple sources, namely RSUs and nearby OBUs, while minimizing packet loss. To do so, a dedicated micro-service listens for packets on the WAVE interface and places them on two dedicated queues - the application queue and the forwarding queue - for post processing according to their needs and functions.

The forwarding queue is consumed by the packet handling thread that decides how to process each packet. It makes the decision of whether or not to forward it, and to which of its neighbour OBUs. This decision process needs to be efficient so that minimal overhead is introduced in the network, while packet delivery shall be high and with very small delays. In this sense, the process is decentralized and needs

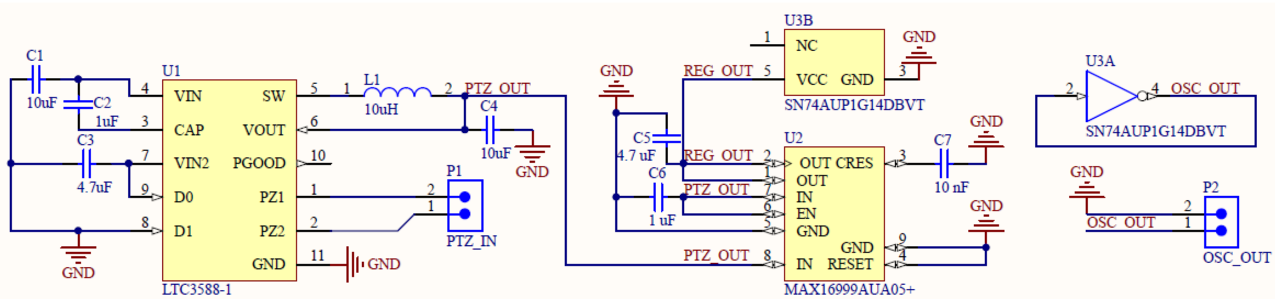

FIGURE 6. Crosswalk sensor schematic.

sequence number	timestamp	source node ID	list of crosswalk states and positions

FIGURE 7. Vehicular network: packet structure.

Algorithm 2 OBU's Information Processing Behaviour

while ∞ **do**
  if *ForwardingQueue not empty* **then**
    $packet \leftarrow getFromQueue$
    if $packet.Crosswalks.positions \leq maxInterestThresh$ **then**
      $propagator, nextReceivers \leftarrow chooseNextPropagator(packet)$
      if $propagator == myID$ **then**
        $packet.sourceNode \leftarrow myID$
        if $strategy == unicast$ **then**
          foreach $nextReceiver$ **do**
            $sendUnicast(packet, nextReceiver)$
          end
        end
        else if $strategy == broadcast$ **then**
          $sendBroadcast(packet)$
        end
      end
    end
  end
end

no exchange of information beyond the already present beacons from IEEE 802.11p/WAVE standard. The Information Processing Behavior is detailed in Algorithm 2.

For each received packet, each OBU needs to make the following decision: should I forward this information? To that end, each OBUs check if the current packet is still relevant, that being if the the distance between the OBU and the crosswalks to which the packets refers to is smaller than (*maxInterestThresh*). In case the decision is to forward the packet, each OBU elects the best propagator from the set of nodes that have received the packet. Ideally, this node should be the one furthest from the source node, under a high degree of certainty that it has successfully received the packet. Every OBU in this set should agree on the best propagator, so that no extra overhead is introduced in the network in the form of redundant information. This process must occur without the need of additional information exchange (Algorithm 3).

When electing the node that will act as the next propagator of a packet's information, each OBU uses the source node identification in the packet, its own GPS position and its neighbour information present in the Node Status Information (NSI) table. The NSI table of a given node is built using the information received from the nearby neighbours' beacons implemented according to the IEEE 802.11p standard. From this table, each node extracts the GPS position of its neighbours and the Radio Signal Strength Indicator (RSSI) to each of them. With this information, each node is capable of identifying the source node, from which it has received the packet currently being handled, and calculate the distance from the source node to itself and to its neighbours.

Given the distance and RSSI of itself to the source node, the node handling this packet is able to estimate the RSS from each of its neighbours to the source node, through a distance to RSSI conversion function, for vehicular environments [40]. This value is then compared to a minimum threshold required for communication (*minThreshComm*), which has been determined through real measurements in the real vehicular network in Porto [39]. Finally, the OBU divides the set of neighbour nodes, excluding the source node, in two sets: the nodes with an estimated RSSI to the emitter above the reception threshold, and therefore should have been able to receive the packet from the source node (propagator candidates' set); and the nodes with an estimated RSSI to the emitter below the threshold, and thus should not have received the packet (next receivers' set).

The OBU elects the best propagator from a group containing itself and the propagator candidate set by choosing the node with the lowest RSSI, as presented in Algorithm 3. By doing so, the elected propagator should be the node furthest away from the source node that, within a good degree of certainty, has successfully received the current packet being processed. Therefore achieving a good compromise between delivery rate and network overhead (in the form of repeated packets in the network).

Algorithm 3 Elect Propagator Function

```
function CHOOSEPROPAGATOR packet
returns propagator,nextReceiversList
neighbours ← getNSI()
myPosition ← getGPSposition()
sourceNode ← packet.sourceID
foreach neighbour in neighbours do
    neighbour.pos ← neighbour.getGpsPos
    neighbour.rssi ← neighbour.getRssi
    neighbour.distanceToSourceNode ←
    distance(neighbour.pos, sourceNode.pos)
    neighbour.rssiToSource ←
    estimateRssi(neighbour.distanceToSourceNode)
end
threshold ← minThreshComm
propagator ← myID
foreach neighbour in neighbours do
    if neighbour != sourceNode then
        if neighbour.rssiToSource < threshold then
            nextReceiversList ← neighbour
        else
            if neighbour.rssiToSource <
            propagator.rssiToSource then
                propagator ← neighbour
            end
        end
    end
end
```

This process should produce the same propagator when executed in all OBUs that received a given packet, and only the OBU that elects itself as the propagator will forward the packet to the next receiver set. This can be done through unicast to each node in the set of next receivers, or by broadcasting the packet. Both strategies were tested and the results will be discussed in section IV. This process ends when a configurable distance away from the crosswalks is reached.

3) DISPLAYING THE INFORMATION

The information regarding the crosswalks' position and state needs to be presented to the user inside the vehicle to serve as auxiliary information to the driver. In order to achieve this, packets in the application queue are processed by a different thread that decides whether any of the crosswalk's information contained in it are relevant for the vehicle's driver.

This decision process uses GPS and heading information, and takes into consideration if the mobile nodes are heading in the opposite direction and away from the crosswalk. If so, the crosswalk should be considered not relevant.

Finally, the selected packets are transformed into an application compatible format and broadcasted to the WiFi network, so that any devices connected to the OBU's access point may use this information. These end-user devices consuming the crosswalk status information may be integrated into the infotainment system of the vehicle. However they can also be displayed using an independent device, such as a mobile phone, connected to the WiFi network provided by the vehicle's OBU access point.

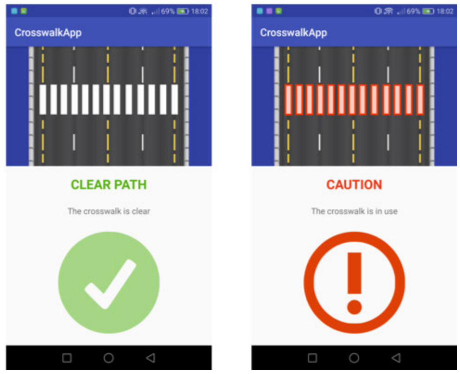

FIGURE 8. Notifying the driver.

In order to offer a full end-to-end solution, an Android application was developed to warn the driver about the presence of vulnerable users. This application listens for packets and notifies the driver about the status of the next crosswalk. A screenshot of both status is illustrated in Figure 8.

IV. PERFORMANCE EVALUATION

This section evaluates the entire system, from the crosswalk up to the driver. Following the same rationale, we divide the analysis in two parts. First, we assess the performance of the passive sensor and backscatter communication. Then, we validate the election and dissemination processes inside the vehicular network. Finally, we present the overall system in practice.

A. CROSSWALK SENSOR

The test of the multiple elements of the crosswalk sensor require a setup composed by the piezoelectric transducers and an oscilloscope (RTO 1022 from Rohde & Schwarz), as can be seen in Figure 9.

As described previously in Figure 5, the crosswalk sensor is composed by different elements. The first element is the set of piezoelectric transducers, which can be seen in Figure 4. When someone steps on this board, it generates energy by the form of two voltage peaks, one negative and another positive. The energy can be extracted depending on the way how the set of piezoelectric elements is stepped. To better understand the dynamic range that may be produced by the board, an extensive experimental validation was realized by different people walking through it. In this way, it was possible to understand that the negative peak is around -8.3 V and the positive one is near 26.5 V. Figure 10 presents the results of some iterations, more precisely three steps.

The piezoelectric response is then managed by two blocks to generate a stable voltage. The nano power energy harvesting power supply (LTC3588-1) is used to generate a stable voltage of 2.5 V with a very low quiescent current

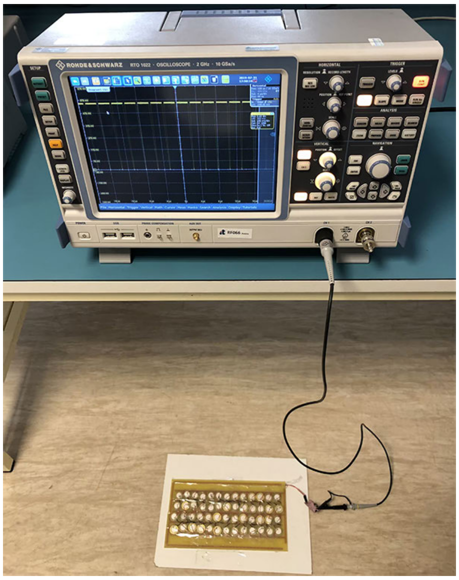

FIGURE 9. Setup to evaluate the crosswalk sensor.

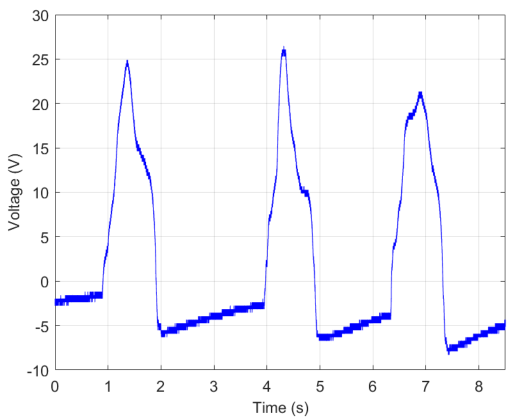

FIGURE 10. Piezoelectric element response after being stepped.

to ensure that one step would provide enough charge to the capacitor, and consequently to the following elements, Figure 6. The linear regulator (MAX16999AUA05+), whose schematic is also presented in Figure 6, receives the 2.5 V and outputs 0.5 V. Those 0.5 V will supply the low power single schmitt-trigger inverter (SN74AUP1G14), which generates a 362 kHz oscillation, as can be seen in Figure 11. Thus, the voltages produced by the oscillator will switch ON and OFF in a transistor (ATF54143 from Agilent Technologies), that will generate the modulation to perform the backscatter communication.

B. BACKSCATTER COMMUNICATION

After presenting the results from the harvesting and management of energy, the following step is to approach the backscatter communication. To provide this step, it is established an outdoor setup to replicate the real environment conditions: the set is composed by the crosswalk sensor, interrogator/reader

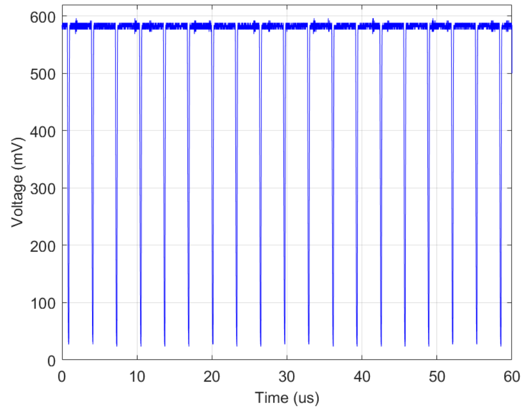

FIGURE 11. Oscillation generated by the crosswalk sensor.

FIGURE 12. Setup to evaluate the backscatter communication.

and the Spectrum Analyzer (FSP, from Rohde & Schwarz) to obtain the power received from the sensor, as can be seen in Figure 12.

In the first test, the crosswalk sensor is placed at a distance of 6 m from the interrogator/reader, and the interrogator transmitted power varied from -4 dBm to 10 dBm. Considering a reader sensitivity of -90 dBm, it is possible to detect the sensor with a transmitted power of 0 dBm (1 mW). The results are presented in Figure 13.

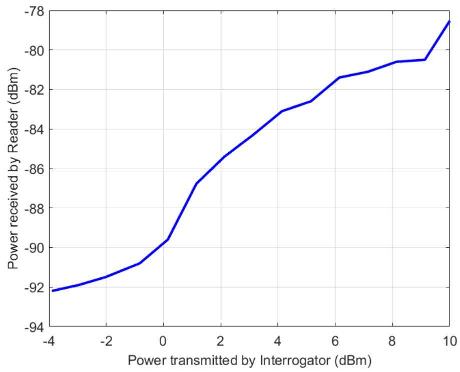

FIGURE 13. Reader received power, varying the interrogator transmitted power, for a distance of 6 m between reader/interrogator and crosswalk sensor.

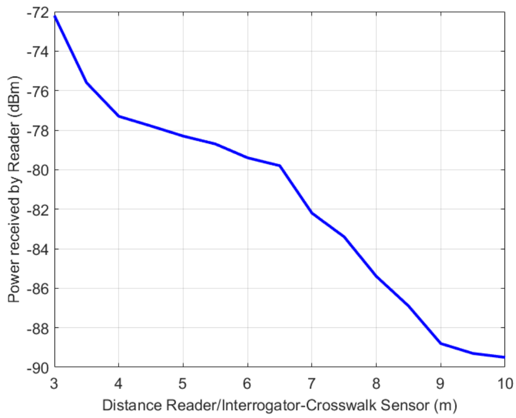

FIGURE 14. Distance between reader/interrogator and crosswalk sensor for a transmitted power of 10 dBm.

In the second test, the interrogator transmitted power is set to 10 dBm, and the power received by the the reader as well as the distance are measured. The results shown in Figure 14 present a read range up to 10 m.

In order to measure the time between the moment that someone steps on the crosswalk sensor, and the moment at which the information is available at the reader a new test was performed. To do that, two signals were connected to the oscilloscope (RTO 1022 from Rohde & Schwarz), one was the piezoeletric output, presented in Figure 10, and the other was an analog output from the reader that is set to the high level when the signal is received. The measured time encompasses the piezoeletric energy harvesting, the backscatter communication and the time used by the reader to process the information. As the energy provided by the piezoeletric highly depends on the strength applied to it, the test was performed by four different people, with weights varying from 42 *Kg* to 76 *Kg*, stepping in the crosswalk sensor. It was asked to the individuals to walk normally over the circuit, and it was not possible to correlate higher delays with lighter weights. This can be explained due to the fact that people walk in different ways, pressing the floor with distinct intensity.

TABLE 1. Crosswalk sensor delay.

Tester	Weight [Kg]	Average delay [ms]
Individual 1	76	965.4
Individual 2	58	884.6
Individual 3	65	801.2
Individual 4	42	982.6
Average delay		908.5

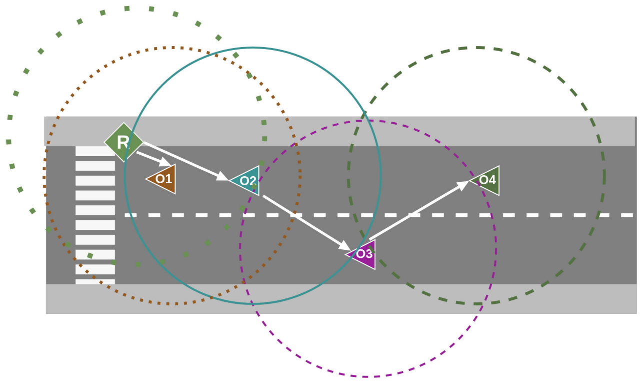

FIGURE 15. OBU positions and expected information flow.

The results, presented in Table 1, show an average delay of 908.5 *ms* with a difference of 181.4 *ms* between the individuals with higher and lower averages.

C. VEHICULAR NETWORK

Evaluation tests to the vehicular network are conducted using real scenario conditions and real hardware, namely 1 RSU **R** and 4 OBUs **O**, displayed as illustrated in Figure 15. The transmission power is set to 33 dBm (the maximum power allowed), resulting in the neighboring set as illustrated by the circles in Figure 15, *i.e.*, RSU **R** had **O1** and **O2** as neighbors, **O1** can contact with **RSU** and **O2**, **O2** can contact with **R**, **O1** and **O3** and finally **O3** can contact with **O4**.

Four performance tests are carried out with different dissemination settings:

- Broadcast without election: the RSU and all OBUs broadcast the information, without any control or election process;
- Broadcast with election: the RSU and the elected OBUs broadcast the information;
- Unicast with one burst: the RSU broadcasts the information, and the elected OBUs forward the information to other OBUs using unicast transmissions;
- Unicast with three bursts: the RSU broadcasts the information three times, and the elected OBUs forward the information to other OBUs using unicast transmissions.

For each scenario, 260 crosswalk events are generated with a 500 ms interval between them, whose information must be sent to every node in the network inside the zone of interest. For each performance test, we extract the following metrics: the delay according to the distance, for one

TABLE 2. 1 hop IEEE 802.11p/WAVE delay versus distance.

Distance [m]	Average delay [ms]
50	0.42
100	0.43
150	0.44
200	0.42
250	0.48
300	0.46

TABLE 3. Packet delivery ratio for single unicast.

OBU	Packet Delivery Ratio [%]
O1	100
O2	98.05
O3	96.98
O4	95.92

TABLE 4. Packet delivery ratio for single unicast (excluding packet loss from previous hops).

OBU	Packet Delivery Ratio [%]
O1	100
O2	100
O3	98.91
O4	97.83

TABLE 5. Packet delivery ratio with broadcast and election process.

OBU	Packet Delivery Ratio [%]
O1	99.62
O2	99.62
O3	99.62
O4	99.62

TABLE 6. Packet repetition with broadcast and forwarder election process.

Average number of received packets	Total number of transmitted packets	Packet Repetition [%]
3.39	778	0

hop and end-to-end transmissions, the percentage of packets that reached the OBUs (here represented as Packet Delivery Ratio - PDR), the total number of packets transmitted, and the average number of repeated packets received per OBU.

First, we start by analyzing the delay of a one hop communication using a WAVE communication link and how the distance impacts this metric. This information is useful to set a ground floor with respect to the delay. Table 2 presents the average communication delay between two OBUs for several distances.It is observed that, for the set of selected distances in which we consider a good coverage probability, the average delay is kept the same and with very small values (this is very important for the dissemination of this emergency information).

Then, we analyze the packet delivery ratio, which represents the ratio of crosswalk events that are received by the OBU, and consequently, displayed to the driver. Table 3 shows a high packet delivery ratio for all OBUs, considering the unicast transmission with one burst. Althouth, as the OBUs move away from the crosswalk, the packet delivery ratio decreases. This occurs because each OBU retransmits the information received from previous elements (OBUs or RSUs) and, if the first propagator (**O2** in this scenario) does not receive all packets from the RSU **R**, it cannot transmit all packets to the remaining OBUs, **O3** and then **O4**.

Table 4 shows the packet delivery ratio if we only consider the number of packets received from the previous elected propagator. This way, we are excluding the packet loss from previous IEEE 802.11p/WAVE links. With these results we can quantify the packet loss on each vehicular hop, which is always very small.

1) COMPARISON OF DISSEMINATION SCHEMES

The previous results were obtained using a unicast forwarding strategy with the propagator election process as described in Section III.C. Acknowledging that a packet delivery ratio of 100% should be achieved in safety and critical situations, we have decided to assess the impact of using broadcast messages instead of unicast messages, along with the proposed election process. By using broadcast messages, we are increasing the reachability of each message, but we are losing reliability on each transmission, because broadcast messages are not acknowledged, and consequently, not retransmitted.

Table 5 presents the packet delivery ratio using a broadcast strategy with the proposed election process. The results are close to 100% with only one packet lost, among 260, between the RSU and OBUs **O1** and **O2**. In addition no other packets were lost during the OBU to OBU forwarding process.

As expected, in a broadcast scenario the number of received packets increases, because each received packet is decoded by all OBUs in the range of communication. Nevertheless, because we are using a controlled replication method, supported by the proposed election process, the packet repetition is the same as in the unicast scheme. Table 6 shows the average number of packets received per OBU, the total number of transmitted packets for the entire network, and the packet repetition (the amount of repeated packets observed in the network). A packet repetition of 0% means that every packet received is the first one of its kind. A packet repetition of 50% means that half of the packets received were already seen. The broadcast strategy with the election process, although not being able to guarantee the reception of each transmission, results in a higher packet delivery ratio without additional overhead.

In a broadcast transmission scheme without any election process, which means that every OBU retransmits the information previously received, the packet delivery ratio is 100% due to the blind retransmissions of packets. Table 7 shows the packet repetition introduced by this strategy: a higher

TABLE 7. Packet repetition with broadcast without election process.

Average number of received packets (per OBU)	Total number of transmitted packets	Packet repetition [%]
3.9	1304	67.17

TABLE 8. Average notification delay introduced by the vehicular network [ms].

Distance	Single Unicast	Broadcast with election	Broadcast without election
Range 1	0.41	0.41	0.41
Range 2	0.82	0.82	0.86
Range 3	1.23	1.23	1.32
Network Average	0.72	0.72	0.75

number of packets were transmitted by the entire vehicular network, resulting in a packet repetition of 67.17% which can be critical in highly dense networks. The higher number of received packets per OBU justifies the high packet delivery ratio observed in both broadcast strategies.

In driving assistance systems, the amount of time elapsed between the detection of an event and the notification in the vehicle is extremely important. Table 8 presents the average delay between the occurrence of a crosswalk event and the driver notification. In this case, instead of representing the delay per OBU, we are representing the delay per communication range, where Range 1 includes OBUs **O1** and **O2**, Range 2 includes OBU **O3** and Range 3 includes OBU **O4**.

The results are similar for all evaluated strategies. In fact they are the same for both strategies with the election process because, when all drivers are notified, they are using the same propagator. In this case, the difference is reflected in the packet delivery ratio. For the broadcast scheme without election, the delay increases because the number of hops for a given packet, at some events, increases. This means that the path followed by the packet is not the shortest, increasing the network delay. However, the higher packet delivery ratio registered in this strategy demands for a tradeoff between packet delivery ratio and notification delay.

2) UNSTABLE CONNECTIVITY

This type of networks, composed of mobile nodes, presents some challenges regarding the link availability. Using either a unicast or a broadcast strategy, in the case of no available communication link, it is not possible to guarantee the delivery of information. For this reason, a second experimental scenario is tested to assess the performance of the triple burst unicast with election strategy. This strategy increases the probability of packet delivery by transmitting, from the application point-of-view, the same crosswalk event using a burst of unicast messages. In this second scenario, OBU **O3** is placed in the limit of the communication range with **O2**, therefore creating an intermittent path with the rest of the vehicular network.

TABLE 9. Packet delivery ratio [%] per OBU with unstable network.

OBU	Single Unicast Burst	Triple Unicast Burst
O1	100	100
O2	98.05	99.65
O3	22.93	31.10

FIGURE 16. Overall real setup and platform.

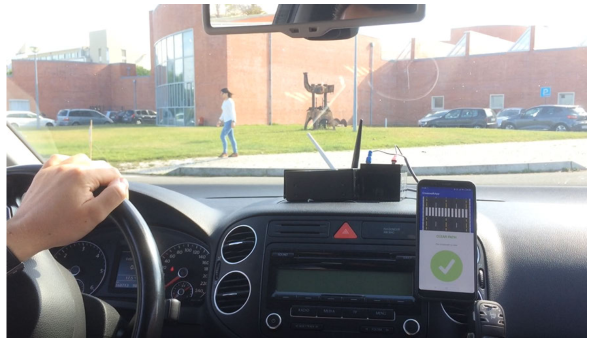

FIGURE 17. Driver information when the crosswalk is clear.

Table 9 shows the packet delivery ratio for both unicast single and triple burst. Using the single unicast burst, **O3** can only receive 22.93% of crosswalk events due to the poor communication link, while with triple unicast burst the same OBU is notified of 31.10% total crosswalk events, representing an increase of 35.8% of event notifications.

D. END-TO-END VALIDATION

This section presents the overall setup for the end-to-end validation. Figure 16 shows the pedestrians and the battery-less sensors (on the right side of the road), the setup for the backscatter communications and the RSU (on the left side), and the vehicle equipped with an OBU (on the front side).

When the pedestrians step on the sensors, the signal is sent to the RSU and then disseminated to the OBU in the vehicle. This OBU, shown in Figures 17 and 18, contains a wireless interface to connect to the mobile phone in the vehicle. As shown in Figure 17, while the sensor does not sense the pedestrian, the driver information shows a clear path. However, when the pedestrian steps on the sensor approaching the crosswalk, the driver information warns for a closed path (Figure 18). In the future, this information will be sent directly to the vehicle's driverless control.

For the final validation we have decided to measure the delay from the moment that a pedestrian steps on the crosswalk until the moment the driver is notified. For that we

FIGURE 18. Driver information when the crosswalk is in use.

TABLE 10. Average end-to-end notification delay (ms).

Distance	Notification delay
1-hop	881.11
2-hops	881.52
3-hops	881.93

considered the delay introduced by the piezoeletric crosswalk sensor and the transmission delay of the vehicular network, when considering the Broadcast with election strategy and several hops of notification (the maximum vehicular communication range was set to 600*m*). The results, represented in Table 10, show that a 1-hop notification takes in average 881.11*ms*, while a 3-hops notification requires 881.93*ms* which means that most of the time is spent in the crosswalk detection system.

This overall scenario has been tested extensively, and the efficiency of message warning through batteryless sensors and in a vehicular network is complete. This is a major advance in the state of the art in the path to driverless and sustainable systems.

V. CONCLUSION

In this work, we have jointly demonstrated and validated the use of different technologies, such as backscatter radios, passive sensors and vehicular communications to increase the safety of vulnerable road users, such as pedestrians. First of all, we designed a passive crosswalk sensor and developed a reader to perform and measure the effectiveness of the backscatter communication, in terms of power to be transmitted as a function of the distance needed for the crosswalks. Through these measurements, we were able to perform a backscatter communication link at a distance of 10 m with a transmitted power of 10 dBm and considering a reader sensitivity of -90 dBm.

Regarding the vehicular network, several dissemination strategies were evaluated to efficiently and with high accuracy send the warning messages to the vehicles approaching the crosswalks. A decentralized scheme for the election of the next forwarder was proposed, and its applicability was validated using either unicast or broadcast strategies. A real vehicular scenario was used for the evaluation process, and the results showed that the election scheme is able to considerably reduce the number of packet retransmissions, without compromising the packet delivery ratio. The results also showed that a tradeoff between packet delivery ratio and delay should be ensured, especially in highly density networks, and poor and unstable communication conditions.

From a general point of view, and comparing the proposed solution with other solutions to detect pedestrians in the crosswalk, as video cameras, radars or light detection and ranging (also known as Lidar), it can be said that it presents: lower costs - the crosswalk sensor does not require any expensive component, and the RSU has a simple architecture as well as the OBU; higher energy efficient - once it uses energy that other way would be lost, and more versatility - besides autonomous vehicles, this solution can be easily implemented in normal vehicles as well as in other transportation methods, motorcycles, bicycles, etc.

With respect to future work, on the backscatter communication, it is essential to work in aspects regarding security aspects. One option is to create code names for each crosswalk sensor, which may be implemented using different voltage regulators that would create different resonance frequencies. On the vehicular communication, new dissemination strategies will be presented considering additional elements in the election process, such as speed, link reliability, and even the use of different communications technologies, such as Cellular-V2X.

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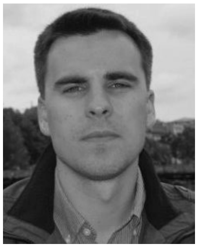

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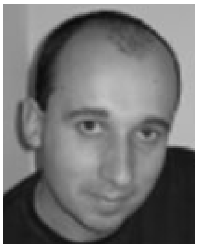

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