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Empirical mapping for evaluating an LPWAN (LoRa) wireless network sensor prior to installation in a vineyard

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ABSTRACT

The main aim of this study was to use Empirical mapping to test the efficiency of local low cost wireless network sensors (LPWAN - Low-Power Wide Area Network) before being applied in real wine-growing conditions. The second aim was to obtain information on the communication distances to be expected from a LPWAN, taking into account the specific needs and real conditions of a vineyard. A hand-held autonomous end-device was specifically built to simulate short messages sent by sensors via a locally designed LPWAN. This device was used to test the quality of the network from different locations within an entire vineyard and also inside the cellar. Two parameters were used to test the quality of reception of the messages: i) The Received Signal Strength Indication (RSSI), which is the received signal power measured in decibels (dB or dBm), and ii) the Signal-to-Noise Ratio (SNR), which is the ratio of the received signal power to the ambient noise power. Maps of signal reception and errors between the observed and the theoretical signal highlighted how vineyard environment (e.g., hedges, topography, and buildings) affects the signal. The results show that the maximum communication distance differed considerably from distances published in the literature. In the open field, the signal, although attenuated by the distance, was received up to 600 meters away, or even more in favourable conditions. Meanwhile, in urban areas the signal was attenuated by buildings and the electro-magnetic environment and therefore communication distances were very short (< 50 m). Empirical mapping has great potential for determining how the local environment affects signal quality and as a decision support tool for identifying the optimal location for the sensors and gateway. With a single well-positioned gateway, such low cost wireless sensor networks (LPWAN-LoRa) could be used by small to medium-sized vineyards to collect information from sensors either outside in the fields or indoors in the vineyard cellar. This paper proposes a very cheap method (< 40 €) for testing and spatialising the quality of a low cost wireless sensor network before its implementation, and it also provides information on zones with low quality reception.

KEYWORDS

wireless network sensor, vineyard, LoRa technology

INTRODUCTION

Many papers have shown the importance of wireless sensor networks (WSN) in agriculture (Subashini and Mathiyalagan, 2016; Jawad *et al*., 2017; Liu, 2018; Thakur *et al*., 2019; Farooq *et al*., 2020). It can be used in both research projects and as decision support for commercial services. WSN can be used for monitoring air temperature for frost/freeze protection (Pierce and Elliott, 2008; Diedrichs *et al*., 2014) with specific applications in orchards (Marković *et al*., 2013) and vineyards (Valente *et al*., 2011), as well as for scheduling irrigation (Haule and Michael, 2014; Lea-Cox, 2012), managing site-specific irrigation (Kim and Evans, 2009; Matese *et al*., 2009), optimising plant growth (Hwang *et al*., 2010), and monitoring farmland (Corke *et al*., 2010) among others. Vineyards have characteristics that favour the use of WSN, like small fields with infrastructure (posts) to attach the sensors to (Morais *et al*., 2008), for different relevant purposes (Burrell *et al*., 2004; Togami *et al*., 2011; Lloret *et al*., 2011; Lopes *et al*., 2015). There is potential for using WSNs in cellars, particularly for monitoring winemaking processes (Costa *et al*., 2007; Anastasi *et al*., 2009; Chinchamalatpure and Sakhare, 2012). The advantage of installing WSN in pre-existing buildings such as cellars is that it would not entail significant additional costs due to minor renovation work being required and to wireless technologies.

Among the range of possible wireless communication technologies (e.g., Wi-Fi, GPRS, Wimax, etc.), LPWAN (Low-Power Wide Area Network, -868 Mhz in Europe) has great potential for a variety of purposes (Lucas *et al*., 2020; Rana and Naveed, 2019), especially in agriculture (Jeyashree *et al*., 2019; Shamali and Radhika, 2019), mainly because : i) it has a low energy consumption, which gives it significant autonomy and limits maintenance constraints, ii) its communication rate, although limited to short messages (approximately 1 to 200 bytes), can deal with the monitoring of most agricultural processes, iii) the cost of the radio chipset is low (< 2 euros) and the subscription cost is reasonable for commercial solutions (< 1 euro/year) and can even be free if it has its own gateway, and vi) the communication distance is large (5-10 km) (Jawad *et al*., 2017). There is therefore good reason to consider the extensive implementation of LPWAN in agriculture and particularly in viticulture. Nevertheless, very few studies related to the use of LPWAN under the specific conditions of viticulture have been reported in the literature (Davcev *et al*., 2018; Silva *et al*., 2019; Spachos, 2020).

The main challenges to overcome before a WSN can be implemented in agriculture are those related to radio signal propagation in conjunction with the variability of the (changing) environment (Kurt and Tavli, 2017). In particular, radio path loss is a key factor to consider in the design of any wireless communication system. This factor is critical because it constrains the maximum possible distances between the end-devices (sensors) of the network and the antenna of the gateway. Signal path loss is essentially the reduction in power density of a signal as it propagates through the environment, which can be caused by many factors, including free space loss due to distance and atmospheric phenomena like reflection, absorption, and scattering components, and to the presence of different obstacles, such as buildings, hills or vegetation. Many studies have investigated the vegetation effect on signal propagation in agriculture (Sabri *et al*., 2013; Kamarudin *et al*., 2010); some of them focused on specific crops like potato (Thelen *et al*., 2005), rice fields (Gao *et al*., 2018), wheat canopy (Li *et al*., 2010), date palm orchards (Rao *et al*., 2016), citrus (Wen *et al*., 2010) and apple orchards (Andrade-Sanchez *et al*., 2007). Grapevine has, however, received little attention until now (Rudeš *et al*., 2018; Correia *et al*., 2017). For this crop, canopy interference effect may be an issue, since it may not be possible to obtain line of sight between end-devices and the gateway because of the trellising system and the resulting vertical positioning of the canopy.

Authors have reported signal strength as a function of distance to be weaker in the presence of canopy than predicted signal strength derived from a theoretical model propagation without any path loss (Sabri *et al*., 2013; Kamarudin *et al*., 2010). It has also been demonstrated that radio transmission in orchards (Vougioukas *et al*., 2013) is only moderately affected by changes in the vegetative growth stage (from dormant to full canopy). However, when trying to quantify the plant/canopy effect of specific cultivation, recent studies have focused on homogeneous environments (the block); as a result, the maximum distance reported is always determined by the size of the plot under study, for example 120 meters in the study by Vougioukas *et al*. (2013) for orchards.

Moreover, with the exception of specific studies on silage or cereal storage (Larsen *et al*., 2011),

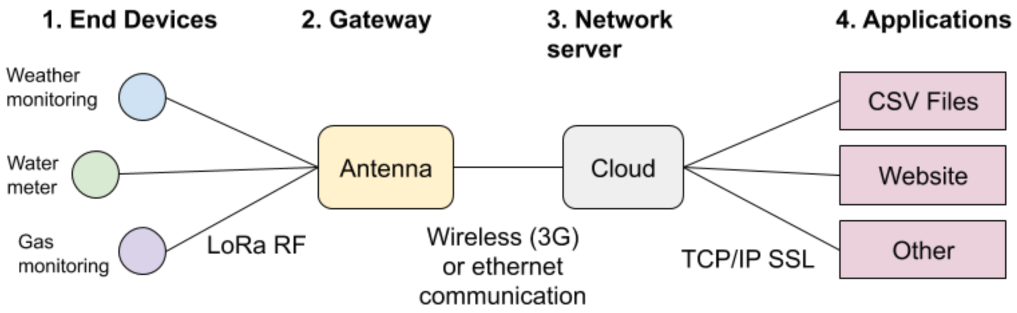

FIGURE 1. General architecture of the LoRaWAN network sensors (LPWAN-LoRa) tested in this study.

there are very few studies on signal attenuation in complex environments like cellars. To our knowledge, there are no references that give specific details about signal attenuation in environments as complex as those of a cellar which have components like tanks filled with grapes, wine must or wine.

Factors likely to affect the propagation of a signal of an LPWAN are multiple, complex and difficult to model and predict when it comes to setting up a sensor network in a real environment. The use of an LPWAN in viticulture raises necessary questions, because vineyards often have complex characteristics, such as vertical canopy positioning and trellising, small plots often separated by tree, hedges and marked topography due to the crops being on hillsides. This environment becomes even more complex when a WSN is used to simultaneously monitor the vine cultivation (plots) and the wine production (in the cellar). It is therefore difficult for a practitioner intending to install an LPWAN to predict the quality of reception under the particular conditions of his/her vineyard or experimental site. This study used a simple, low cost and pragmatic method based on interpolated maps to determine the efficiency of a local LPWAN before being implemented in real wine-growing conditions; the ultimate aim was to verify whether such an approach could be used as a decision support tool for LPWAN implementation in the whole vineyard. To our knowledge, empirical mapping has not yet been proposed to study the characteristics of a network in a complex environment like that of a vineyard, including the fields and cellar. The mapping would need to highlight the real characteristics to be expected of an LPWAN in a specific situation. This study particularly aims at verifying whether the proposed empirical mapping method can reveal: i) the locations with the highest signal reception, ii) the locations where the maximum distance for reception can be expected, iii) the locations where environmental features like hedges, topography and buildings could affect signal propagation, and iv) how the components of a cellar (mainly tanks), in conjunction with their relative location, could affect the spatial distribution of signal reception. The proposed approach is based on two pieces of information: an interpolated map of the observed signal reception quality, and a map of the error between the observed reception quality and the theoretical reception quality obtained by a signal propagation model. The aim of the error map is to highlight the effect of the environment on the reception quality.

MATERIALS AND METHODS

1. Network system

The LPWAN tested in this study was based on LoRa technology (LoRa Alliance). The long-range and low-power nature of LoRaWAN makes it a suitable candidate for smart sensing technology in viticulture. The network usually includes different types of items (Figure 1): i) end-devices (wireless modules generally associated with sensors) which allow messages to be sent through the network; there can be several end-devices within a study area, ii) a gateway which receives messages from all the end-devices and forwards them to the iii) network server with a high throughput (Ethernet or 4G), and iv) applications for storing, exchanging and/or visualising the data on a website, etc.

In order to be able to test the quality of the network within a whole vineyard, a hand held autonomous end-device was used. This system does not have any sensors; it simply allows a short message to be sent from a given site as if a sensor has been positioned there with its own end-device. The hand held end-device was self-built at Montpellier SupAgro using the components listed in Table 1. The system has been designed with a push button to trigger the sending of a message in the LoRaWAN network by an operator. An LCD screen shows the user the code number (ID) of the sent message, among other information. This aspect is important for geolocating the information (see next section). The entire system (Figure 2) was encapsulated in a homemade 3D-printed plastic shell, and it was easily transportable since it measured 10 x 7 cm and weighed less than 0.1 kg. The reader can refer to Thingiverse (2019) to build a similar device. The total price of the end-device was 40 €. Note that commercial solutions, such as Adeunis LoRaWAN Field Tester (Adeunis, Crolles, France), can also be used to test the quality of LoRaWAN networks. Their price varies from 300 to 400 €. However, due to costs and in order to better control the network settings, the homemade solution as described above was preferred for this study.

The end-device was set up to send messages at 5.4 Kbits/sec, with RF TX Power set to 10 dB on the 433 MHz band (limited to meet regulations); in that way, the maximum payload size for each message was 243 bytes (Mekki *et al*., 2019), which was more than enough for the experiment. Note that the bit rate was one of the key parameters, because it directly affected the autonomy of the end-device and, indirectly, the maximum possible distance between the end-devices and the gateway.

2. Acquisition system

The LoRaWAN gateway used was the Things Gateway (The Things Network, Netherlands), which cost 300 €. The practical advantage of this solution was its ability to collect the messages sent by the end-devices and convert and send them via the internet to a cloud server. Under the study conditions, this single LoRaWAN gateway can support 120 end-devices, assuming each of them transmitted 20 bytes every 16.7 minutes (Bor *et al*., 2016). The proposed system uses The Think Network's reference API and default configurations. The spreading factor (SF) was set at the default value (SF = 7) as recommended by The Things Network. The SF influences the message reception distance (Reynders *et al*., 2017). A local server was installed to recover and back-up the data. Data were saved in a .CSV file format.

3. Signal considerations

The intensity of the received signal was determined from the RSSI (Received Signal Strength Indicator) parameter, used to estimate the signal reception quality at the gateway (Cama-Pinto *et al*., 2017). RSSI can be influenced by many factors, such as the surrounding environment, antenna height and transmission power. Therefore, as in Augustin *et al*. (2016), RSSI was used to assess the strength of the signal. RSSI values usually range from 0 dB (very strong signal) to -120 dB (weak signal). A second indicator of signal quality was the Signal to Noise Ratio (SNR), which compares the power of the signal to the power of the ambient noise. It usually ranges from -20 dB (the signal is drowned out by ambient noise) to +10 dB (the signal is very strong compared to the ambient noise). The RSSI threshold can be determined from the theoretical sensitivity of a radio receiver at environmental temperature (Bor *et al*., 2016). This threshold takes into consideration the thermal noise, the receiver bandwidth and the SNR by the underlying modulation scheme. According to the configuration, the minimum RSSI value RSSI was -140 dB, below which no message was considered to have been received.

4. Experimental site

The study area was a vineyard located in a peri-urban area of a city of 10,000 inhabitants (Villeneuve les Maguelone, France, 43.532300, 3.864230, WGS84). The vineyard buildings and the cellar are located within the city. The experiment took place over fields located within a radius of 1 km around the cellar (Figure 3).

For practical reasons (access to the Internet network and electricity supply), the antenna of the gateway was positioned outdoors on a terrace close to the cellar at approximately 4 m above the ground (see next section for more details).

TABLE 1. Components and price of the end-device.

Devices	Function	Manufacturer	Cost
Arduino Uno SMD R3	Microcontroller	Arduino, Italy	20 €
RN2483	Wireless LoRa module	Microchip, USA	11 €
VMA 203	LCD & keypad display	Velleman, Belgium	8 €
868MHz Antenna	Antenna	RS, UK	2 €
Battery 9V	Power supply	Varta, Germany	3 €

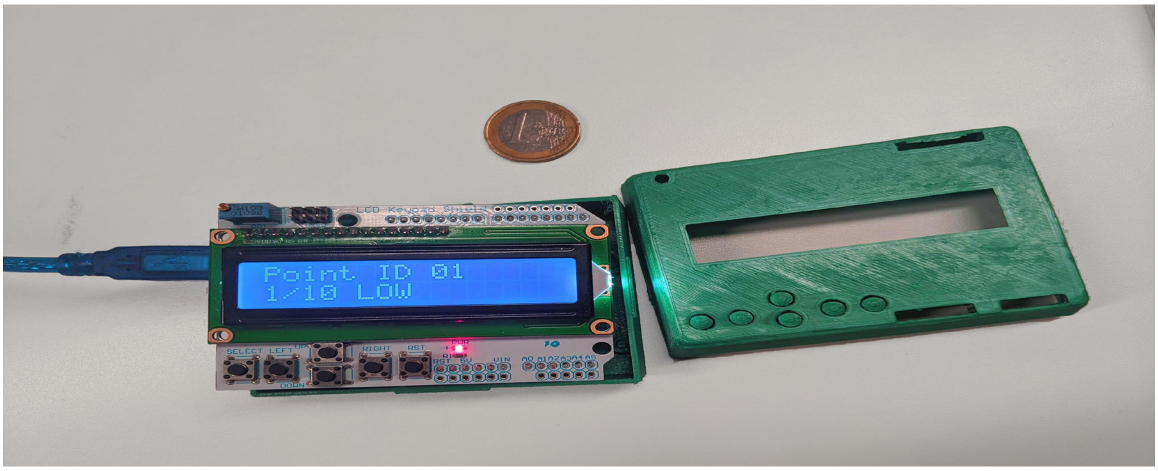

FIGURE 2. Hand held end-device (with its plastic shell) used to send data during the experiment.

Four distinct areas were identified via a visual analysis performed from the antenna position: i) open field corresponding to cultivated fields, vineyard or crop in the line of sight of the antenna, ii) partially hidden field (vineyard or crops) corresponding to areas occulted or partially occulted by vegetation, trees or topography, iii) closed area corresponding to urban areas (city center and courtyard of the domain) comprising stone buildings 5-6 m high with narrow streets, and iv) the interior of the wine cellar. The cellar is an old building, which is 8 m high, 15 m wide and 50 m long. The roof is made of a semi wood and steel frame and the stone walls are 60 cm thick. Inside the cellar, different tanks made out of stainless steel or concrete are used for wine processing.

5. Data acquisition

Sampling was carried out in the whole experimental site with a regular minimum distance of about 50 m between each sample. The sampling scheme was adapted to the sampling zones. In the closed area (city), sampling was conditioned by accessibility; i.e., it was carried out in streets, roads and squares. In the open fields and partially hidden open fields, the area was larger and more homogeneous; therefore, the aim was to carry out sampling in the entire study area with at least one or two samples per plot (Figure 3). At each sampling site, the end-device was positioned at a height of 1.7 m to simulate a position above the trellis system, thus maximising the line of sight of the gateway.

Finally, for indoor acquisitions (inside the cellar), the sampling aimed at testing the effect of the tanks on signal the end-device was therefore positioned in front and behind the tanks at different distances from the gateway. It should be noted that the gateway was located outside the cellar building and therefore the stone wall was a factor which affected all indoor measurements.

At each sampling site, five messages were sent. The gateway collected the RSSI and SNR of each message. When all the data had been collected, the final table contained the following attributes for each measurement site: i) the message ID, ii) the number of received messages (varying from 0 to 5), iii) the mean RSSI of the received messages, and iv) the mean SNR of the received messages. The experiment collected 244 RSSI values distributed over the entire study area (Figure 3). The samples below the reception threshold of -120 dB were recorded as having an RSSI value of -140 dB.

6. Data geolocation

For outdoor acquisitions, the operator was equipped with a GNSS receiver (Etrex, Garmin, Olathe, Kansas, United States) in order to geolocate each sampling site. For each acquisition, the message ID (visible on the end-device screen display) was recorded to ensure that the message ID and its geolocation corresponded. For indoor acquisitions (cellar), a geo-referenced cellar plan was used. The position of each sampling site, along with the sample ID, was recorded on the map by the operator. We verified that the geolocation corresponded to the collected data for each sampling site in a second step.

7. Propagation model

A propagation model was used to predict the theoretical RSSI values between the end-device and the gateway at each sampling site. This model aimed at describing the spatial distribution

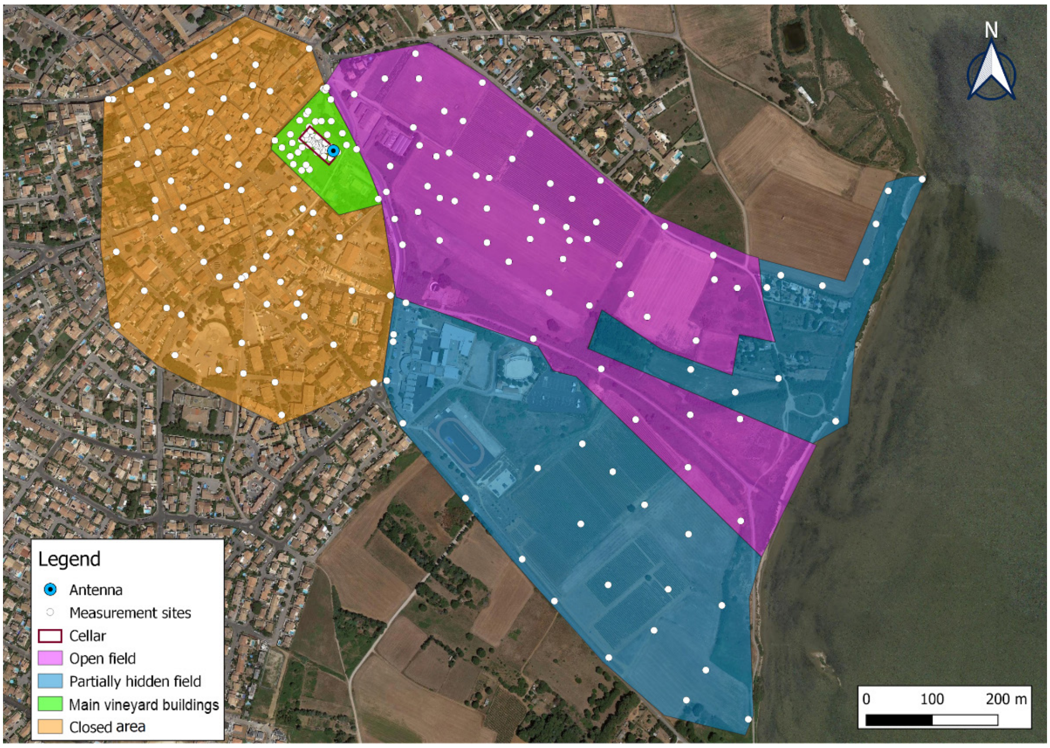

FIGURE 3. Characteristics of the study area and location of the measurement sites.

of RSSI values over the study area when no local environmental factors were assumed to affect signal propagation. The difference (errors) between observed and theoretical RSSI values was expected to highlight how and where local features (e.g., buildings, trees and topometry) affected signal propagation. The log-distance propagation model was used. This model - also referred to as the one-slope model - is a general path loss model that has been used in a large number of indoor and outdoor environments (El Chall *et al.*, 2019). It assumes that path loss decreases exponentially with distance (Correia *et al.*, 2017) (Equation 1):

$$R_{th}(d) = R(d_0) - 10n\ Log_{10}(d/d_0) \qquad (1)$$

where $R_{th}(d)$ is the theoretical value of RSSI (in dB) at a distance d (in metres) from the gateway, $R(d_0)$ is the real value of RSSI measured at a reference distance (d_0) from the gateway and n is the path loss exponent, which usually ranges from 2 to 6 (Kurt and Tavli, 2017). In our study, $R(d_0)$ was measured 1 m from the gateway, and n was obtained from the average of 10 samples taken at different locations in the open field. $R(d_0)$ and n were -47 dB and 2.42 respectively. Once calibrated, the propagation model was used to estimate the theoretical values of each sampling site (Figure 3). The differences (errors) between the modeled and observed RSSI were then calculated for each sampling site.

8. Data processing and mapping

Data mapping was performed using QGIS (Quantum GIS Development, V3, Open Source Geospatial Foundation Project) by importing Easting and Northing values for each sampling site. The same methodology was used to map measured RSSI and errors to determine the difference between observed and theoretical (modeled) RSSI values. Data interpolation was performed using GeoFIS (V0.1, INRAE/Montpellier SupAgro, France). The interpolation method used in this study was based on universal kriging. Semi-variogram analysis and interpolation were performed with GeoFIS (Leroux *et al.*, 2018).

RESULTS

1. Signal quality in the different zones

Outdoors, observed RSSI changed with distance from the gateway (Figure 4). Three zones were considered: open field, partially hidden field and urban area. In the open field, the signal, although attenuated by the distance, was received from distances of up to 600 m, or even more in favourable conditions (lack of obstacles). The theoretical values computed from the propagation model follow exactly the same general trend, thus validating the relevance of the propagation model calibration. In urban areas (closed area), the signal is strongly impacted as from 50 m,

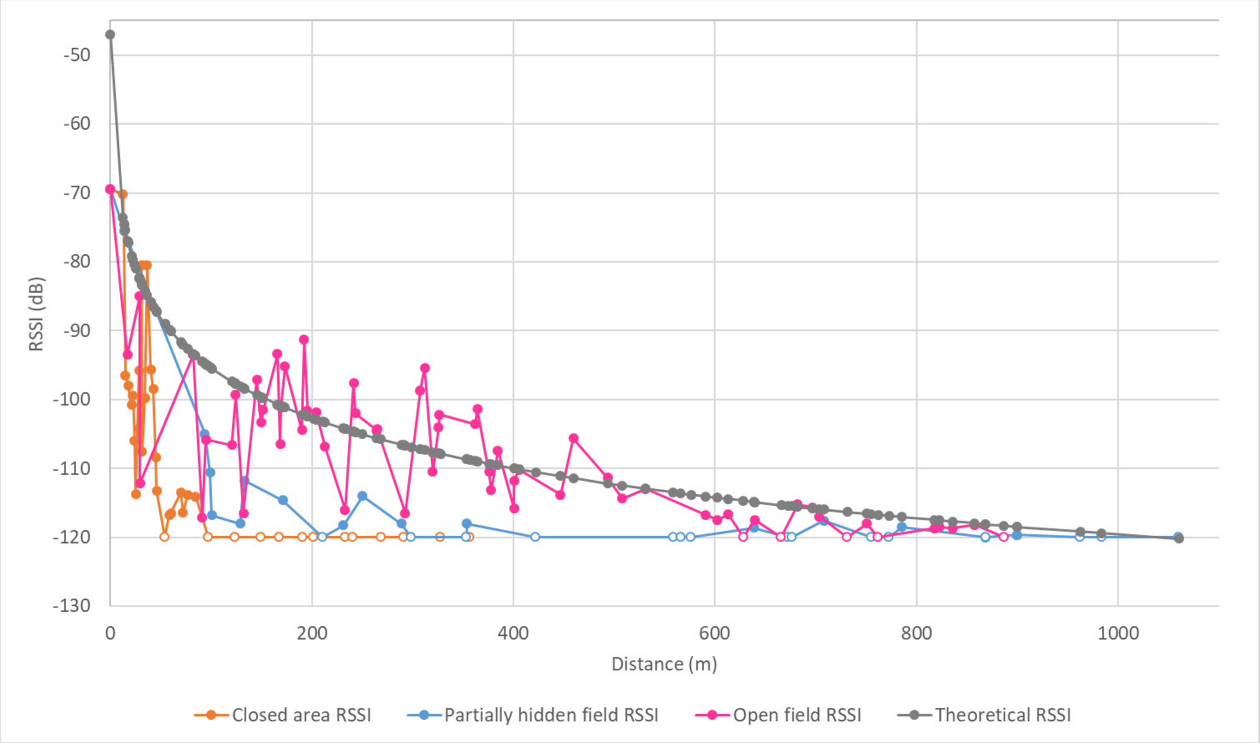

FIGURE 4. Signal reception quality as a function of the distance between the end-device and the gateway antenna for the three zones (closed area, partially hidden field, open field and theoretical RSSI).

showing how buildings, natural obstacles and the noisy electromagnetic environment affect signal propagation. The impact of the noisy electromagnetic environment was confirmed by the low SNR values (approximately +2 dB on average) observed in these conditions. In relation to the latter two zones, intermediate results were obtained from the partially hidden field.

The general trend of the plots shown in Figure 4 confirms the relevance of the three broadly defined reception zones (Figure 3). For open field conditions, the results are in accordance with the orders of values found in the literature for this type of network. For closed areas, the results show that the quality of the signal can be strongly altered over short distances. It should be noted that the positioning of the gateway antenna was subject to practical constraints (e.g., accessibility and power); therefore, better results would certainly have been obtained with optimised gateway positioning.

Figure 4 shows a high variability in the curves, suggesting that reception quality in the real environment is more complex than in a log-distance propagation model. This was particularly the case in the open field, where RSSI decreased and increased by +/- 20 dB in a few tens of meters. This variability suggests that particular local effects are at play, which are analysed in detail in the next section.

2. Spatial RSSI distribution within the outdoor areas of the vineyard

A kriged map of measured RSSI is shown in Figure 5. The spatial distribution of the measurements was highly spatially structured; the observed spatial patterns being determined by the spatially organised factors linked to the environment in which the simulated sensor network was tested. Overall, the map confirms the effect of the different areas: i) in open field the signal quality was high (-60 dB < RSSI < -80 dB) and relatively homogeneous, even over distances of more than 1 km, ii) in a closed area (i.e., the city) the signal quality deteriorated very quickly and was lost (RSSI < -120 dB) over very short distances (~ 50 m), and iii) in partially hidden fields the signal varied substantially depending on the presence of elements that affected its propagation. The map shows how signal reception was altered by topography. This can be observed in the eastern part of the study area, which has a lower elevation that obstructs direct visibility with the gateway antenna. Signal reception is also affected by the presence of a grove of trees

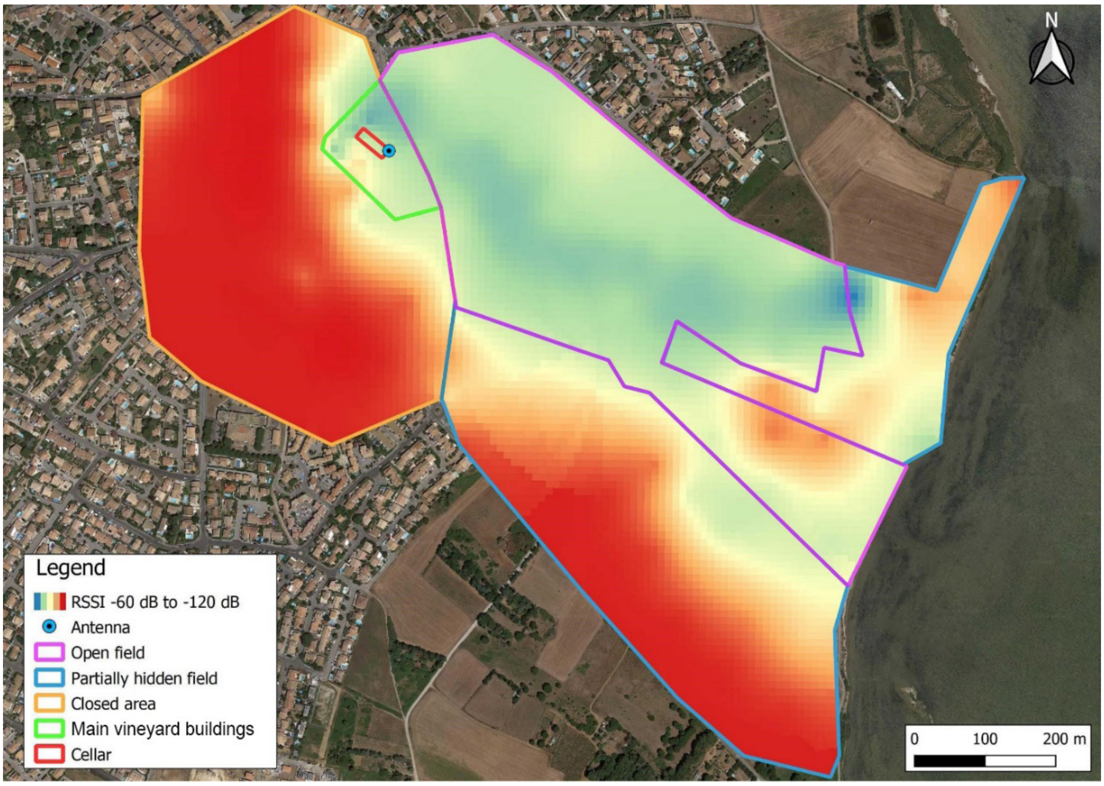

FIGURE 5. Kriged map of the RSSI reception quality obtained with the end-device over all the studied areas.

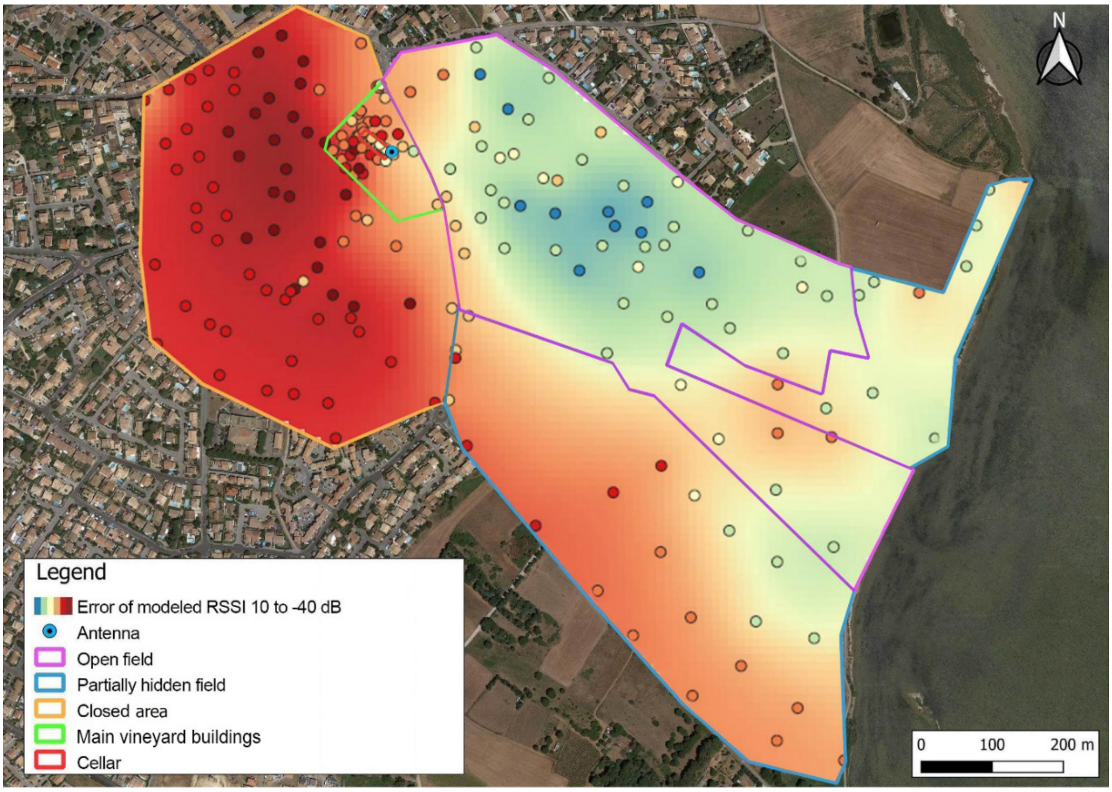

FIGURE 6. Kriged map of errors between theoretical (modeled) and observed RSSI values over the studied areas.

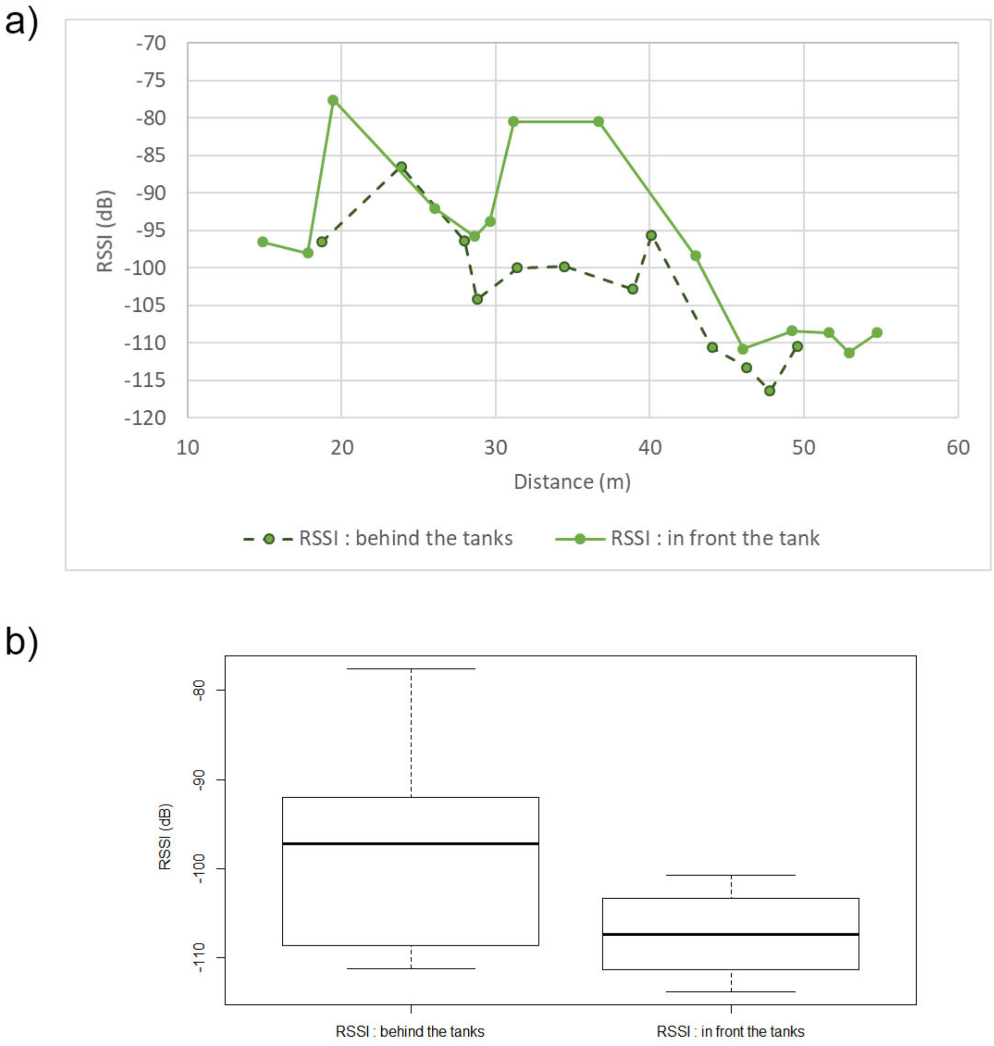

FIGURE 7. a) Signal reception quality as a function of the distance to the gateway antenna for end-devices behind or in front of the tanks, and b) comparison of RSSI variations with the sensor antenna outside and in the tanks by box plot.

in the east-southeast part. Finally, the signal in the entire southern area is affected by the presence of buildings that obstruct direct visibility with the gateway antenna. The kriged map of RSSI is useful for specifying the quality of signal reception per zone, which had been roughly defined at the beginning of the study. In particular, it shows that areas initially considered as “closed areas” have in reality little effect on the quality of signal reception. Conversely, the initial “open field area” seems to be more affected by environmental factors than expected. Both these phenomena are clearly visible in the south eastern part of the study area.

Figure 6 shows the kriged map of errors corresponding to the difference between theoretical RSSI (without interference) and observed RSSI. It clearly shows that observed errors are not randomly distributed, but once again clearly spatially organised according to factors related to the surrounding environment. The error map broadly shows the same trend as the RSSI map, but with notable local differences; for example, near the gateway antenna, although the reception quality remains high enough (-90 dB) and reception is in the open field, the error shows that the urban environment significantly affects the reception quality over a large area. Conversely, in the eastern part of the study, the error map shows that topography only slightly affects signal propagation. However, this is a zone far from the gateway leading to low the RSSI in that area; moreover, the changes in elevation slightly affected RSSI, which are at the limit of signal reception (RSSI < -110 dB). The error map also highlights zones where the signal quality is higher than the one estimated by the model (sites in blue).

This result can be explained by a combination of two effects: a slightly higher elevation zone favouring the line of sight between the gateway and the end-devices and the presence of a hedge and buildings, which may have caused the signal to be reflected, thus accounting for the reception quality observed in this particular zone.

3. Quality of reception in the cellar

The proposed empirical mapping method did not prove to be pertinent for inside the cellar. Indeed, the RSSI map (like the error maps) did not show clear spatial structures within the building (results not shown). As shown in Figure 7(a), changes in RSSI with distance to the gateway for two acquisition modes (in front of and behind the tanks) did not show any clear trends. Although a slight decrease in the signal can be observed for acquisition distances larger than 40 m, it was not significantly affected by distance to the gateway. This result can be explained by the low acquisition distance (< 100 m) and the absence of spatially-organised factors that may have affected the quality of reception within the cellar. It should be noted, however, that the tanks may have slightly altered the reception quality of the signal. Although the differences were not found to be statistically significant, reception was slightly better when the end-device was placed in front of the tank (Figure 7(b)). The results suggest, however, that better reception is obtained when the end-device is in front of the tank.

DISCUSSION

The data obtained in this study are specific to the study vineyard, and they should therefore be extrapolated to other vineyards very carefully and be considered as just an example of a real application. However, the results have revealed important points to be taken into consideration by professionals and researchers wishing to install a low cost LoRaWAN sensor network. The ranges of communication distance which were observed in our conditions differs considerably from most data published in the literature. The communication distance of a LoRaWAN network is often reported to be about 10 km (Jawad *et al*., 2017), but in our conditions the actual distances were much lower. These differences can be explained by several factors. First, the quality of the network components and configuration (e.g., size of the messages to be sent and flow rate of the network) may have an impact on the quality of message reception and on communication distance. In particular, the choice of the spreading factor (default set to 7 by The Things Network in our case) influences the message reception distance as shown by Reynders *et al*. (2017). These aspects were not the purpose of this study, which rather focused on a low cost simple network with realistic configuration for viticulture, and the reader can refer to Petäjäjärvi *et al*. (2017) for detailed information on these aspects. Second, the position of the gateway antenna was not optimal in our conditions; choice of position was based on a compromise between the highest possible location and constraints like security against theft or damage, maintenance operations and access to the Internet network and electricity power. As a result, the position of the antenna was far from ideal for covering the studied area. However, such constraints are likely to be encountered in many real situations, thus requiring similar reasoning and resulting in the suboptimal positioning of the gateway antenna. Lastly, the position of the end devices is very important, especially for vertically trellised crops, where the positioning of the end devices above the trellising is preferred in order to promote line-in-sight with the gateway.

As shown in Petäjäjärvi *et al*. (2017), adjusting the spreading factor is the most effective method for significantly increasing the network range. However, this setting requires precise knowledge of the size and frequency of the data (message) to be transmitted; moreover, it substantially increases the phenomenon of data collision (~ information loss) when several end-devices use the same gateway. The life cycle of the batteries is greatly reduced (by a factor of 40) and the transmission of messages is much more impacted by the environment (e.g., noisy electromagnetic environments). Adjusting the spreading factor is therefore an option for improving the range, but it can limit the diversity of the end-devices to be installed. Based on these observations, to improve the range between the gateway and the end-devices, we recommend that first the position of the antennas (gateway and end-device) be optimised to ensure that they are in the line of sight, then more powerful hardware be purchased, and lastly the spreading factor be adjusted.

Empirical mapping as proposed in this paper is could be useful for determining the potential of a LoRaWAN in real vineyard conditions. When mapping outdoors, it is possible to highlight zones that are clearly spatially organised according to the environment in which the sensor network is implemented. The RSSI map highlights the real conditions related to the operation of WSN, and how and where local environmental factors could affect signal propagation. The RSSI map may constitute a relevant decision support tool for optimising the locations of sensors throughout the vineyard, as well as for the optimal positioning of one or more gateway antennas to improve network coverage. From an operational point of view, the error map is less informative than an RSSI map. However, the joint analysis of the RSSI map with the error map could be useful for characterising the spatial impact of an environmental factor on signal quality; for example, in this study, the spatial impact of the urban area would have been underestimated without this information.

Our study shows that a communication distance of 600 m can be expected in such a location with a low cost network similar to ours. The communication distance could decrease drastically depending on the environment. Indeed, our study clearly highlights zones where different environmental factors (e.g., hedges, buildings and topography) affect signal reception. In our conditions, the method highlights large zones where the electromagnetic environment (e.g., personal Wi-Fi networks and electromagnetic signals from other equipment) has a significant impact on signal reception. This phenomena would have been underestimated without prior mapping and must be taken into account when setting up a network close to residential or industrial areas. Our study also shows that for reasonable distances (< 60 m) a LPWAN can be used inside a cellar without any difficulty. However, it should be noted that, in our case, the gateway was located outside the cellar, and it may thus be possible to obtain larger communication distances if it were inside the cellar. The presence of tanks (made out of either stainless steel or concrete) in the cellar does not seem to have a limiting effect on the signal; however, due to the slight effect that was observed it is recommendable to ensure a direct line of sight between the end-devices and the gateway when possible.

CONCLUSION

In order to install a WSN within a whole vineyard, a practitioner would need to overcome the difficulty of predicting the quality of reception in the conditions of the area in question. By applying empirical mapping methods using a low cost (< 40 €) end-device as described in this paper, it is possible to identify potential dead reception zones and the ideal location for the gateway antenna(s) or end-devices for optimal message reception. It shows how and where the variety of factors like hedges, buildings and topography can affect the quality of message reception. Such mapping was not found to be pertinent for the cellar, where factors affecting the signal quality reception are not necessarily spatially organised. Based on a real vineyard, our study confirms that LPWAN could be a useful and low cost method for either replacing or supporting monitoring. A single well-positioned gateway could ensure that the data is collected, either from the fields or/and from the cellar. The empirical mapping approach could therefore be of great interest for the viticultural industry, especially for small to medium vineyards with open vine fields located close to the winery, as well as for research experimentation.

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