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Link Quality Analysis for Buried Pipeline Monitoring using LoRa

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***Abstract*—This work focuses on the analysis of link quality in the context of monitoring buried pipelines using wireless underground sensor networks. The study examines three communication channels: pipe to ground, ground to pipe and in-pipe. The investigation considers factors such as burial depth and the material of the pipe. Various metrics, including received signal strength indicator, signal-to-noise ratio and packet delivery ratio, are observed and analyzed for all the communication channels. The experimental investigation conducted at a frequency of 868 MHz using LoRa technology reveals strong signal strength and reliable communication across the three communication channels.**

***Index Terms*—LoRa, underground, pipeline monitoring**

I. INTRODUCTION

Wireless Underground Sensor Networks (WUSNs) have emerged as a promising solution for monitoring infrastructures, particularly in pipeline monitoring, where there is a pressing need for efficient communication with buried pipes [1]. In the context of pipeline inspection, the effectiveness of communication is of utmost importance to ensure seamless operation and data transmission between the deployed sensor nodes and control systems. Nevertheless, communication in underground environments presents several challenges, such as signal attenuation, limited bandwidth, and interference from surrounding soil and structures. Maintaining the quality of communication within WUSNs is paramount for the successful implementation of pipeline inspection. It enables accurate data collection, efficient inspection processes, and timely detection of pipeline anomalies, thus contributing significantly to the overall integrity and maintenance of the pipeline infrastructure [2]–[4].

Link quality plays a crucial role in the development of communication protocols specifically tailored for WUSNs, particularly in the challenging underground medium. Factors such as high path loss, weak signal transmission from low-power radios, and the impact of nonisotropic antenna radiation patterns introduce significant difficulties for wireless communication in underground environments. As a result, accurately characterizing link quality becomes essential for the efficient development of protocols specific to WUSNs [5]–[7].

On the other hand, Long Range (LoRa) technology is an well-suited solution for buried pipeline monitoring due to its suitability for long-range, low-power communication and ability to penetrate dense substances like soil [2]–[5], [7]–[9]. It offers exceptional signal range, even in challenging underground environments, ensuring reliable data transmission between sensor nodes and monitoring systems. Additionally, its low power consumption extends battery life for prolonged operation. With robustness against interference and the ability to detect anomalies in real-time, LoRa 868 MHz technology facilitates efficient and reliable communication for effective buried pipeline monitoring. Extensive literature supports the utilization of LoRa technology for evaluating link quality in diverse underground conditions and infrastructure, as evident from several scholarly works [3]–[5], [7], [8]. Within WUSNs, three channel types exist: Underground to Above-ground (UA), Above-ground to Underground (AU), and Underground to Underground (UU). While UA and AU channels are commonly considered due to the challenges associated with establishing UU links, the star topology with UA and AU channels often proves adequate for numerous applications. The link quality characteristics of LoRa-based WUSNs through experiments are investigated in [3], [10] that analyze the impact of burial depth, propagation direction and LoRa physical layer parameters. The findings highlight the symmetry between UA and AU links and provide guidance for designing communication protocols for WUSNs. LoRa-based nodes operating at 433 MHz and 868 MHz are developed and tested in real conditions for UA data transmissions in [4]. Results revealed the benefits of using 868 MHz radio modules with higher transmit power compared to 433 MHz modules. The inclination of the receiving antenna and the burial depth of the emitting node were found to be crucial, with the best configuration achieving UA ranges of over 275 meters. Another study [5] experimentally investigates the link quality characteristics of three communication channels in WUSNs for underground pipeline monitoring. The results reveal that the UU channel is symmetric and stable but has limited range, while the AU and UA channels exhibit asymmetry with temporal properties similar to over-the-air communication. Additionally, the study finds that received signal strength is a better indicator of packet reception ratio than the link quality indicator for all three channels. The link quality characterization of the UU channel is explored in [11], where the authors investigate the path loss and bit error rate associated with communication through soil.

Additionally, another study [12] presents a theoretical model for the UU channel and validates it through experimental analysis using LoRa technology, considering various burial depths and internode distances.

To the best of author's knowledge, there is a limited literature that specifically investigate the link quality of LoRa 868-MHz communication between nodes located inside underground pipes and the ground. While pipeline monitoring using LoRa 433-MHz has been explored [5], these studies typically involve burying the sensor nodes in the soil rather than placing them inside the pipeline. Additionally, other studies focusing on LoRa 868-MHz [3], [4], [12] have primarily examined the channel characteristics within the soil environment. Hence, it becomes imperative to thoroughly determine the link quality characteristics in this specific scenario to gain a more comprehensive understanding of the link behavior in realistic underground environments.

In this paper, we investigate the link quality between the nodes in a buried pipe and the ground station communication utilizing LoRa 868 MHz technology for the purpose of pipeline inspection and monitoring. We conducted experimental investigations to assess the performance for LoRa 868 MHz in three communication channels: pipe to ground, ground to pipe and in-pipe. The pipe to ground, ground to pipe channels experiments are conducted using two nodes. For in-pipe channel, an exploration was conducted into a cooperative communication setup involving three nodes. For each channel, we measured various performance parameters, such as Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR) and Packet Delivery Ratio (PDR), considering different burial depths and pipe material. We believe that this research contributes to the efficient and accurate methods for monitoring and maintaining critical pipeline infrastructure. To the best of author's knowledge, this work is first of its kind to investigate LoRa for buried pipeline monitoring.

The remaining sections of the paper are organized as follows: Section II discusses the system setup, including details about the experiment's site, transceiver configuration, and procedure. Section III presents the results and discussions, while Section IV provides the conclusion.

II. System Setup

A. Experiment site

All field experiments are conducted at The National Facility for Distributed Water Infrastructure [13]. It is a part of Integrated Civil Infrastructure and research centre at the University of Sheffield, United Kingdom.

B. Transceiver Configuration

The experiment utilizes the transceiver LoPy4, a development board designed by Pycom. The LoPy4 is a multifunctional MicroPython-enabled device, supporting four different communication protocols: LoRa, Sigfox, WiFi, and Bluetooth. It incorporates the Espressif ESP32 chipset and Semtech LoRa transceiver SX1276 [14]. The LoPy4 is connected to RF FLEXI-SMA-868 antenna, which have a gain of 2 dBi and a length of 13.6 cm. Detailed information regarding the transceiver's configuration can be found in Table I.

C. Experiment Setup and Procedure

The experimental setup includes a set of transceivers, a rechargeable lithium-polymer battery, and a laptop. One of the transceivers, referred to as the source (S) node, is powered by a battery bank. The second transceiver, denoted as the destination (D) node, is powered through the USB port of a connected computer. The S node is placed inside a buried pipeline through a manhole and moved using a remote control robot with wheels, while the D node is positioned above ground level, as illustrated in Fig. 1. Two types of pipes are utilized in the experiments: a concrete pipe with a diameter of 300 mm and a Polyvinyl Chloride (PVC) pipe with a diameter of 200 mm. The experiments involve varying the burial depths of the S node within the pipe and utilizing different pipe materials. At the test site, these pipes are buried in a combination of sand and a layer of coarse stone. In the case of the concrete pipe, two depths are taken into consideration for the S node: 45 cm and 75 cm. As for the PVC pipe, the depths considered are 105 cm and 130 cm. The D node is positioned 100 cm above the ground level, as illustrated in Fig. 2. It is important to note that these depth measurements are taken from the top of the antenna to the surface of the sand. Throughout the experiments, a total of 300 packets are transmitted in one round. For each packet, the RSSI and SNR are recorded. Each experiment is conducted three times, and the results are averaged for clarity and presentation purposes. Packet delivery ratio is calculated after each round and averaged over all rounds.

III. Experimental Results and Discussion

To evaluate the impact of LoRa transmission on the link quality of the pipe-to-ground, ground-to-pipe and in-pipe channels, three primary tests are conducted.These tests encompass the depth test, range test, and cooperative transmission test. The depth test involves manipulating the depth of the source node while keeping the destination node stationary. This test allows us to ascertain the maximum depth at which reliable communication can be achieved. Conversely, the range test focuses on adjusting the internode distance between the S and D nodes. By moving the D node along the ground while the S node remains fixed at a specific depth, this test helps determine the maximum distance over which effective communication can be established. The cooperative transmission test enhances network reliability by enabling signals to traverse multiple paths instead of a single path.

A. Depth test

The results of RSSI, SNR, and PDR for the pipe-to-ground and ground-to-pipe channels in a concrete and PVC pipes are presented in Tables II and III, respectively. For concrete pipe, at a depth of 75 cm, the RSSI value is approximately -87 dBm, indicating a good signal strength. This result is expected due to the dry sand composition in which the pipe

(a) The S node placed inside the buried concrete pipe of diameter 300 mm.

(b) The S node placed inside the buried PVC pipe of diameter 200 mm.

(c) The D node placed above the ground connected and powered by the laptop.

Fig. 1: Photos of nodes placement at the test site in concrete and PVC pipes while destination is placed on the ground.

Modulation	Frequency	Transmission power	Bandwidth	Spreading factor	Coding rate
LoRa	868 MHz	12 dBm	125KHz	12	4/5

TABLE I: LoRa transceiver configuration.

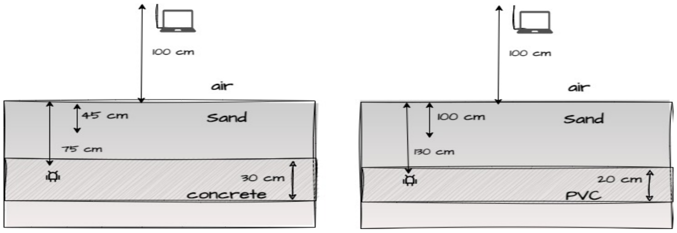


Fig. 2: Left: In a buried concrete pipe with node at 75cm and 45 cm. Right: In a buried PVC pipe with node at 105 cm and 130 cm. Surface node is place 10o cm above the ground.

is buried. It is worth noting that the RSSI values for both channels do not exhibit significant differences, suggesting comparable signal strengths for both directions. Comparing the SNR values, it is observed that the ground-to-pipe channels exhibit slightly higher SNR compared to the pipe-to-ground channel. However, there is no noticeable change in the SNR values at different depths. Regarding the PDR, the results show a consistent 100% delivery rate for both channel directions at the tested depths.

Regarding the PVC pipe, as illustrated in Table III, the signal strength at a depth of 130 cm is -92.5 dBm, which remains satisfactory even with the increased depth owing to the dry sand composition. Both channels display slight disparities in signal strength, with the ground-to-pipe channel experiencing more signal loss due to the presence of medium interfaces. The higher refractive index of sand leads to increased wave reflection at the air-sand interface. Notably, the PDR remains at 100% for both channels at these depths.

In summary, it can be concluded that the signal effectively propagates through the sand at a frequency of 868 MHz using LoRa technology in both the concrete and PVC pipes. Moreover, the conducted tests in both pipes indicate good signal strength (as indicated by RSSI) and reliable communication (PDR) for both the pipe-to-ground and ground-to-pipe channels. Although a slight variation in SNR is observed between the two channel directions, it does not affect the overall quality of the link. These findings provide valuable insights into the performance of LoRa transmission in such conditions and can guide the optimization and design of communication systems underground pipeline monitoring.

Concrete pipe				
	Pipe to ground		Ground to pipe	
Depth (cm)	45	75	45	75
RSSI (dBm)	-80.45	-86.54	-80.92	-87.01
SNR (dB)	5.6	5.6	6.13	6.13
PDR (%)	100	100	100	100

TABLE II: Summary of results in a concrete pipe for both channels.

PVC pipe				
	Pipe to ground		Ground to pipe	
Depth (cm)	105	130	105	130
RSSI (dBm)	-97.67	-92.5	-98.9	-93.7
SNR (dB)	5.4	5.7	6.4	6.5
PDR (%)	100	100	100	100

TABLE III: Summary of results in a PVC pipe for both channels.

B. Range Test

A range test, illustrated in Fig. 3, was conducted to determine the maximum distance at which the pipelines could be accurately measured while on the ground. This test is in the concrete pipe with a node positioned at a depth of 45 cm, as

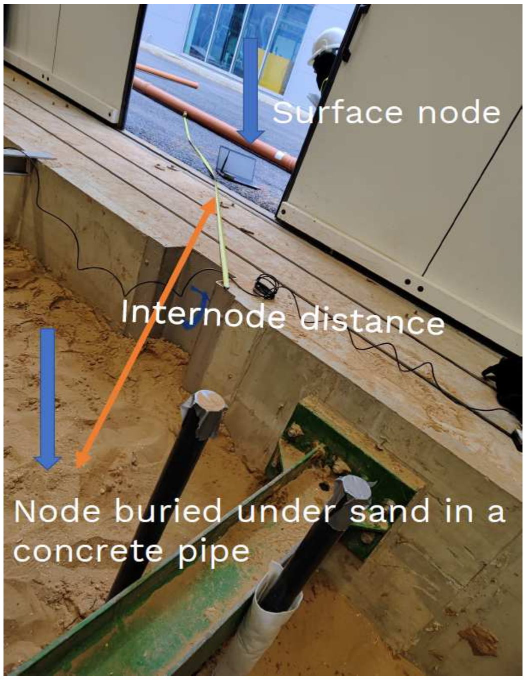


Fig. 3: Photo of test site for range test in a concrete pipe. S node placed 45 cm below the ground. D node's vertical distance is 100 cm above the sand. The internode distance is varied up to 50 m.

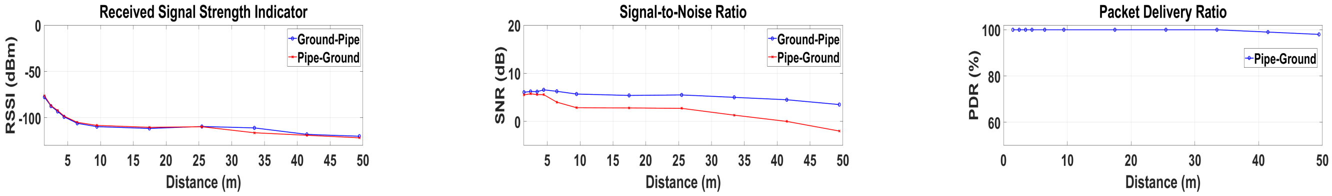
depicted in Fig. 4. Upon analyzing the results, it becomes evident that the RSSI values exhibit a downward trend as the internode distance increases, regardless of the channel direction. Furthermore, the RSSI values for both channels overlap, indicating similar signal strengths. When considering the SNR, a noteworthy disparity is observed between the two channels. The pipe-to-ground channel experiences more signal losses, which can be attributed to the high refractive index of the soil, ultimately impacting the SNR performance. Despite these variances, the PDR remains consistently high, reaching approximately 98% even at a 50-meter internode distance. This signifies a robust delivery rate for the transmitted packets, further highlighting the reliability of the communication link. The range test results reveal that as the distance between the nodes increases, the RSSI tends to decline, while the SNR performance is affected by the refractive index of the soil. However, the PDR remains remarkably high, indicating the successful transmission of data packets over significant distances.

C. Cooperative Transmission Test

The assessment of the pipe-to-ground and in-pipe channels is also conducted within the framework of cooperative transmission. In the context of cooperative communication, an additional node, referred to as the Relay (R) node, is introduced. Rest of the setup details are same as in Section II-C, unless otherwise stated. The transmission process operates in time slots. A ”time slot” signifies a specific duration within which a packet is transmitted over a communication link. During the initial time slot, S broadcasts to both R and D. Subsequently, in the subsequent time slot, R retransmits whatever it has received from S to the D node. This approach results in the destination having two instances of the same signal, allowing it to select the optimal one from the two available choices, rather than just one. The R node employs a ”decode and forward” cooperative transmission strategy, wherein the received data is decoded, corrected and subsequently re-encoded before being forwarded to the destination. The arrangement of S, R and D is visually illustrated in Figs. 5a, 5b, and 5c, respectively. S and R are positioned in a concrete pipe (300 mm diameter) buried under sand, each at varying depths. The distance between S and R is 11 m. On the other hand, D is positioned at an elevation of 90 cm above ground. D is moved in the three settings. RSSI and SNR performances are measure for direct transmission and relayed transmission. Direct transmission denotes the scenario where D receives signals directly from S, while relayed transmission pertains to the transmission route from S to R, and subsequently to D.

In setting 1, as depicted in Fig. 5a, the analysis of RSSI reveals noteworthy observations. Specifically, the relayed transmission demonstrates a more favorable signal strength, averaging at approximately -80 dBm, Fig. 5a. This enhanced signal strength is notable even though the relay node is positioned at a greater distance from the D node. In contrast, direct transmission exhibits an average signal strength of -95 dBm. This discrepancy can be attributed to the relative depths of the R node and the S node within the buried infrastructure. Given the drier nature of the sand medium, the relay node achieves improved signal propagation when transmitting the refined signal from the source, thereby yielding the observed superior signal strength. Turning to SNR performance, as illustrated in Figure 5g, the outcomes within Setting 1 are characterized by a noteworthy similarity between the two transmissions. The SNR values exhibit marginal fluctuations, averaging around 6 dBs, irrespective of whether the transmission is direct or relayed.

In setting 2, shown in Fig. 5b, the situation is such that the D node is placed between S and R above the ground. When considering the RSSI performance, Fig. 5e, of both direct and relayed transmissions, it closely resembles what was observed in setting 1. This similarity is because the adjustment in the D node's position, despite being present, is quite minor. As a result, it does not have a significant impact on the results. The change in the D node's location is so slight that it doesn't make a noticeable difference. Although the distance between the S and d has slightly increased due to this minor adjustment, the signal strength experiences a small reduction. On average, the signal strength decreases to around -100 dBm. On the other hand, the distance between R and D has also slightly changed, but this adjustment does not seem to have a noticeable effect on the RSSI performance. The overall RSSI results remain relatively consistent, despite these slight variations in distances. Similar behaviour of SNR performance is observed in Fig. 5h.



(a) Received signal strength indicator (b) Signal-to-noise ratio (c) Packet delivery ratio

Fig. 4: RSSI, SNR and PDR performances for both channels when one node is placed in a concrete pipe at 45 cm depth and other node is on the ground.

The scenario in setting 3, a configuration is introduced where the D node is positioned above the R node. This arrangement results in a reduced distance between the R and D. Additionally, the depth at which the R is buried is shallower compared to the depth at which the DD is situated. These combined factors contribute to a notable enhancement in signal strength, averaging around -60 dBm. Notably, the improvement in signal strength is a result of the decreased distance between the R and D, as well as the relatively shallower depth of the R node. Conversely, in the context of direct transmission, the signal strength is lower due to the greater distance between the S and D nodes, coupled with the deeper burial depth of the D node within the sand medium. This trend is consistently observed in the SNR performance, as depicted in Figure 5i. In this figure, the direct transmission exhibits superior SNR values in comparison to the relayed transmission scenario. In conclusion, the cooperative transmission tests demonstrate that in scenarios where one path is less favorable, the availability of alternative paths allows for the selection of the optimal transmission route from the two available options.

Concerning signal strength within the buried pipe, the average RSSI measures at -120 dBm, as depicted in Fig. 6. This result is observed with a node-to-node distance of 11 meters, and respective depths of 85 cm and 60 cm for S and R nodes. The SNR performance averages around 2 dBs as shown in Fig. 7. These values persist consistently across all three settings due to unchanged distance and node placements in the cooperative setup. Furthermore, a 3% packet loss is observed in in-pipe propagation. The signal strength at an 11-meter distance is influenced by dry sand conditions and the presence of open manholes. Multipath propagation may allow signals to be received through manholes, contributing to the observed strength. The potential for signal reception from outside the pipe is indicative of this behavior. Notably, had the sand been wet, in-pipe propagation could have been further compromised.

In buried pipeline areas, soil and water can weaken LoRa signals, making them travel shorter distances. Metal structures can mess with signals too. Also, terrain and plants can block them. To fix this, planners need to be careful with how they set up the network, where they put antennas, and how strong the signals are. They might also need to use other tech to make the network work better.

IV. CONCLUSION AND FUTURE WORKS

This study has examined the link quality of LoRa 868-MHz technology in underground pipeline monitoring applications, specifically focusing on the communication between nodes in a buried pipe and the ground station. Through experimental investigations, it has been determined that the signal effectively propagates through sand, both in concrete and PVC pipes, at a frequency of 868 MHz using LoRa technology. The tests conducted in these pipes have demonstrated favorable signal strength and reliable communication for all the channels, as indicated by the received signal strength indicator and packet delivery ratio. The results of the range tests further emphasize that as the distance between nodes increases, the RSSI decreases, while the SNR is influenced by the refractive index of the soil. However, the high PDR indicates successful data packet transmission over substantial distances. The results of the cooperative transmission tests demonstrate that even in scenarios where one path is unfavorable, alternative paths remain accessible. This redundancy allows for the selection of the optimal path among the available options.

In the future, our aim is to construct a comprehensive communication channel model tailored to the context of monitoring underground pipelines. This model will offer a methodical comprehension of signal propagation attributes, taking into account variables like soil composition, pipe materials, and burial depths. Additionally, we plan to conduct experiments under wet soil/sand conditions and investigate channel dynamics in the presence of neighboring pipelines, such as water pipes in the vicinity.

ACKNOWLEDGMENT

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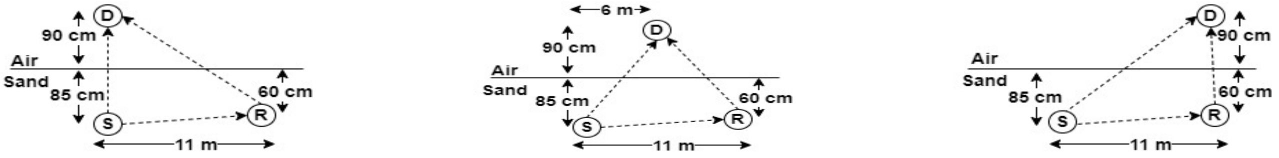
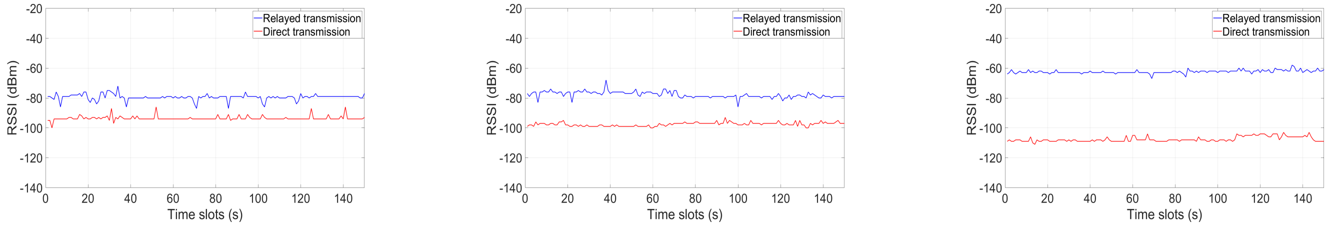


(a) Setting 1

(b) Setting 2

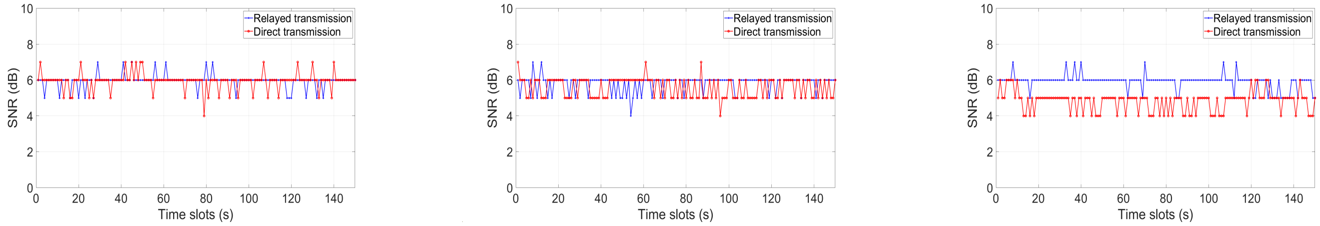
(c) Setting 3



(d) Received signal strength indicator performance for setting 1

(e) Received signal strength indicator performance for setting 2

(f) Received signal strength indicator performance for setting 3



(g) Signal-to-Noise Ratio performance for setting 1

(h) Signal-to-Noise Ratio performance for setting 2

(i) Signal-to-Noise Ratio performance for setting 3

Fig. 5: Received signal strength indicator and Signal-to-Noise Ratio performance performances of direct and relayed channels in three cooperative settings.

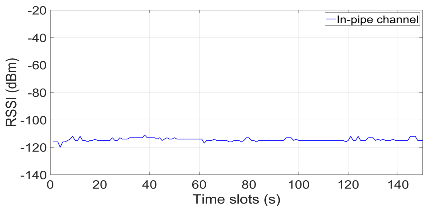


Fig. 6: RSSI of in-pipe channel when both nodes are placed inside a buried concrete pipe.

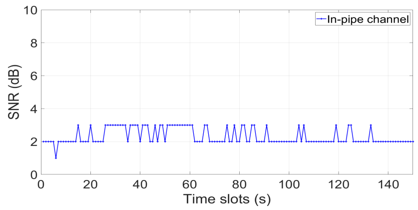


Fig. 7: SNR of in-pipe channel when both nodes are placed inside a buried concrete pipe.

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