LoRaWAN “Breadcrumbs”: Location-Aware Multi-Hop for the Monitoring of Workers in Underground Environments

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***Abstract*—This paper proposes a novel sensing infrastructure to enhance the safety of workers operating in underground environments, such as mines or railway tunnels. The system combines a wearable sensing platform with an innovative Long Range Wide Area Network (LoRaWAN)-based linear multi-hop network. The sensing platform collects data on environmental parameters, including concentrations of explosive gases and other chemical substances. The LoRaWAN network is supported by a series of portable relays, referred to as "Breadcrumbs", to be deployed by workers at specific intervals before starting their activities. The aim of this deployment is to establish a continuous linear link throughout the underground environment. A network protocol is proposed for the propagation of information from the initial receiving nodes through the intermediate relays. The target of the proposed protocol is also to estimate the worker's approximate position, which is crucial for locating individuals in case of an accident.**

***Index Terms*—Breadcrumbs, Environmental Monitoring, Linear Network, Localization, LoRaWAN, Multi-Hop, Workers safety.**

I. Introduction

Ensuring workers’ safety is a task of crucial importance: several working environments present significant risks in terms of mechanical stress, presence of pollutants or occurrence of extreme meteorological events. In all those contexts, it is of utmost importance to keep under control in real time physiological parameters, check the presence of unexpected poisonous substances, control potential explosion risks and so on. All these tasks require the deployment of accurate sensors and measurement tools. At the same time, the acquired parameters need to be remotely transmitted or, at least, to be analyzed on board the monitoring tools to provide alerts to the workers in case of critical conditions. Another crucial aspect is the localization of the workers to promptly rescue them in case of accidents or any sort of critical event.

User localization can be easily carried out through Global Navigation Satellite Systems (GNSSs) in case of operations in the open air. Conversely, alternative solutions need to be identified for closed environments. In these contexts, localization exploiting some sort of networking technology can be carried out, be it radio [1][2] or optical [3][4]: however, this requires the deployment of an ad-hoc network infrastructure and the implementation of algorithms for the extraction of positioning information from the received signals. Nevertheless, the deployment of such infrastructures can be almost unfeasible in many operational scenarios, like the underground one. Working environments such as mines, tunnels, aqueducts and so on make the implementation of a network infrastructure for localization purposes extremely expensive and technically complex. Indeed, besides deploying a number of radio receivers allowing the coverage of the whole area to be monitored, some solutions for the powering of these devices have to be identified. Energy sources like solar cells can be hardly exploited underground: the powering of the devices can thus rely only on batteries or on the connection to the grid. Moreover, the deployment of a fixed network infrastructure may be even redundant: working activities on these sites may be carried out occasionally, like in the case of maintenance operations.

To overcome these issues, the approach proposed in this paper focuses on the use of wearable monitoring devices collecting in real time a number of environmental parameters [5]. Data is then transmitted using the Long Range Wide Area Network (LoRaWAN) technology, adopting a multi-hop configuration allowing it to cover even large distances. While this configuration is not typical in LoRaWAN networks, a number of works has demonstrated the effectiveness of LoRaWAN mesh networks [6], in particular linear networks [7][8]. Indeed, previous works proved that in underground linear structures LoRa signal degrades significantly due to attenuation and multipath fading [9]. To avoid the installation of useless network infrastructures, the use of mobile relay nodes is envisaged: operators are expected to position these devices before maintenance interventions and remove them afterward. These devices operate as sorts of “Breadcrumbs”, allowing for the reconstruction of a worker's approximate position. This is achieved through an ad-hoc protocol that introduces location-aware information in the packets forwarded by the multi-hop infrastructure.

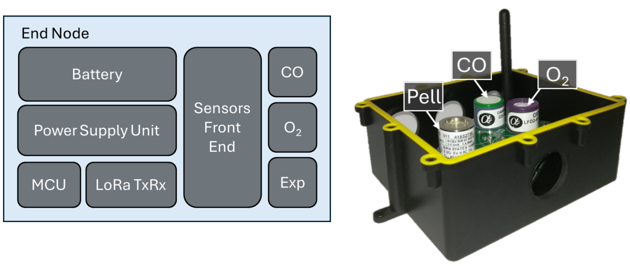
The rest of the paper is structured as follows: in Section II, the architecture of the monitoring platform is described in detail, while Section III is devoted to the networking aspects as well as to the multi-hop location-aware protocol. Some preliminary results about gas concentration monitoring are presented in Section IV. Finally, Section V provides some conclusive remarks.

II. System Architecture

The system is composed of two types of devices: a wearable sensor node (called env node), embedding gas sensors and wireless LoRaWAN connectivity, and a node (called breadcrumb node) acting as a LoRaWAN router to extend the network area as presented in Section III. Both sensor nodes are designed to operate using a battery as power supply. The block diagrams describing the nodes' structures and the pictures of the prototypes are reported in Fig. 1 and Fig. 2 for the env node and the breadcrumb node, respectively.

A. Env Nodes

The env node is based on the sensor node structure presented in [10] and is designed to wirelessly transmit environmental data, such as temperature, humidity, pressure, and gas concentrations, using LoRa modulation and LoRaWAN network protocol. The proposed system is highly modular, as it can mount different sensors depending on the monitoring requirements without the need for redesigning it. The core of the device is the main board hosting an STM32 low-power microcontroller unit (MCU) (ST Microelectronics), an RFM95x LoRa transceiver, and a BME280 environmental sensor (Bosch) measuring temperature, relative humidity and atmospheric pressure. The sensor hat houses the air quality sensors and their associated front-end electronics. It can support up to six gas sensors that use different sensing technologies: four amperometric electrochemical sensors (2, 3 or 4 electrodes), one non-dispersive infrared sensor and one resistive sensor. These devices can measure a variety of gases, including toxic compounds and flammable hydrocarbon gases, which are critical for air quality monitoring and, in general, for workers' safety in constrained environments.



(a) (b)

Fig. 1. (a) Block diagram and (b) image of a prototype of the env node.

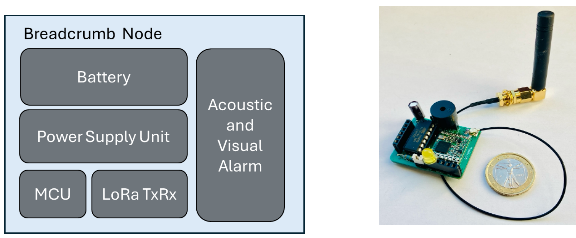
Among the possible integrable sensors, the following set was mounted to guarantee worker safety: electrochemical sensors for CO and O_2 monitoring and a catalytic sensor (pellistor) for the propane, butane, and methane detection. The commercial sensors used in this work are the CO-A4 (Alphasense) for carbon monoxide, the O2-A4 (Alphasense) for oxygen and the CH-A3 (Alphasense) for explosive gases.

The choice of gas compounds to be monitored depends on the risk of the working environment. In the context of underground worksites, which are characterized by limited access openings and unfavorable natural ventilation, the major risks consist in the presence of dangerous chemical agents (for example gas, vapors, dust) or in the absence of oxygen. The situations in which it is necessary to monitor gaseous agents can be identified both from literature and current regulations and the following risks can be identified:

- Explosion risk: continuous monitoring should be performed when there may be doubts about the dangerousness of the atmosphere. A combustible gas sensor (pellistor) can be installed to generate an alarm in advance in case of explosive gas concentration close to LEL (Lower Explosive Limit);
- Risk deriving from substances hazardous for health or oxygen deficiency: it is necessary to verify that the confined environment has a concentration of oxygen suitable for breathing and that there are no dangerous concentrations of asphyxiating, toxic or flammable chemical agents. Two electrochemical sensors can be installed to monitor the oxygen concentration and, in this specific case, carbon monoxide presence.

B. Breadcrumb Nodes

The breadcrumb nodes are designed to extend the network coverage in an underground environment. These devices can receive and transmit LoRa packets, acting as routers to forward packets into the network. They are basically composed of an ATTiny84 MCU by Atmel and an RFM95x LoRa transceiver, plus a few additional components (e.g., a buzzer and a LED). They are also able to interpret the packets that are forwarded, using LoRaWAN protocol. They can also generate acoustic and visual local alarms if any of the env nodes detect a critical event. The multi-hop network implementable with the breadcrumb nodes to extend the network coverage is thoroughly described in Section III.



(a) (b)

Fig. 2. (a) Block diagram and (b) image of a prototype of the breadcrumb node.

C. Power Consumption

In terms of power consumption, the most critical device is the env node that must be installed in a wearable package, limiting the battery capacity. For this application, a standard 18650 Lithium Ion (Li-Ion) battery has been considered. The power consumption analysis, based on real measurements on the sensor node transmitting one packet every two minutes, is reported in Table I.

With these configurations, a single Li-Ion battery in the env node can power the device for a full working week. However, the transmission frequency can be further reduced to meet the network's latency and delay requirements, potentially extending battery life. The power consumption estimation of the breadcrumb nodes is less deterministic. However, since these nodes are not wearable, using a larger battery is not critical. Assuming continuous operation for 24 h per day, four Li-Ion batteries can guarantee the breadcrumb node's functioning for one week.

TABLE I. ENV NODE ESTIMATED POWER CONSUMPTION FOR CONTINUOUS OPERATIONS AND PACKET TRANSMISSIONS EVERY 120 S.

Subsystem	Consumption (mW)	Total (mW)
Main Board	15	**216**
Catalytic Sensor	200	
Electrochemical Sensors	0.66	
Radio Module	0.3	
Average power consumption		216.0 mW
Battery capacity		10.0 Wh
Battery lifetime		**46.3 h**

III. NETWORKING AND LOCALIZATION

A linear network with multi-hop refers to a communication architecture where nodes are arranged in a linear sequence, and data is transmitted across the network in multiple steps or "hops". In such a network, communication between two nodes that are out of direct range is achieved by passing data through a series of intermediate nodes, rather than through direct communication [11]. This type of network is commonly used in scenarios where direct communication between distant nodes is not feasible due to limitations in range, transmission power, or environment topology, such as in tanks, wells, and tunnels [12]. By leveraging the multi-hop technique, the network can extend its range and improve communication reliability without requiring each node to be in direct range of every other node.

In a typical multi-hop linear network, each node functions as both a receiver, forwarding data to the other nodes in the sequence. When a node has data to transmit, it sends the packet to its immediate neighbor, which acts as a relay. This neighbor, in turn, forwards the packet to the next node, and so on, until the packet reaches the end of the node sequence. Each intermediate node listens to incoming data and determines whether to forward the packet further down the line. Hence, the nodes in the network can be in an idle listening state (waiting for incoming packets) or in a transmitting state (sending the directly received data or routing those packets received by other breadcrumb nodes of the network).

Several critical issues can affect the network's efficiency and reliability, including redundancy and packet duplication, packet loss, collisions, delay and potential interruption of the data flow when intermediate nodes are no longer accessible. Addressing these issues typically requires implementing robust error handling, efficient routing protocols, and careful network management strategies [13].

The fact that the same packet might be retransmitted several times over similar multiple paths can be avoided with appropriate techniques aimed at recognizing if that packet has been previously received from another path and therefore is not retransmitted. On the other hand, reliability can be severely affected in case of collisions. Since the nodes must share the same communication medium, multiple nodes trying to simultaneously transmit data can result in packet loss, and this is more likely to happen when there is congestion or bottlenecks at certain points in the network. However, managing collisions requires retransmission of packets, further increasing network delays and complexity, or specific strategies in the transmission stage (i.e., random transmission delays, multi-channel transmission, etc.). Another critical issue is the failure or unavailability of an intermediate node, which can result in a complete disconnection of the communication link between the source and the destination. This makes communication completely unreliable, and this issue is particularly problematic in applications which require a high level of reliability (e.g., monitoring of workers in risky environments). To prevent this event, redundant strategies should be adopted (e.g., increasing the density of the network so that each node routes its packets not just to its immediate neighbor but to a certain number of subsequent nodes), to the detriment of efficiency, communication speed and network complexity. To conclude, the designed network should go hand in hand with the specific application under study and its requirements in terms of data readiness, latency, distances to be covered, reliability level, admissible power consumption, etc.

A. The Proposed Linear Network

A multi-hop linear network based on LoRaWAN class C breadcrumb nodes is proposed for the monitoring and localization of workers in underground restricted environments such as tunnels or tanks, where real-time radio communication is generally hindered. Unlike class A and B nodes, which respectively open receiving windows after data transmission or periodically at scheduled times, class C nodes are constantly active in receiving mode, listening to incoming packets except during transmission phases. They are suitable for applications where low-latency and immediate communication are crucial since they can receive data at any time.

A qualitative picture of the network structure with two transmitting env nodes is reported in Fig. 3. In this example, the packets from envA and envB are received by two and three breadcrumbs, respectively. In the ideal situation, these five packets should be forwarded through the network until reaching the final hop (i.e., bc1) and then the gateway.

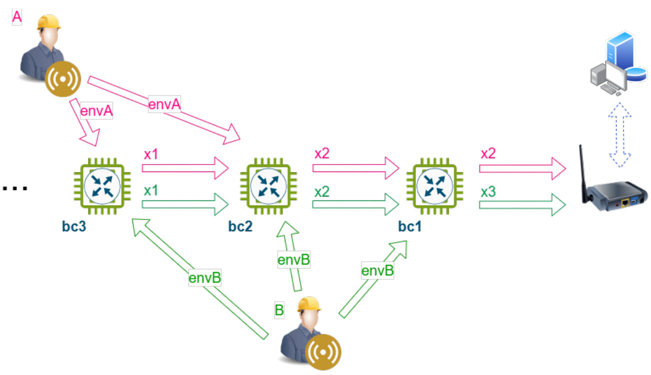


Fig. 3. Qualitative representation of the proposed multi-hop linear network with a sequence of breadcrumb nodes and two env nodes transmitting.

Numbered breadcrumb nodes are preliminarily distributed along the path to create the multi-hop network; each node is identified by a unique identifier (bcID), whose value increases from the node closest to the gateway to the furthest one. The breadcrumbs continuously listen to the packets transmitted by the mobile env node worn by the worker, which monitors environmental parameters and broadcasts data periodically and asynchronously to all the nodes in the network. Once the network is established, it can last for at least one week before battery replacement considering continuous operations of the breadcrumbs. Assuming a fixed distance of 100 m between the breadcrumbs, which is a reasonable radio coverage for LoRaWAN in constrained environments [9], and a maximum number of 10 breadcrumbs, constrained environments of about 1 km-length can be covered.

To guarantee a sufficient level of reliability, each breadcrumb node can see at least two subsequent nodes and not just the closer one. In this way, if a breadcrumb node loses the packet because it is not available in receiving mode, the packet will still be forwarded to other nodes in the sequence, increasing the probability that it will arrive at the final destination. Finally, the packets routed by the last two nodes in the sequence are received by the gateway which is positioned at the entrance of the confined environment, thus allowing the data to be made available at the server side.

Regarding the management of collisions and packet losses, two strategies are proposed:

- Random waiting intervals before a transmission by each node;
- Creation of a simplified Acknowledgement (ACK) system and packet retransmission mechanism (more details are reported in subsection III.C).

Furthermore, the transmission frequency of the env node must be compatible with the times associated with the data flow across the entire network. In this sense, a transmission every 5 minutes can be considered acceptable and compatible with the safety needs of the application. However, the packets received by the LoRaWAN breadcrumbs are stored in the receiving FIFO structure, reducing the risk of packet loss.

B. The Packets Structure

The payload structure of the two types of messages exchanged in the network is reported in Fig. 4.

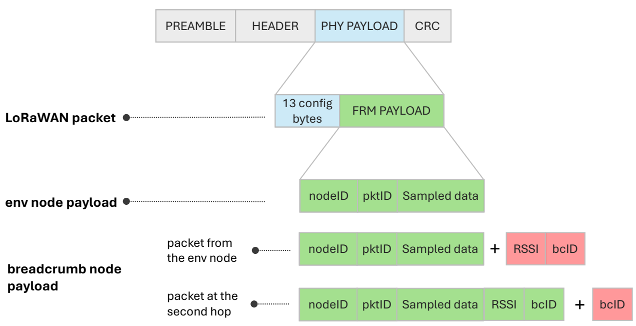


Fig. 4. Schematic representation of the payload structure of the packets exchanged in the proposed network.

The env node payload contains an ID number used to identify the transmitting node (i.e., nodeID), the sensors acquisitions and a random ID number (i.e., pktID) which identifies the transmitted packet. The Cyclic Redundancy Check (CRC) byte is computed over the entire payload. At the breadcrumb side, when a packet from the env node is received, the original payload is modified by adding two bytes, one byte with the RSSI of the received packet and one byte with the bcID, and the CRC is updated. On the other hand, when the packet arrives from a previous breadcrumb in the network, only one byte with the bcID is added at the end of the payload.

In this way, if the transmission chain is not interrupted, the packet received at the gateway contains not just the sampled data and the initial RSSI information, but also the entire history of the performed hops. More details about the data flow and the retransmission management are reported in subsection III.C.

C. The Data Flow and Localization

An example of data flow between 3 nodes is reported in Fig. 5. In this example, the same packet transmitted from env node A and with payload envA arrives both at bc3 and bc2 (in red and blue respectively) and from there it is routed in the network following different paths. Downlink packets are indicated by dashed arrows while uplink packets (toward the end of the breadcrumbs sequence) are indicated by solid arrows. The main issues to be managed are:

- The increasing number of multiple routes that convey the same message (e.g., packets envA+[RSSI3,3]$_A$ and envA+[RSSI3,3,2]$_A$ in Fig. 5 which both reach bc1);
- Avoiding the re-transmissions of those downlink packets received back from subsequent nodes in the network (e.g., packets envA+[RSSI2,2]$_A$, envA+[RSSI3,3,2]$_A$, envA+[RSSI3,3,2,1]$_A$ and envA+[RSSI2,2,1]$_A$ in Fig. 5) and due to the fact that the LoRAWAN breadcrumbs send data with a broadcast modality hence the packets can reach even previous breadcrumbs in the network;
- The implementation of a retransmission policy when an ACK is not received.

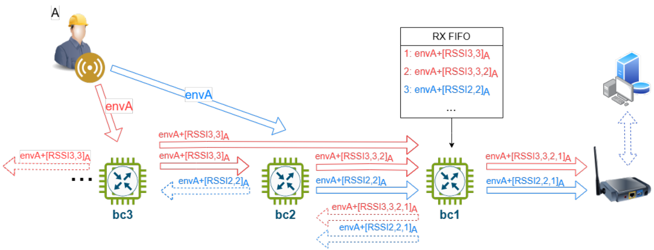


Fig. 5. Example of a packet flow between 3 nodes in the case that the packet transmitted by env node A is reached by two breadcrumbs (bc3 and bc2 in red and blue respectively). Downlink packets are indicated by dashed arrows while uplink packets (toward the end of the breadcrumbs sequence) are indicated by solid arrows.

As already mentioned, at the breadcrumb side, two types of packets can be received: from the env node or from an intermediate breadcrumb node. When a packet from the env node is received by a breadcrumb *i*, it is decoded and the pktID is checked. If it is a new packet not yet received, the breadcrumb modifies the original payload and updates the CRC as explained in subsection III.B. On the other hand, if the pktID is the same as the last 5 recorded pktIDs, that packet is discarded.

When the breadcrumb receives a packet from another breadcrumb it decodes it and, depending on the situation, the following checks are performed:

- Check of the last bcID: bcID of the transmitting node higher than that of the receiving node (i.e., the packet arrives from a breadcrumb before the receiving node). It is the case of uplink packets envA+[RSSI3,3]$_A$, envA+[RSSI3,3,2]$_A$ and envA+[RSSI2,2]$_A$ in Fig. 5 which reach bc1, one carrying the information of RSSI2 and two carrying the information of RSSI3;
  - Check of all the packets with the same pktID and present in the node receiving FIFO structure;
  - Identification of all the unique couples (pktID, first bcID) and discarding of the replicas (e.g., uplink packets envA+[RSSI3,3]$_A$ and envA+[RSSI3,3,2]$_A$ in Fig. 5 carry the same information envA+RSSI3);
  - Routing of the unique packets associated with the specific (pktID, first bcID) couple after appending to the total packet payload an additional byte with the node bcID and after updating the CRC.
- Check of the last bcID: bcID of the transmitting node smaller than that of the receiving node (i.e., the packet arrives from a breadcrumb after the receiving node). The packet is never re-forwarded in the network and, if the appended bcIDs sequence contains the same bcID of the receiving node, it is used as an ACK for signaling the successful uplink transmission towards the subsequent nodes of the network (e.g., downward packet envA+[RSSI3,3,2]$_A$ in Fig. 5 which reaches back bc3 signaling that the envA+[RSSI3,3]$_A$ packet reached at least bc2). Indeed, if the downward packet is not received (e.g., because of collisions, interferences or node in transmitting mode during the packet reception), the node tries to retransmit it for a certain number of attempts (i.e., three times).

To conclude, considering the data flow of Fig. 5, only the packets envA+[RSSI3,3,2,1]$_A$ and envA+[RSSI2,2,1]$_A$ are forwarded across the network and continue the hops sequence until arriving to the gateway.

On the server side, given that the order and numbering of the breadcrumbs is known, it is also possible to adopt strategies to roughly locate the worker along the chain by exploiting the knowledge of the RSSI and of the first bcID of the hops sequence. Indeed, the RSSI provides information about signal attenuation as a function of the distance from the receiving breadcrumb, hence it can give an approximate estimate of the worker position.

IV. Preliminary Tests

Preliminary laboratory tests were performed on the env node to test the gas sensors' reading capability after calibration. To this aim, a mass flow-meters bench controlled via LabVIEW and connected to certified gas cylinders was employed to generate gas fluxes with controlled flow rates and concentrations. The first test consists of exposing the sensors to a mixture at different concentrations of CO, O_2 and N_2. The test procedure alternates a mixture of 10 ppm of CO and 16% of O_2 and 20 ppm of CO and 12% of O_2 with phases with no CO and 20% O_2. The obtained results are reported in Fig. 6.

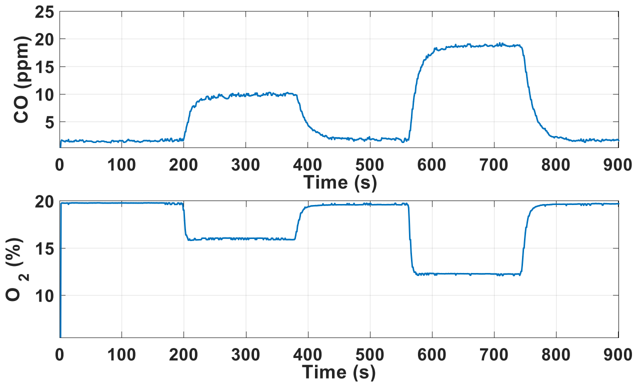


Fig. 6. CO and O_2 sensors test.

The second test consists of exposing the explosive gas sensor to a mixture of CH_4. Since explosive gas sensors are not selective to a specific gas, the calibration was performed taking into account the LEL of different compounds. The sensor detects, with different sensitivity, butane, propane and methane; however the sensitivity of the sensor toward methane is lower with respect to the other compounds (butane and propane sensitivity is 150% of methane sensitivity). For this reason, pellistors are typically tested with methane. The minimum explosive level (LEL) for methane is 5% while for butane it is 1.8% and for propane it is 2.1% in volume.

From calibration procedure, performed with methane, it is possible to obtain a sensitivity to this gas that we call S_{CH_4}. From producer specifications, it is possible to obtain the relative sensitivity of the other compounds with respect to methane. For example, with the used sensor, butane and propane sensitivities are approximately 150% of the sensitivity to methane. Considering the LEL values of the three compounds, we have that the sensor output ($OutLEL_{CH_4}$) corresponding to the LEL of methane is:

$$OutLEL_{CH_4} = (S_{CH_4}) * [5\%] \tag{1}$$

For butane, the sensor output ($OutLEL_{C_4H_{10}}$) corresponding to the LEL is:

$$OutLEL_{C_4H_{10}} = (S_{CH_4} * 1.5) * [1.8\%] \tag{2}$$

For propane, the sensor output ($OutLEL_{C_3H_8}$) corresponding to the LEL is:

$$OutLEL_{C_3H_8} = \left(S_{CH_4} * 1.5\right) * [2.1\%] \tag{3}$$

From these considerations it is possible to set the alarm threshold for this sensor to the lower LEL, that in this case is $OutLEL_{C_4H_{10}}$, also applying an additional safety margin of 30% thus achieving a threshold equal to $0.7 * OutLEL_{C_4H_{10}}$. During the test the sensor was exposed to a concentration spike of approximately 2.5% of methane (minimum methane equivalent butane LEL is 2.7%) to test the sensitivity and the response time. The obtained results are reported in Fig. 7.

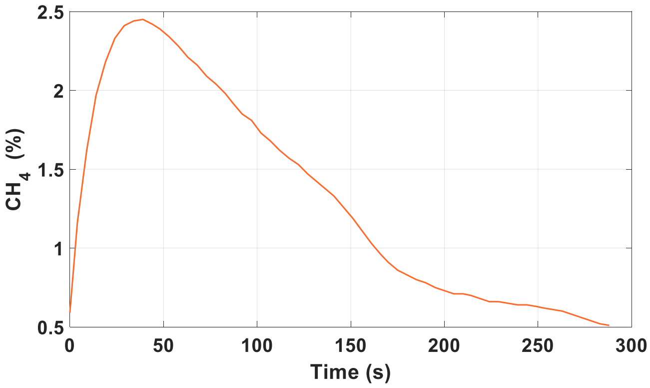


Fig. 7. Explosive gas sensor test with methane.

V. Conclusions

The aim of this paper was to propose a novel infrastructure for monitoring workers operating in underground environments. An ad-hoc sensing tool was developed and characterized to monitor several parameters which may lead to dangerous situations. Along with the measurement issues, criticalities related to the communication were also discussed.

For this purpose, a novel protocol exploiting multi-hop was proposed. In this protocol, intermediate nodes acting as relays are expected to be temporarily positioned by the workers as sorts of "breadcrumbs" before performing their activities. Then, thanks to the linearity of the network infrastructure, rough indications concerning the positions of workers can be inferred through the proposed protocol, which is customized to carry information related to the path followed by the packet, from the worker to the gateway at the end of the network. This would allow for prompt intervention in case of accidents. We start from the assumption that the linear network was previously installed and that the needed connections between the nodes are active, however, solutions are under study to propose an automatic settling of the network by exploiting downlink communication from the server and by using the information from the packets' RSSI to determine the maximum allowable distance between breadcrumbs.

The hardware of the two node types is already designed and tested: analogously, the network infrastructure that manages the communication link between nodes, LoRa gateway and cloud server has been put in place and validated using a communication chain involving a Chirpstack server, a javascript-based back-end, a SQL database and a Grafana dashboard. While the multi-hop communication was already tested with three nodes, the proposed linear network is a proof of concept that needs to be tested in future activities to practically prove the network performances. Indeed, actual large-scale implementation would require the deployment of several breadcrumbs, as well as the identification of a test site with peculiar characteristics in terms of internode distances: future work is thus expected to be carried out to fully implement and validate the complete operating scenario.

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