Novel communication system for buried water pipe monitoring using acoustic signal propagation along the pipe

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MANUSCRIPT DETAILS

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ABSTRACT:

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An acoustic communication system was developed based on the requirements of low cost (tens of pounds at most), low power supply capacity (in the order of 1 Watt-hour) and miniature (centimetre scale) size for a wireless communication node. The developed system was further tested along a buried steel pipe in poorly graded SAND (SP) and a buried medium density polyethylene (MDPE) pipe in well graded SAND (SW).

With predicted acoustic attenuation of 1.3 dB/m and 2.1 dB/m along the buried steel and MDPE pipes respectively, reliable acoustic communication is possible up to 17 m for the buried steel pipe and 11 m for the buried MDPE pipe.

Although an important first step, more research is needed for validating the acoustic communication system along a wider water distribution pipe network.

CUST_PRACTICAL_IMPLICATIONS_(LIMIT_100_WORDS) :No data available.

CUST_SOCIAL_IMPLICATIONS_(LIMIT_100_WORDS) :No data available.

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NOVEL COMMUNICATION SYSTEM FOR BURIED WATER PIPE MONITORING USING ACOUSTIC SIGNAL PROPAGATION ALONG THE PIPE

Abstract

Purpose - Wireless sensor networks (WSN), as a solution for buried water pipe monitoring, face a new set of challenges compared to traditional application for above-ground infrastructure monitoring. One of the main challenges for underground WSN deployment is the limited range (less than 3 m) at which reliable wireless underground communication can be achieved using radio signal propagation through the soil. To overcome this challenge, a new approach for wireless underground communication using acoustic signal propagation along a buried water pipe was investigated.

Design/methodology/approach – An acoustic communication system was developed based on the requirements of low cost (tens of pounds at most), low power supply capacity (in the order of 1 Watt-hour) and miniature (centimetre scale) size for a wireless communication node. The developed system was further tested along a buried steel pipe in poorly graded SAND (SP) and a buried medium density polyethylene (MDPE) pipe in well graded SAND (SW).

Findings – With predicted acoustic attenuation of 1.3 dB/m and 2.1 dB/m along the buried steel and MDPE pipes respectively, reliable acoustic communication is possible up to 17 m for the buried steel pipe and 11 m for the buried MDPE pipe.

Originality/value – This paper shows the possibility of achieving reliable wireless underground communication along a buried water pipe (especially non-metallic material ones) using low frequency acoustic propagation along the pipe wall.

Research limitations/implications – Although an important first step, more research is needed for validating the acoustic communication system along a wider water distribution pipe network.

Key words: Buried pipeline monitoring, Wireless Sensor Network, Acoustic data communication, Wireless underground communication

Paper type: Research paper

1. Introduction

Water pipes, like any other civil infrastructure, are prone to failures which compromise their ability to provide regular service to a community. For example, between April 2019 and March 2020, in England and Wales, approximately 3 Gl of water was lost daily due to leaks in the water supply and distribution networks (Water UK, 2020). With 1 cubic metre (1000 l) of water costing approximately £1.3 (Severn Trent, 2019), this translates to a daily loss of over £3.9 million in possible revenue. Many buried water pipe monitoring technologies have therefore been developed over the decades, each with its own benefits and drawbacks for proactive (i.e., before a leak materialises) or reactive (i.e., detecting a leak) pipeline monitoring (Datta and Sarkar, 2016; Liu & Kleiner, 2012; Hao et al., 2012; Misiunas, 2005). Proactive pipeline monitoring, owing to its preventive nature, is advantageous because it avoids the potential cost implications of complete pipe failure and repair. For the water industry however, due to the relatively low cost of water (£1.3 per cubic metre), proactive failure management techniques need to be economically justifiable for buried pipeline monitoring as generally, monitoring the early stage of pipe deterioration requires more complex and expensive pipeline monitoring techniques (Sadeghioon, 2014; Misiunas, 2008, 2005). There are two fundamentally different approaches to proactive pipe deterioration monitoring. Repeat surveys using pipeline inspection gauges, surface geophysics or temporary sensors (e.g., Lee, 2017; Datta & Sarkar, 2016; Liu and Kleiner, 2013). A common drawback, however, is the need for on-site technical personnel and equipment deployment to successfully run inspection operations. An alternative is to use permanently installed sensors, which enable continuous monitoring. Here, the most critical aspect is reliable communication between sensors or to the ground surface enabling data processing for further decision making by the utility owner (Makar & Kleiner, 2000). However, existing sensing technologies which use underground wireless communication for data transmission have limited range (less than a few metres) in the underground environment (e.g., Akyildiz and Stuntebeck, 2006). While the range could be extended using higher powered sensors, this is not unproblematic either due to the limited power sources below the ground surface and the inability to regularly change e.g., batteries. Such short-range sensor deployment can quickly become cost prohibitive for buried water pipe monitoring over an extended network, especially when the sensors are installed retrospectively on legacy assets, where the cost of digging the whole to the pipe itself is a major contributor to the overall costs. With the cost of water itself being low in many countries, it would make the sensor network uneconomical. Another option for longer range inspection (at least tens of metres) is guided wave testing (GWT) (e.g., Rose, 2014; Rose et al., 2008) but as noted by Liu et al. (2012), this technique requires significant labour and equipment costs (which can reach thousands of pounds) for each inspection operation.

Long-term continuous monitoring of the buried pipeline asset, with cost-effective underground sensor deployment is therefore an attractive proposition for proactive buried water pipe monitoring. Wireless sensor networks (WSN) have emerged as robust and cost-effective solutions for buried pipeline monitoring owing to their unique advantages of low cost (a maximum of a few tens of UK pounds), low power supply capacity (of the order of 1 Watt-hour), and small size (centimetre scale) requirements for each individual wireless sensor node (BenSaleh et al., 2013; Whittle et al., 2013). However, radio signal attenuation in the soil surrounding a pipeline is one of the main challenges in WSN deployment for buried pipeline monitoring. Compared to radio signal propagation in air, radio signal propagation in certain soil types shows rapid attenuation due to path losses experienced by radio waves in soil as a result of water, soil, air matrix, and charged particles (Pal et al., 2023; Vuran & Silva, 2009; Li et al., 2007; Akyildiz and Stuntebeck, 2006). This has limited reliable wireless underground communication through soil to less than 3 m (Zhao et al., 2023; Lin et al., 2022, Sadeghioon, 2014).

Another option for wireless underground communication which has been investigated in the literature is magnetic induction (MI) communication. Guo et al. (2023), for example, proposed a through-metal magnetic induction communication system for metallic pipe monitoring using off-the-shelf electronic components. Although a data rate of up to 500 bits per second (bps) was reported, the communication system was limited to a data transmission range of less than 4 cm. Sun & Akyldiz (2010) and Akyldiz et al., (2009) also proposed an MI waveguide technique in response to the limited radio signal propagation range within an underground soil environment. The MI waveguide method relies on mutual magnetic induction between electrical coil pairs for signal transmission along a buried water pipe. A magnetic field, unlike an electromagnetic field, shows little variation in air, water, or soil (due to the similar magnetic permeabilities of air, water, and most types of soil) and so MI-based signal transmission would be largely unaffected by the presence of underground soil or water (Liu et al., 2021; Sun & Akyldiz, 2010; Akyldiz et al., 2009). However, the MI signal path loss within a waveguide system depends on the radius (and electrical parameters such as coil resistance and capacitance) of the MI relay coils wrapped around the pipe. Maintaining a signal transmission range within tens of metres will therefore necessitate bespoke electrical coil designs for buried pipes of different diameters which is not only challenging but also cost intensive for deployment along a buried pipeline network.

A separate (i.e., non-electromagnetic or magnetic induction based) approach for enabling wireless underground communication through soil is achieved by using the buried water pipe as an acoustic waveguide. To overcome the challenge of limited (less than 3 m) underground signal propagation range using electromagnetic (EM) signal transmission, the use of buried water pipes as acoustic waveguides has been considered in the literature (although to a comparatively limited extent). Unlike EM signal transmission, acoustic signal transmission requires the presence of a medium for wave propagation between a digital communication transmitter and receiver. Being mechanical in nature, acoustic wave propagation is therefore immune to the path loss limitations of radio wave propagation in soil. This introduces the possibility of extending the digital communication range within a wireless underground sensor network beyond 3 m by using the buried water pipe as an acoustic waveguide.

Kokossalakis (2006) investigated acoustic-based data communication along a water pipe waveguide using the internal medium of an empty polyvinyl chloride (PVC) pipe (100 mm diameter and 9 m length) as the acoustic communication channel. However, the results indicated that the reliability of the communication system varied between 0% and 80%. In addition to its unpredictability, the data communication nodes needed to be deployed inside the pipe which, according to Pal (2008), can pose health and safety risks for customers (owing to potential water contamination) in addition to the additional costs of creating access points within the pipe. Joseph et al. (2018) further demonstrated underwater acoustic data communication along a buried steel pipe using non-invasive acoustic transducers; however, there is currently no evidence of the applicability of this technique to non-metallic pipes. Rather than using an internal fluid medium, Jin et al. (2013) investigated the pipe wall as an acoustic communication channel by designing an ultrasonic-based digital communication system using time reversal pulse position (TR-PPM) modulation. Although acoustic communication along the pipe wall was reported by the authors, reliable digital communication distances along the pipes were limited to less than 2 m. Moreover, the digital communication experiments were only conducted along exposed water pipes (of metallic nature) within a laboratory environment without further examination of buried water pipes. Jin et al. (2013) also showed the dispersive nature of a pipe wall in contributing to data communication unreliability (increased bit error rate (BER)) along the pipe. For plastic pipes, which are significantly more dispersive than metallic pipes (e.g., Muggleton et al., 2002), poorer digital communication performance is expected, resulting in even shorter ranges of reliable acoustic data communication. One option for minimising the acoustic signal dispersion along the pipe is by using low-frequency (less than 1 kHz) acoustic excitation, where a minimum number of acoustic wave modes propagate along the pipe. One such acoustic propagation mode is the fundamental longitudinal acoustic wave. Acoustic transmission experiments by Long et al. (2003) along a buried ductile iron pipe showed the possibility of generating and detecting this acoustic wave mode along a pipe wall at distances approaching 10 m using non-invasive acoustic excitation of the pipe. However, these studies were limited to pipe condition assessment and so the possibility of using this fundamental longitudinal acoustic wave propagation mode along a buried water pipe for reliable wireless underground communication remains unexplored.

To address the challenge of cost-effective and real-time buried water pipe monitoring based on the current state-of-the-art wireless underground communication for buried pipeline monitoring, the key features of a potential communication system solution are to:

I. Operate at a minimum internode distance of 3 m to reduce deployment costs of individual data communication nodes which, according to Johnson et al. (2009), costs approximately £100 per node for a traditional radio-based communication system.

II. Enable reliable digital communication at less than 1% BER (based on the recommendation of Akyildiz et al. (2009) for reliable wireless underground communication) with a data transmission rate of at least 1 bit per second (bps) which is the minimum requirement for real-time data communication.

III. Operate with a power supply capacity of less than 10 W, available from a miniature off-the-shelf single-cell battery with maximum physical dimensions of tens of millimetres. Compared to energy-harvesting solutions, the battery cell approach is more flexible in terms of node installation location along the buried pipeline network (especially in cases where wireless underground communication nodes are retrofitted to existing pipes), non-invasive, and can enable long-term buried pipeline monitoring through efficient power management (Metje et al., 2012; Walton et al., 2011). For example, using a 9 V commercially available battery with a nominal power supply capacity of 6 Watt-hour (Battery Station, 2021) data transmission of 10-minute duration once every 24 hours can potentially enable continuous system operation beyond 1 year (before replacing the battery) if the power consumption is less than 0.1 W per data transmission. Therefore, it is advantageous for the communication system to prioritise power conservation over data transmission capacity to prolong the battery lifetime.

Based on these requirements, this paper describes the development of a low cost (a maximum of a few tens of UK pounds), low power supply capacity (in the order of 1 Watt-hour), and miniature (centimetre scale) size wireless underground communication solution for the real-time monitoring of buried water pipes. The main contribution of this paper is therefore to demonstrate, for the first time, the possibility of achieving reliable acoustic wireless underground communication, at distances beyond the traditional radio-based limit of 3 m, using low frequency acoustic propagation along a buried non-metallic water pipe.

2. Methodology

2.1 Operational layout

The prototype communication system is digital in nature owing to the unique advantage of the possibility of transmitting digitally compressed information, to potentially minimise the power consumption of a digital communication node. A block diagram of the prototype system, involving the core elements of a standard digital communication system, is shown in Figure 1. The system can be divided into digital transmitter and receiver sections comprising the following core elements: message generation, message encoding, digital modulation, signal transmission (in this case, acoustic wave transmission along a pipe), digital demodulation, message decoding, and message reception. Figure 1 also shows a synchronisation component within the communication system, which, along with the other communication stages, will be described in Sections 2.4 and 2.5.

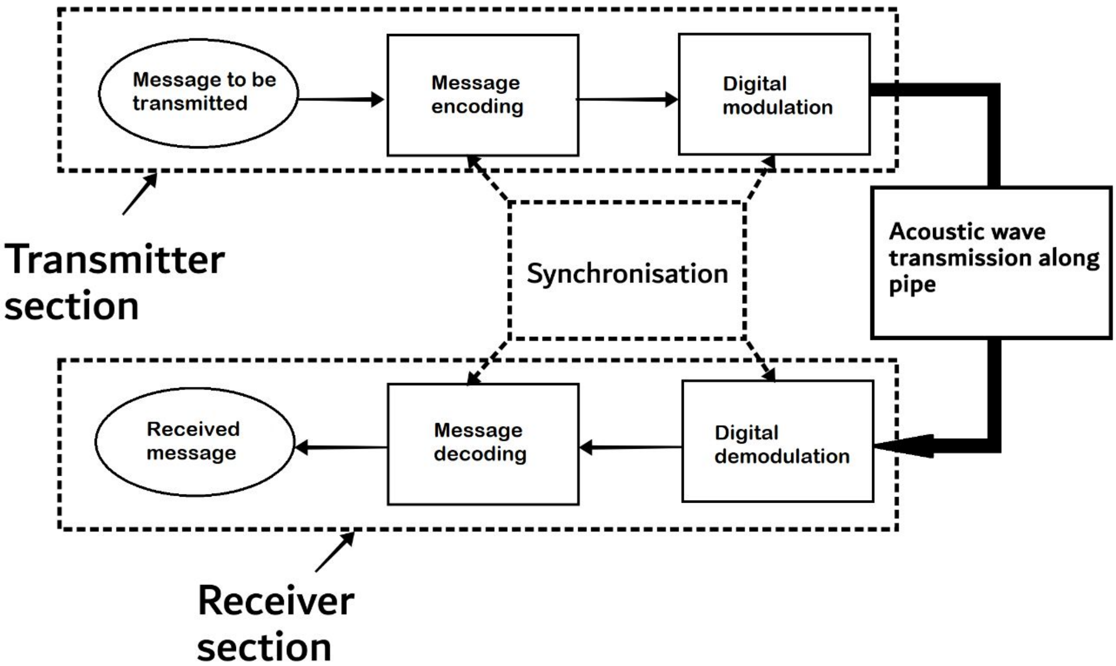


Figure 1. Operational stages of the proposed communication system

2.2 Hardware layout

Based on the system requirements in Section 1, a maximum hardware cost of £100 was stipulated for each digital communication node. A 9 V battery with a height of 49 mm, width of 26 mm, depth of 17 mm, and nominal power supply capacity of 6 Watt-hour (Battery Station, 2021) was also employed as the power source at each digital communication node. The hardware specifications of each digital communication node are summarised in Table I.

Table I: Hardware specifications for a digital communication node

Maximum cost (£)	Maximum physical dimensions (mm)	Power supply capacity (Watt-hour)
100	Length: 200 Width: 100 Height: 50	6

Owing to the cost, size, and power restrictions of the communication system described in this work, an embedded systems design approach (at the heart of which is a microcontroller) was adopted. To develop the embedded system in the laboratory, the hardware layout required to achieve stepwise functions of the proposed communication system is shown in Figure 2.

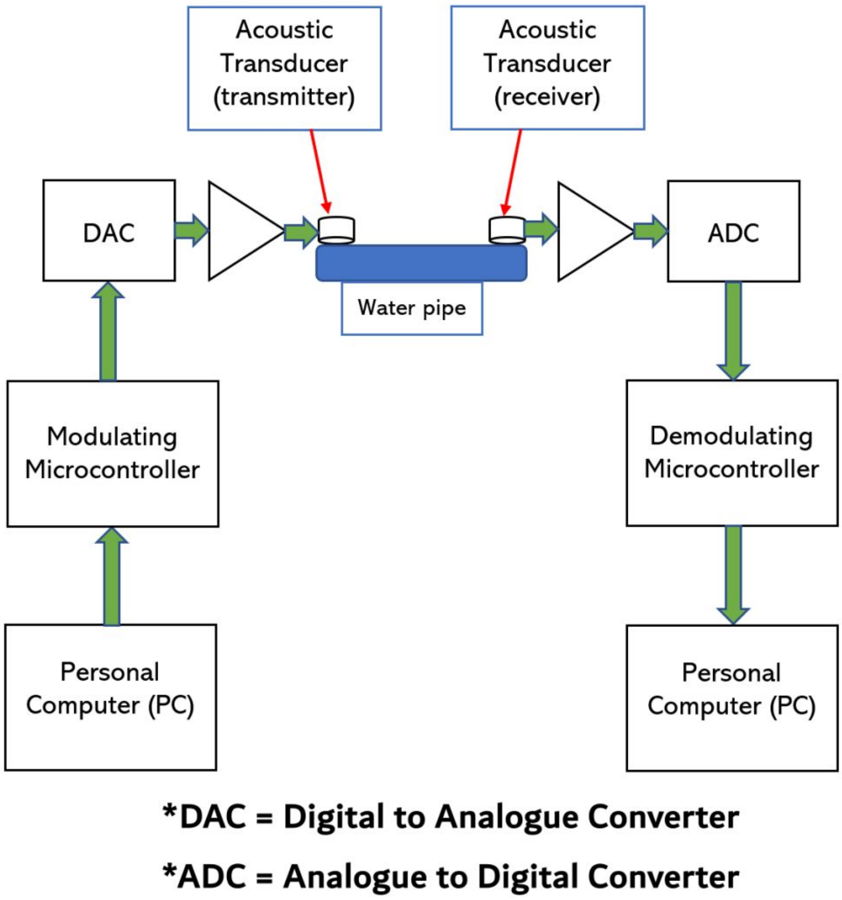


Figure 2. Hardware layout of the proposed communication system in the laboratory

From the perspective of an embedded system design, Figure 2 can be functionally described as a microcontroller module, an external interface circuit, and acoustic transducers. In Figure 2, although the modulating/demodulating microcontroller fulfils the role of the microcontroller module, the PC can also be regarded as an extension of this microcontroller module, as it is itself a collection of multiple microcontrollers connected through the output/input ports of the PC to the modulating/demodulating microcontroller. The digital-to-analogue converter (DAC), analogue-to-digital converter (ADC), and signal amplifiers can further be regarded as external interface circuits between the microcontrollers and acoustic transducers. The embedded system design of the digital communication transmitter or receiver thus comprises a microcontroller, an external interface circuit, and an acoustic transducer which converts electrical energy into acoustic energy (and vice versa).

2.3 Acoustic transducer selection

An acoustic transducer is an acoustic actuator or sensor which can be employed for generating or detecting acoustic waves. Among the various categories of commercially available acoustic transducers, electrical to mechanical (and vice versa) acoustic transducers present two key advantages:

I. Most vibration motion control systems are designed using integrated electronic circuits because of the high pervasion of digital logic circuit designs in vibration actuation and sensing systems (Lee, 2011; Pons, 2005). Digital logic circuit design also presents an important avenue for reducing the physical size of an electronic circuit featuring an acoustic transducer.

II. Owing to the high pervasion of digital logic circuitry, the availability of electronic components is greater for electrical to mechanical energy conversion (and vice versa) in acoustic transducer circuits than for other types of acoustic transducer circuits featuring non-electrical to mechanical energy conversion. This is largely owing to the relatively low cost of transducer fabrication and readily available off-the-shelf electronic components which can be integrated within such an acoustic transducer circuit (Pons, 2005).

To further condense the pool of potential candidates for acoustic transducer selection, additional restrictions on the transducer characteristics are specified as follows:

I. The acoustic transducers must operate below 1 kHz.
II. The acoustic transducers must cost less than £100 (since the overall cost of the digital communication node should not exceed £100).
III. The physical dimensions of the acoustic transducers must be less than the maximum size of the digital communication node (i.e., less than 200 mm long, 100 mm wide and 50 mm high).
IV. The acoustic transducer design must allow for the direct coupling of acoustic energy into a solid as opposed to fluid media. This requirement separates vibration transducers from traditional acoustic speakers.
V. The power supply requirement of each acoustic transducer must be sufficiently low to be supplied by a power source which is sufficiently compact to be integrated within the digital communication nodes. In other words, only acoustic transducers with potential power source dimensions within tens of millimetres were considered.
VI. The acoustic sensors must be "active" (i.e., sensors which, by themselves, do not require an external power supply to operate) rather than "passive" (i.e., a sensor which only operates with an external power supply). An active sensor, as opposed to its passive counterpart, presents a more attractive choice for the communication system because it could potentially reduce the overall power demand at the digital communication receiver.

From a survey of commercially available acoustic transducers, the external eccentric rotating mass (ERM) vibration motor (Precision Microdrives, 2015) was selected over other acoustic actuators for acoustic transmission within the communication system because of its higher acoustic signal amplitude (approximately twice its nearest competitor) compared to other acoustic actuators (Farai, 2021). The macro-fibre composite (MFC) transducer, on the other hand, was selected as the communication system acoustic sensor, due to its unique compromise between structural rigidity and electromechanical conversion efficiency coupled with its low cost. The specific brand of the MFC transducer from Smart Material Inc. (Smart Material, 2015), offering a good compromise of cost, size, and power requirement, was the M-2814-P2 piezoelectric transducer.

2.4 Digital communication transmitter development

From Figure 1, the operational stages of the digital communication transmitter were outlined as the message to be transmitted, message encoding, digital modulation, and message synchronisation (with the digital communication receiver) processes. Message encoding transforms an acquired message at the input of a digital communication system into its corresponding binary format for further transmission across the system (Proakis & Salehi, 2008; Kokossalakis, 2006). The ASCII encoding scheme was employed to transform a digital message entered on the PC in Figure 2 into a binary form. The digital modulation stage followed the message-encoding stage. Digital modulation refers to the process of manipulating the physical characteristics of a signal according to a predefined set of data symbols representing the message to be transmitted (Proakis & Salehi, 2008; Kokossalakis, 2006). Owing to the choice of the ERM vibration motor, its resonant frequency during operation represented the acoustic carrier wave which was modulated with digital passband modulation. . Depending on the property of the carrier wave to be modulated, digital passband modulation can be amplitude shift keying (ASK), frequency shift keying (FSK) or phase shift keying (PSK). Other digital modulation techniques applicable across the digital communications industry include (but are not limited to) quadrature amplitude modulation (QAM) and pulse amplitude modulation (PAM). Non-binary digital modulation techniques, however compared to binary modulation techniques, require increasingly complex signal processing circuitry to minimise symbol detection ambiguity at a digital communication receiver (Kokossalakis, 2006). A binary modulation approach was therefore chosen due to its inherent reliability with minimal signal processing complexity.

The choice of the binary modulation technique was based on a compromise between power and bandwidth considerations for the communication system. While on the one hand, modulation techniques such as amplitude shift keying (ASK) and phase shift keying (PSK) are more suitable for bandwidth limited channels (such as that presented by the ERM motor operating between 0 and 200 Hz), the frequency shift keying (FSK) technique is more suitable for power limited channels (e.g., in an underground environment where power sources are limited). However, the FSK technique is disadvantageous for bandwidth-limited channels owing to its poor bandwidth efficiency (Proakis & Salehi, 2008; Kokossalakis, 2006). Considering these challenges (i.e., limited bandwidth and power supply), a specialised form of ASK known as on-off-keying (OOK) which combines the benefits of bandwidth efficiency (1 bit/Hz) and power conservation (through data transmission by intermittent activation and deactivation of the digital communication transmitter), was adopted for the communication system design.

For the modulating microcontroller shown in Figure 2, an LPC1768 microcontroller (NXP, 2016) was employed due to its low cost, small size, and low power requirement. Furthermore, to implement the OOK modulation algorithm, the microcontroller was interfaced with a vibration motor through an external interface circuit. This external interface circuit was designed to systematically switch the vibration motor between the full power ("on" state) and no power ("off" state) states during digital transmission. To achieve this objective, an L293D integrated circuit (IC) from Texas Instruments (Texas Instruments, 2016) was integrated into the communication transmitter. This L293D is a low-cost (less than £5), small size (38 mm length and 17 mm width), and low-power (as low as 0.04 W) electronic device capable of driving a direct current (DC) motor with currents approaching 600mA in both forward and reverse directions (Texas Instruments, 2016). With a combination of the modulating microcontroller (LPC1768) and the L293D H-bridge circuit, binary information was modulated at the digital communication transmitter using the OOK modulation algorithm. More details on the digital communication transmitter development using the OOK modulation algorithm and the binary data transmission algorithm can be found in Farai (2021). Figure 3 shows the printed circuit board (PCB) design of the digital communication transmitter with a microcontroller, serial port (for PC communication), and H-bridge (L293D) circuit for interfacing with the ERM vibration motor.

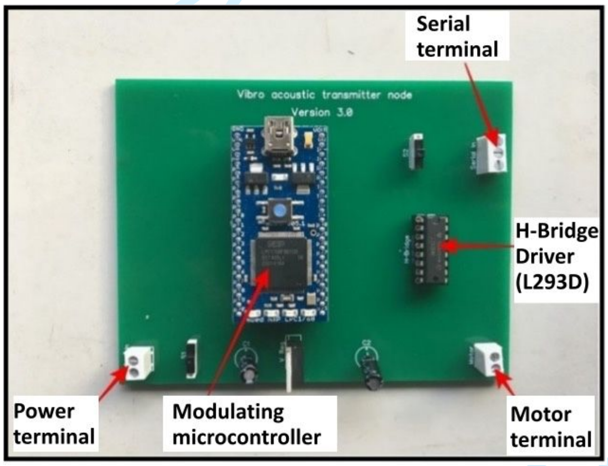


Figure 3: Printed circuit board of the acoustic communication transmitter

The digital communication transmitter developed and described thus far represents one half of the proposed communication system, enabling the transmission of digitally modulated information along a water pipe. The second half of the communication system comprised a digital communication receiver designed to successfully demodulate and extract this digitally transmitted information from the pipe. The method by which this was achieved is described next.

2.5 Digital communication receiver development

Once the acoustic signal was detected along the pipe by the MFC sensor and before digital demodulation could occur, the standard practice of amplifying the detected signal (which, like in any wireless communication system, was expected to have experienced some degree of attenuation between the transmitter and receiver) was implemented. A signal pre-amplifier circuit, the core of which was an operational amplifier (Linear Technology, 1983) with input and feedback resistances of 1 kΩ and 79 kΩ respectively, was designed to interface the MFC sensor with the rest of the digital communication receiver.

Following signal amplification at the front-end of the digital communication receiver, a noncoherent demodulation approach was designed due to the reduced signal processing complexity involved with this approach. To further guarantee digital communication reliability with the non-coherent demodulator, a phase-locked loop (PLL) was implemented as part of the digital communication receiver. With this method, the digital communication receiver was synchronised with the digital communication transmitter using carrier synchronisation. Thus, once the receiver detected and "locked" on to an initially transmitted acoustic pulse (i.e., pilot signal) from the digital communication transmitter, the digital demodulation process was initiated before synchronous demodulation of subsequently transmitted acoustic pulses from the digital communication transmitter.

The hardware employed for noncoherent demodulation at the digital communication receiver was a PLL integrated circuit (IC), LM567, from Texas Instruments (Texas Instruments, 2014). The LM567 is a low-cost (£1), small-sized (9.8 mm length and 6.4 mm width), and low-power (0.1 W) device consisting of phase detectors, a voltage-controlled oscillator (VCO), and a signal comparator. The phase detectors and VCO further operated within an LM567 feedback loop (including a low-pass filter), are shown in Figure 4.

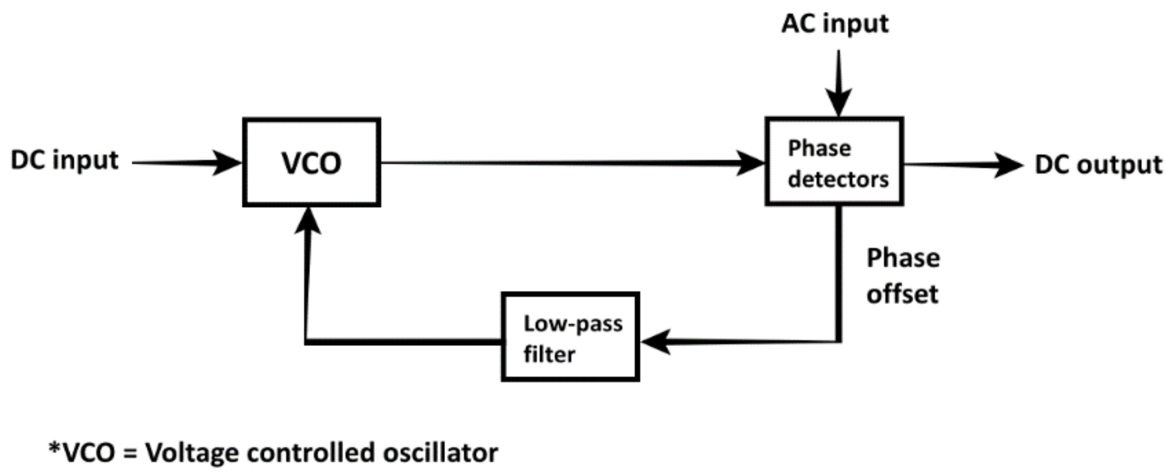


Figure 4. Feedback loop showing the phase detectors and the voltage-controlled oscillator of the PLL

During operation, the phase detectors compared the AC input from the signal preamplifier with a VCO-generated signal. The phase offset between these signals was subsequently fed back into the VCO using a low-pass filter to adjust its frequency. The VCO frequency was thus continuously adjusted through this feedback loop until a constant phase offset was generated, resulting in the "phase locking" of the loop. Once phase-locking was achieved, a DC signal was produced at the output of the phase detectors, signifying a lock condition of the PLL, where the VCO frequency matched the frequency of the input AC signal. For the noncoherent demodulator, this was a crucial step in recovering the transmitted digital information signal.

Once the incoming acoustic signal was locked by the PLL, the DC output signal was subsequently generated by the PLL. As this was vital, a light-emitting diode (LED) which activated upon phase locking was also incorporated into the digital communication receiver to visually confirm this phase locking.

The key to synchronising the operational stages of the digital communication receiver (using carrier synchronisation) with the digital communication transmitter was the creation of an interrupt service routine (interrupt handler) which was triggered at the demodulating microcontroller upon the arrival of an incoming pilot signal. A flowchart of the interrupt handler is shown in Figure 5.

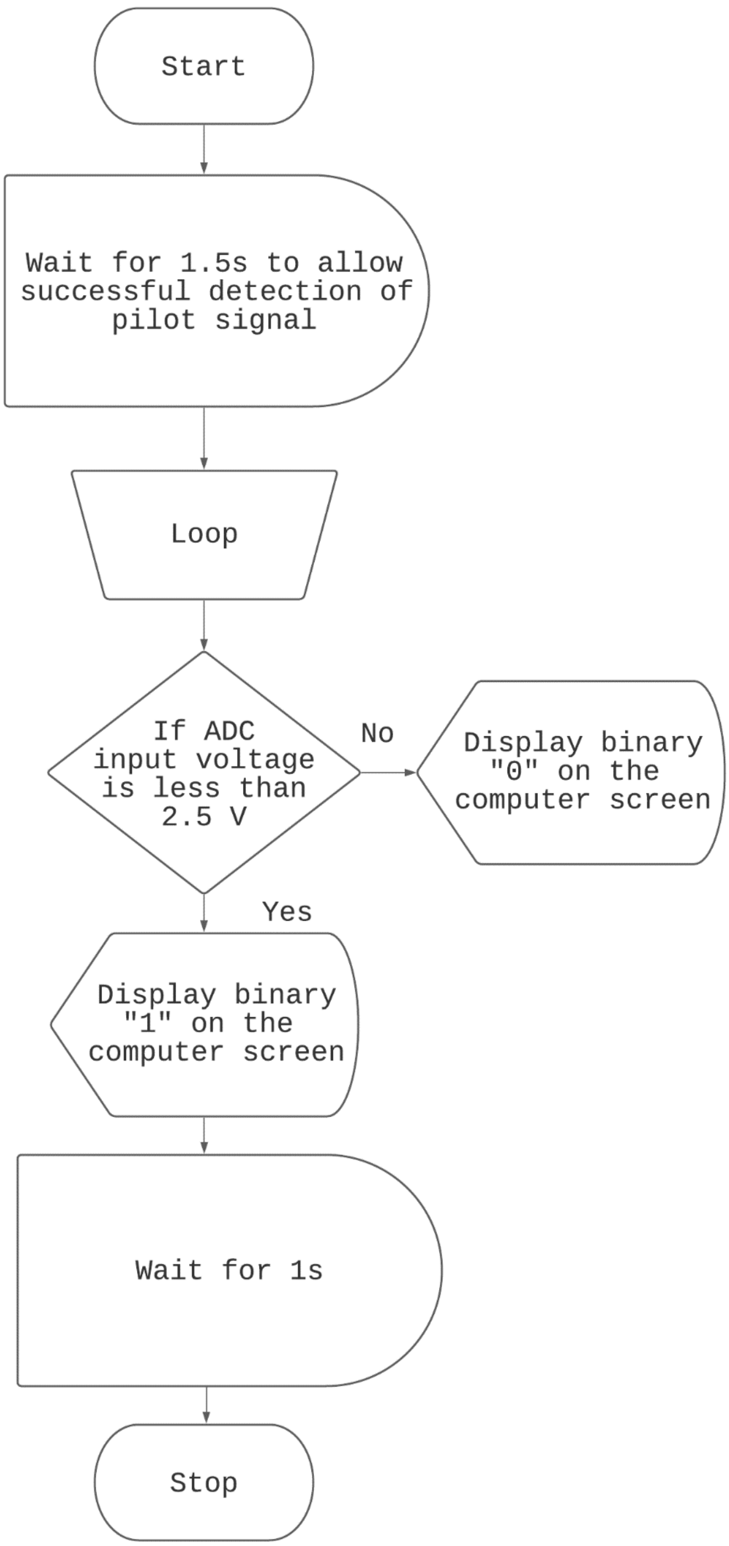


Figure 5. Flow chart for the binary message interrupt handler at the digital communication receiver

The interrupt handler began with an initial 1.5 s delay once it was triggered by the arrival of the pilot signal at the digital communication receiver. Following the pilot signal delay, a decision was repeatedly made (every 1 s) at the input ADC of the demodulating microcontroller regarding the voltage level of the DC signal at the PLL output. With this ADC, the input voltage range for detecting a binary "1" was set as $<$ 2.5 V while the voltage range for a binary "0" was set as $\geq$ 2.5 V based on the active LOW nature of the PLL output DC signal. This 2.5 V threshold was incorporated to further reduce the possibility of random noise interference with correct recovery of transmitted binary information at the digital communication receiver. Figure 6 shows the final hardware design of the digital communication receiver, complete with the demodulating microcontroller, serial port (for PC communication), PLL circuit, LED indicator, and signal pre-amplifiers which interfaced the MFC with the rest of the digital communication receiver.

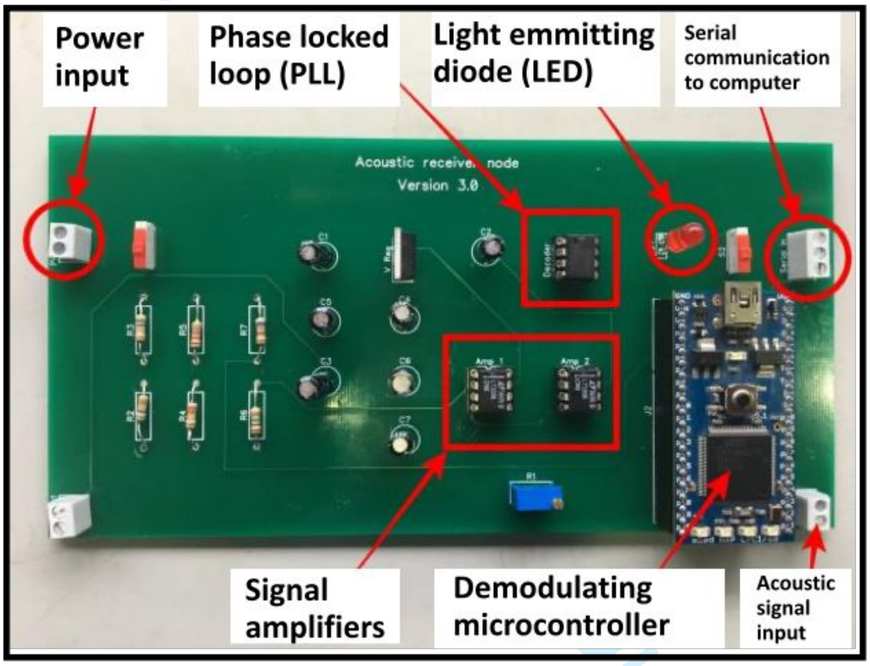


Figure 6. PCB design of the digital communication receiver

2.6 *Laboratory and field trials of the proposed communication system*

Following the development of the digital communication receiver, the complete communication system was tested along two types of buried water pipes in separate field trials. The first field trial featured a 150 mm buried steel pipe in poorly graded SAND (SP). A schematic illustration of the communication system deployment for this field trial is shown in Figure 7 with the ERM vibration motor installed at the pipe valve while the MFC sensors were directly installed along the buried pipe surface. While it would have been preferrable to install the vibration motor directly along the buried pipe, the timing of the leak repair operation by a third party only allowed direct installation of the MFC sensors along the buried pipe. Nevertheless, the field trial still provided valuable insight into the digital communication system performance along a buried steel pipe as will be discussed in section 3.

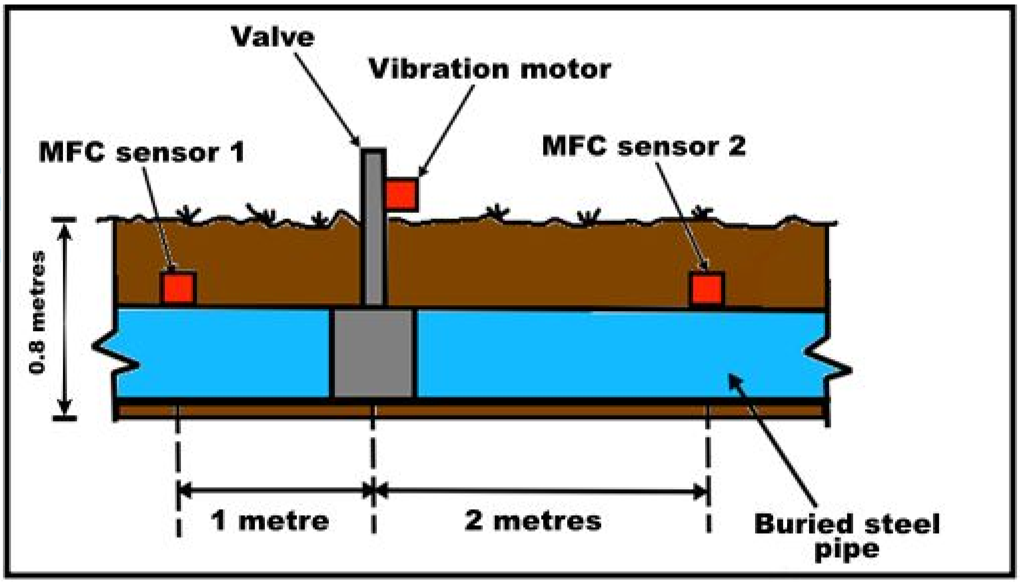


Figure 7: Digital communication system deployment along buried steel pipe

The second field trial of the digital communication system was conducted along a 6 m length MDPE pipe buried at 0.8 m depth in a trench of 8 m length before backfilling the trench with well graded sand (SW). The schematic illustration of the communication system deployment for this trial is shown in Figure 8.

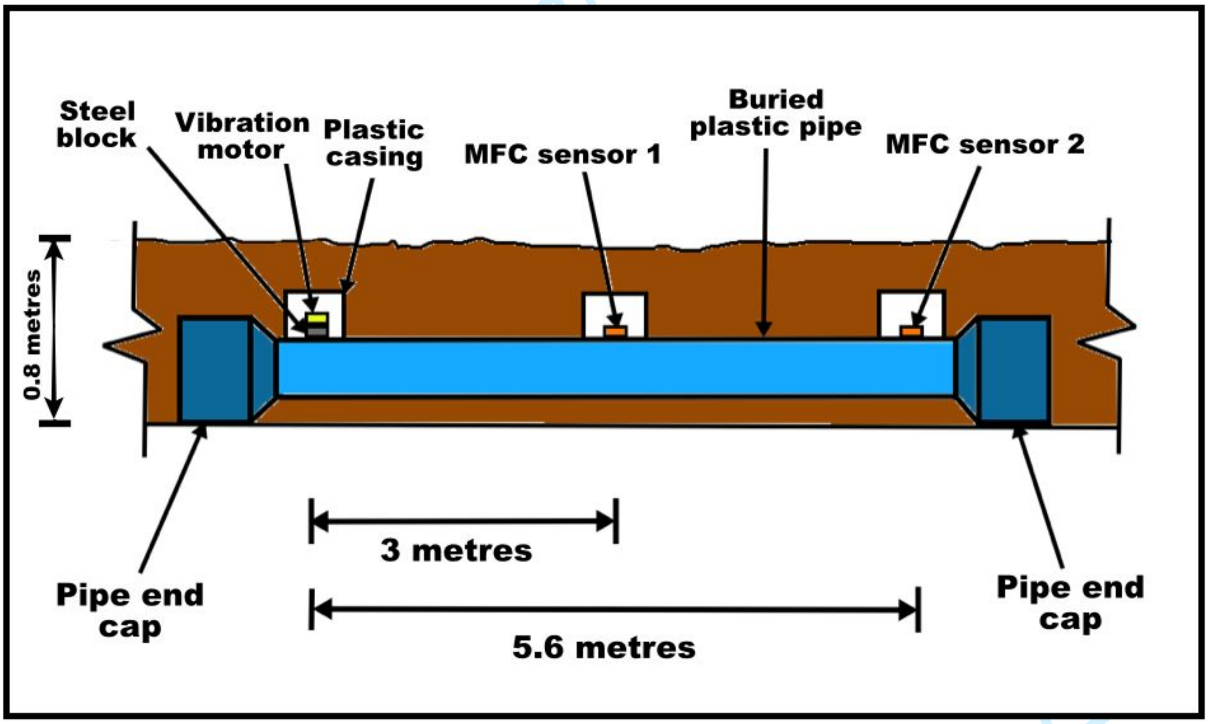


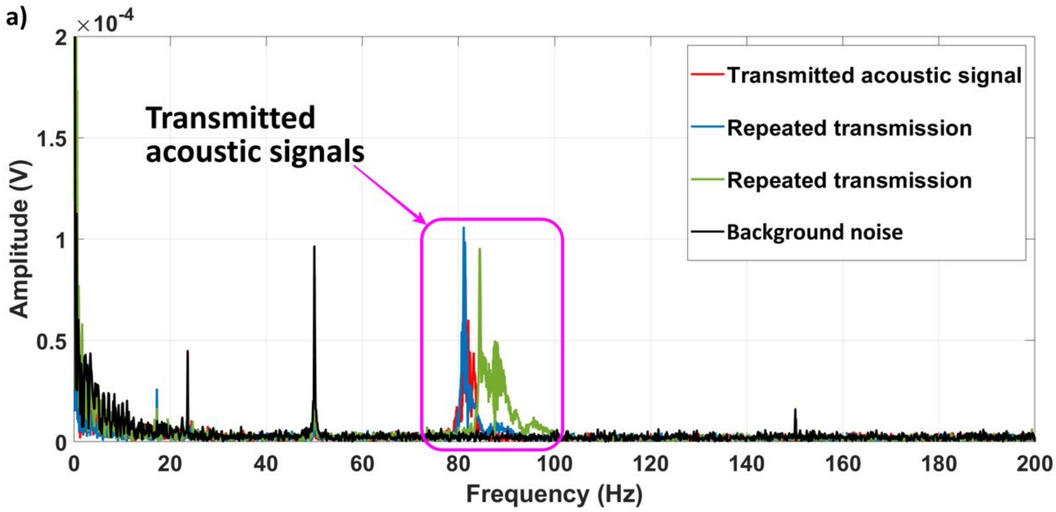
Figure 8: Digital communication system deployment along buried MDPE pipe

For the buried MDPE pipe (as shown in Figure 8), one vibration motor and two MFC sensors were installed along the pipe with the vibration motor installed at one end of the pipe, while the MFC sensors were installed 3 m and 5.6 m from the vibration motor. While 3 m was chosen to reflect the minimum distance threshold of wireless underground communication for the tests, the 5.6 m distance was chosen to test the data communication close to the maximum pipe length. Both the vibration motor and sensors were enclosed within the plastic casings to ensure protection against soil debris after trench backfilling.

In addition to acoustic communication experiments, acoustic signal attenuation experiments were also conducted along the buried pipes to examine the maximum theoretical distance at which reliable digital communication is possible using the proposed communication system along each pipe. For the acoustic attenuation experiments, the piezoelectric (MFC) sensors were connected to a digital acquisition device (DAQ) (National Instruments, 2009) to capture digitally transmitted acoustic pulses along the buried pipes. The acoustic pulse widths were fixed at 1 s to represent a minimum data communication rate of 1 bps. Since acoustic attenuation (decibels/metre) of the fundamental longitudinal acoustic wave propagating along a pipe wall is linear in nature (Farai et al., 2023; Muggleton et al., 2002), acoustic attenuation along the buried water pipes was calculated by dividing the difference in acoustic signal to noise ratio (SNR) at each acoustic receiver by the separation distance between the acoustic receivers. These results, along with a discussion of the communication system performance, are presented next.

3. Results and discussion

For the buried steel pipe, Figure 9 shows the measured acoustic signals at 1 m and 2 m from the acoustic transmitter during repeated acoustic transmissions along the pipe, while Table II shows the average acoustic SNR of the transmitted acoustic signals (70 – 100 Hz) at each acoustic receiver.



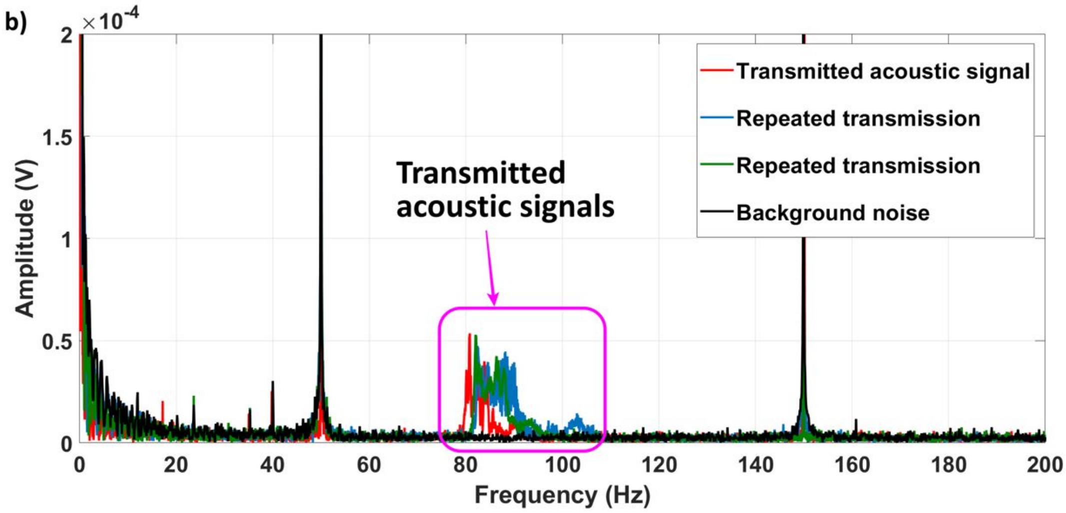


Figure 9: Transmitted acoustic signals along the buried steel pipe at a) 1 m and b) 2 m

Table II: Measured acoustic SNR along the buried steel pipe

Distance (m)	Average SNR (dB)	Standard deviation (dB)
1	32.5	2.1
2	27.4	1.0

The acoustic attenuation along the buried steel pipe was calculated as 5.1 dB/m using data in Table II. Numerical predictions of acoustic attenuation along an infinitely long buried steel pipe were also conducted by Farai (2021) to compare the field results. The selected input parameters for the pipe in the numerical model are summarised in Table III. The soil was simulated as being homogenous and isotropic with a soil bulk density and bulk modulus of 1663 kg/m^3 and 1.7x10^8 N/m^2 respectively. These values represented the properties found in the field.

Table III: Input parameters for the buried steel and MDPE pipes for the numerical model

Parameter	Steel pipe	MDPE pipe
Diameter	150 mm	90.6 mm
Wall thickness	9 mm	9.2 mm
Density	7800 kg/m^3	900 kg/m^3
Elastic modulus	0.2×10^{11} N/m^2	1.6×10^{9} N/m^2
Poisson's ratio	0.310	0.4
Material loss factor	0.002	0.06

The numerical modelling results showed that for the ideal case of an infinitely long buried steel pipe, acoustic attenuation along the pipe was predicted is 1.3 dB/m (Farai, 2021). The field results, on the other hand, show significantly higher acoustic attenuation of 5.1 dB/m due to the presence of pipe wall discontinuities (introduced by the pipe valve connection in Figure 7). This suggests that a more complex numerical model is required to capture the pipe wall discontinuities more accurately.

For the buried MDPE pipe, Figure 10 shows the measured acoustic signals along the pipe at 3.0 and 5.6 m from the acoustic transmitter during repeated acoustic transmissions while Table IV shows the average acoustic SNR of the transmitted acoustic signals (120 – 140 Hz) at these distances.

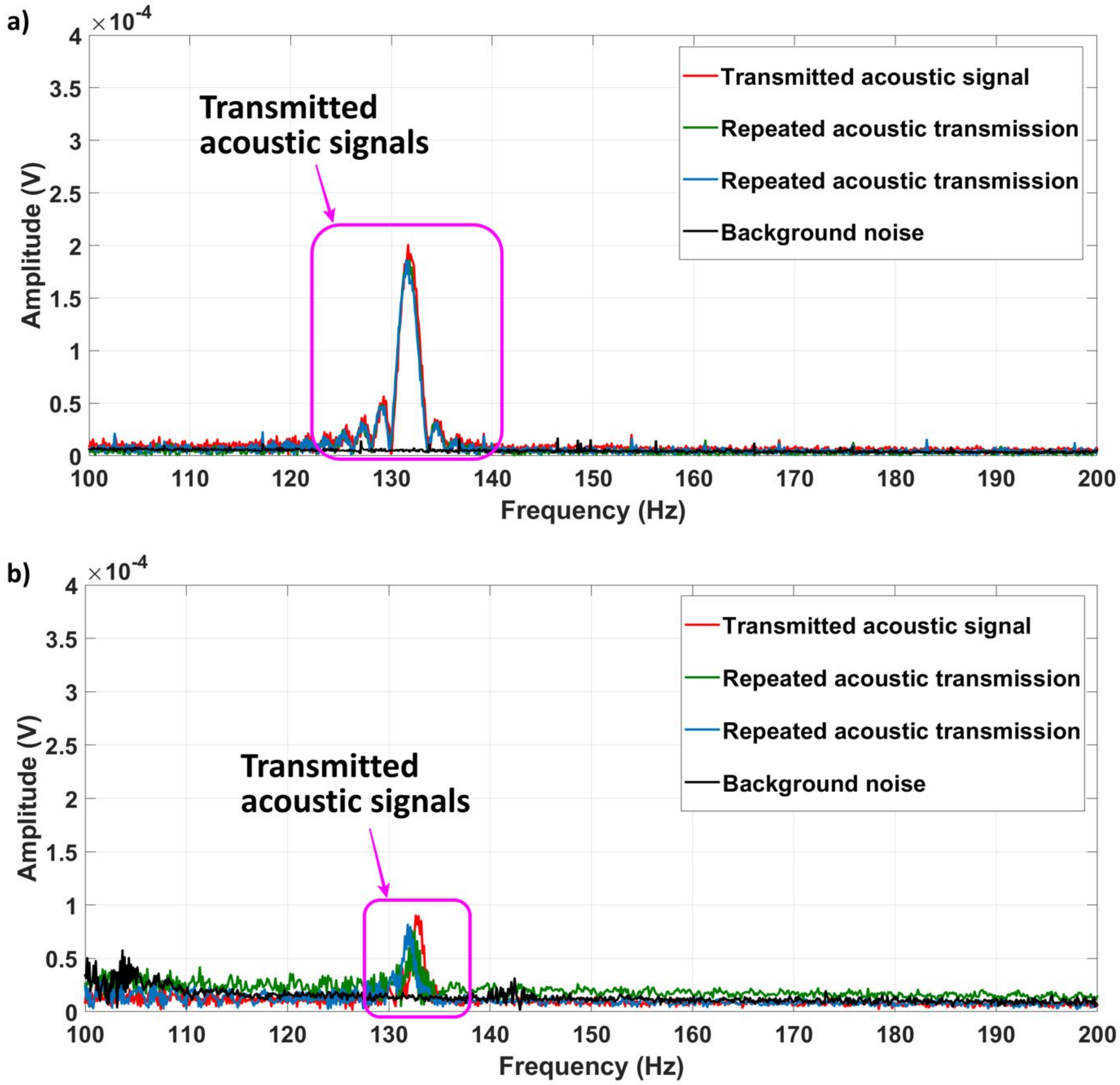


Figure 10: Transmitted acoustic signals along the buried MDPE pipe at a) 3 m and b) 5.6 m

Table IV: Measured acoustic SNR along the buried MDPE pipe

Distance (m)	Average SNR (dB)	Standard deviation (dB)
3.0	37.4	0.3
5.6	25.2	0.3

From Table IV, the change in acoustic SNR between 3 m and 5.6 m was calculated as 12.2 dB. With a sensor spacing of 2.6 m, acoustic attenuation along the buried MDPE pipe was calculated as 4.7 dB/m.

For the buried MDPE pipe, detailed numerical modelling was also conducted by Farai (2021) to predict acoustic attenuation along a finite length pipe (as opposed to an infinitely long pipe) of 6 m. The selected input parameters for the pipe in the numerical model are also summarised in Table III. For the MDPE pipe, the soil was simulated as being homogeneous and isotropic with a soil bulk density and bulk modulus of 2123 kg/m^3 and 1.8×10^9 N/m^2 respectively. Like the case of the buried steel pipe, these values represented the properties found in the field.

The numerical model for the buried MDPE pipe predicted acoustic attenuation of 2.1 dB/m along the pipe (Farai et al., 2023; Farai, 2021). This result is closer to, but still lower than the experimentally measured value of 4.7 dB/m. As noted by Muggleton & Yan (2013), shear wave-controlled radiation from the pipe into the surrounding soil is primarily responsible for acoustic attenuation along a buried MDPE pipe. The numerical model was however limited to only capturing acoustic bulk wave radiation from the pipe into the soil (Farai et al., 2023; Farai, 2021) and so the difference between the experimental results and the numerical model prediction is understandable in this case.

Regarding the maximum acoustic data communication distance along the buried MDPE pipe using the proposed communication system, the bit error ratio (BER) at increasing distances of the data communication receiver from the data communication transmitter was further calculated. BER is the probability of incorrectly decoding a previously transmitted digital information signal at a digital communication receiver (Mutagi, 2012; Kokossolakis, 2006). Using the OOK digital modulation technique of the proposed communication system, the BER along the pipe can be expressed as

$$BER = \frac{1}{2} erfc\left(\sqrt{{}^{1}/_{2}SNR}\right) \quad (1)$$

where BER is the bit error ratio of the digital information signal, SNR is the signal to noise ratio of the digital information signal, and $erfc(x)$ is the complementary error function ($erfc(0) = 1$). Equation (1) shows that the BER depends on the SNR of the transmitted signal (in this case, the acoustic signal transmitted along the water pipe). Owing to acoustic signal attenuation along the pipe, the SNR will decrease at increasing distances along the pipe. Therefore, the objective of this discussion is to use Equation (1) to examine data communication reliability along a buried MDPE pipe, thus predicting the maximum distance at which reliable digital communication can be achieved along the pipe.

For the digital communication receiver described in Section 2.5, the SNR of the signal pre-amplifier output voltage with respect to the input threshold voltage of the PLL was calculated.

Based on the parts selection for the digital communication receiver design, the maximum output voltage of the signal preamplifier was 4 V while the PLL input threshold was 0.2 V. The maximum SNR between the signal preamplifier output and the PLL input threshold was therefore calculated as 26 dB. This maximum SNR can be considered as the point at which there is no acoustic signal attenuation within the communication system, i.e., the acoustic receiver is 0 m from the acoustic transmitter. For constant acoustic transmitter power, this acoustic SNR will continue to diminish as the digital communication receiver moves away from the transmitter owing to acoustic signal attenuation along the pipe.

Using the measured and predicted acoustic attenuation along the buried steel and MDPE pipes, as well as Equation (1), the maximum distances at which reliable digital communication can achieved along the pipes are shown in Figure 11.

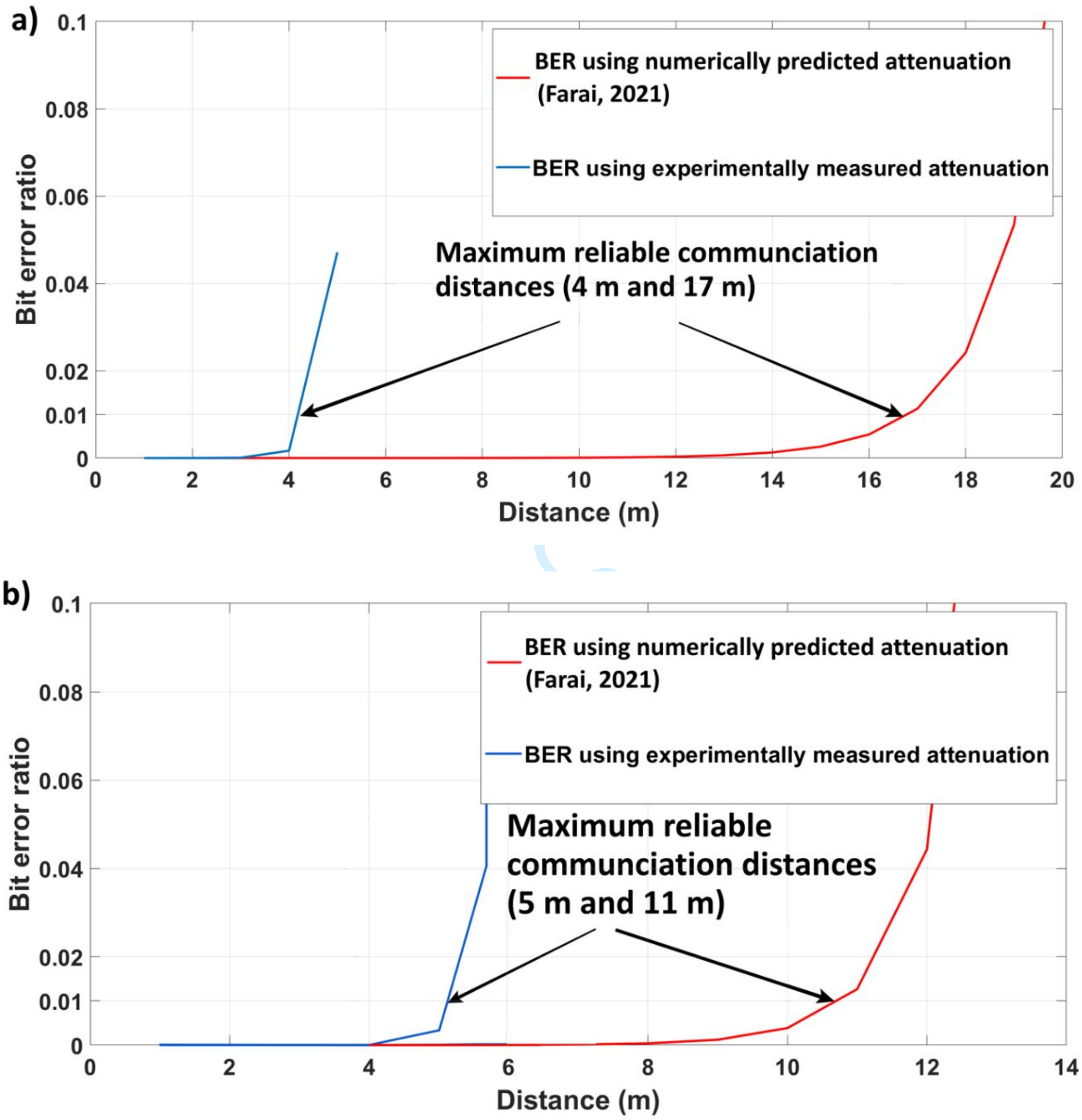


Figure 11: Acoustic data communication reliability along the buried a) steel pipe and b) MDPE pipe

Reliable data communication was assumed when the BER is less than 1% (beyond which data communication becomes unreliable) which was based on the recommendation of Akyildiz et al. (2009) for underground wireless communication. From Figure 11, reliable data communication was predicted at distances of at least 4 m along the buried steel pipe and 5 m along the buried MDPE pipe. It is important to note here that higher acoustic attenuation was measured along the buried steel pipe (compared to the buried MDPE pipe) due to the presence of pipe wall discontinuities at the valve connection (Figure 7) which increased acoustic attenuation along the pipe. Consequently, a lower acoustic data communication range was predicted along the buried steel pipe (compared to the buried MDPE pipe) using the experimental results. Without this valve connection, the numerical prediction shows the possibility of achieving reliable (0% BER) digital communication at distances of up to 17 m along the buried steel pipe. Joseph et al. (2017), by comparison, reported acoustic communication along a buried steel pipe (also using non-invasive acoustic transducers) at a BER of 30% which is significantly higher than the 0% BER demonstrated in this paper. Moreover, the acoustic communication system reported by Joseph et al. (2017) relied on acoustic wave propagation within the internal fluid medium of a fully filled water pipe, thus presenting uncertainties as to whether reliable digital communication is possible along empty or partially filled water pipes. With acoustic propagation along the pipe wall however, Farai (2021) showed that, at less than 1 kHz, the internal fluid medium has minimal impact on acoustic attenuation along the pipe wall. The communication system presented in this paper is thus more robust to the challenges of variable internal fluid conditions within the buried water pipe. This quality is advantageous for system deployment along wider water distribution networks where internal fluid conditions along the buried pipes can vary significantly.

For the MDPE pipe, the experimental and numerical predictions of acoustic data communication along the pipe show that even in the worst-case scenario, reliable acoustic based digital communication is still possible up to 5 m along the buried MDPE pipe (with a potential maximum communication distance of 11 m). It also goes without saying that acoustic data communication would be completely reliable at 3 m (unlike a radio communication option which will degrade at this distance) along the buried MDPE pipe. Figure 12 shows digital communication results, in the form of a binary bitstream, at 3 m along the buried MDPE pipe.

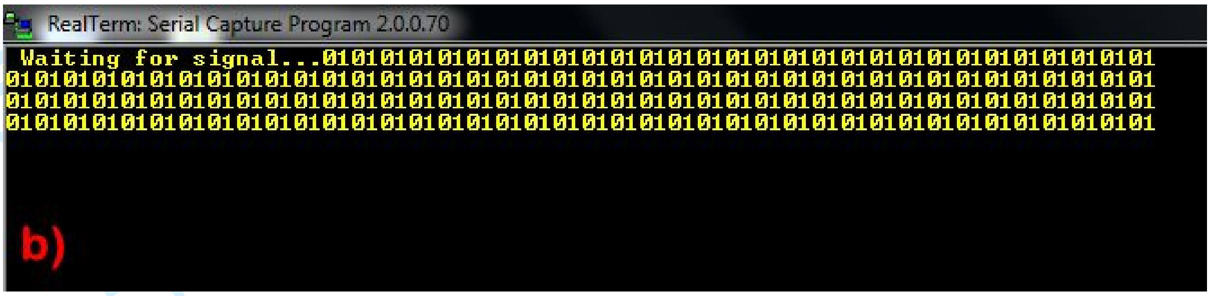


Figure 12: a) Idle status message at the digital communication receiver, b) digital communication results at 3 m along the buried MDPE pipe

From Figure 12, reliable (i.e., 0% BER) digital communication was captured along the buried MDPE pipe at 3 m, thus agreeing with the predicted BER for this distance. The results in Figure 12 demonstrate the first application of a reliable, non-invasive digital communication system along a buried MDPE pipe. Compared to a radio-based solution with similar cost, size, and power supply requirements for reliable wireless underground communication (which is limited to less than 3 m), this acoustic-based technique is an improvement which is especially noteworthy when considering that wireless sensors can be deployed at underground internode distances of up to 5 m compared to 3 m. With an increased internode distance, a buried water pipe network can be instrumented with fewer sensors of similar cost, power supply, and physical size requirements compared to a radio-based solution, thereby potentially reducing deployment costs for continuous pipeline monitoring using the acoustic-based communication system. Furthermore, although this communication system design is bandwidth limited (in the order of 1 bps), this latency may be tolerated for a non-data-intensive pipeline monitoring application (where less emphasis is on real-time data throughput) if, as is the objective of the communication system, longer ranges of wireless underground data communication can be achieved compared to existing solutions based on radio signal propagation.

As discussed in the introduction, proactive buried water pipe monitoring is advantageous for continuous monitoring since the cost implications of a complete pipe failure can be largely avoided with this approach. A potential application of the digital communication system described in this paper is to facilitate data communication of early warning signs of pipe deterioration within continuous pipeline monitoring framework. Since the deterioration processes of buried pipes are slow (Rajani & Kleiner, 2004), i.e., often months and years, a real-time data communication strategy for continuously monitoring should focus on capturing changes in baseline data using two-state logic to capture changes in the pipeline baseline data as determined by a preconfigured threshold at the sensor level. Therefore, during regular data transmission, measured data above a preconfigured threshold can be flagged as an alarm indicating a potential onset of pipe deterioration. Furthermore, data transmission can occur within a fixed time window (e.g., for 10 minutes every 24 hours or even weekly) to conserve limited underground power supply within the communication system thereby extending the operational life of the sensors. Data transmission can also be executed during periods of low environmental activity (e.g., 2am – 4am) to reduce potential communication interference by environmental noise. With this approach, even with a low data rate of at least 1 bps, the communication system described in this paper could be deployed for continuous, proactive buried water pipe monitoring.

For effective spatial sensor deployment, an accurate prediction of the ranges at which reliable wireless underground communication can be achieved between sensor pairs is required. Factors which can affect this digital communication range include the presence of pipe wall discontinuities (which introduce acoustic reflections along the pipe), pipe wall material, and surrounding soil properties, all of which can influence the acoustic attenuation along the pipe. Parametric analyses of these factors with respect to the prediction accuracy of acoustic attenuation along a buried MDPE pipe were discussed by Farai (2021). In terms of pipe wall material, Rogers et al. (2012) also noted that accurate knowledge of pipe material distribution within water supply networks in the UK is challenging because of variations in the type and quality of materials employed since these networks were originally constructed. Because acoustic attenuation is higher along buried nonmetallic pipes than along metallic pipes, it is advantageous to conservatively deploy wireless communication nodes at distances which are based on the predicted data communication range for buried nonmetallic pipes (e.g., approximately 5 m for the MDPE pipe described in this paper) to ensure reliable digital communication along the pipe. The bond between the pipe wall and the surrounding soil is also important because it can couple the acoustic energy between the pipe wall and soil through acoustic impedance matching between the pipe and soil. This is particularly important for buried cast iron pipes, where one of the main factors contributing to pipe deterioration is pipe wall corrosion (Rajeev et al., 2014). The increased acoustic attenuation in such a case will subsequently reduce the acoustic data communication range along the pipe depending on the degree to which acoustic energy is radiated from the buried pipe into the soil (which in turn depends on the strength of chemical bonding between the pipe wall and the surrounding soil).

4 Conclusions

A novel wireless underground communication system for monitoring buried water pipes using acoustic signal propagation along a buried MDPE is presented in this paper. Considering the cost, physical size, and power supply limitations of a wireless sensor node for buried pipeline monitoring, this study successfully demonstrated the possibility of using an acoustic-based digital communication system (as opposed to radio-based data communication) for real-time buried pipeline monitoring while pushing the boundaries of low-cost, low-power, and smaller hardware components for wireless communication nodes. With an embedded systems approach, a new data communication algorithm was developed and culminated in the development of separate low-cost (a maximum of a few tens of UK pounds), low-power supply capacity (in the order of 1 Watt-hour), and miniature (centimetre scale) working prototypes of digital communication transmitters and receivers. The digital communication system design focused not only on enabling wireless underground communication at distances beyond 3 m in an underground soil environment but also on ensuring that such data communication is reliable (i.e.,0% BER). In this regard, results from the field testing of the prototype communication system showed promise with reliable data communication successfully demonstrated at 3 m along a buried MDPE, in addition to a theoretical prediction of up to 5 m along the pipe. With an underground data communication distance of 5 m compared to 3 m (an increase of 40%

assuming linear sensor deployment), significant cost savings (owing to fewer deployed sensors) can be achieved for a wireless sensor-enabled continuous pipeline monitoring application, thus highlighting the potential cost benefit of the novel communication system proposed in this paper compared to traditional radio-based techniques.

References

Akyildiz, I.F. and Stuntebeck, E.P. (2006) 'Wireless underground sensor networks: Research challenges', *Ad Hoc Networks*, 4(6), pp. 669-686.

Akyildiz, I.F., Sun, Z. and Vuran, M.C. (2009) 'Signal propagation techniques for wireless underground communication networks', *Physical Communication, 2(3)*, pp. 167-183.

Pal, A., Guo, H., Yang, S., Akkas, M.A. and Zhang, X. (2023) 'Taking Wireless Underground: A Comprehensive Summary', *ACM Transactions on Sensor Networks, 1(1), pp. 1-42.*

Battery Station (2021). *Duracell Procell 9V PP3 6LR61 PC1604 Batteries | Box of 10*. Available at: https://www.batterystation.co.uk/duracell-procell-9v-pp3-6lr61-id1604-batteries-box-of-10/ (Accessed: 1 April 2021).

BenSaleh, M.S., Qasim, S.M., Obeid, A.M. and Garcia-Ortiz, A. (2013) 'A review on wireless sensor network for water pipeline monitoring applications' *2013 International Conference on Collaboration Technologies and Systems (CTS),* San Diego, CA, USA, 20 to 24 May 2013.

Datta, S. and Sarkar, S. (2016) 'A review on different pipeline fault detection methods', *Journal of Loss Prevention in the Process Industries*, 41(2016), pp. 97-106.

Farai, O. (2021) *Novel Communication System for Buried Water Pipe Monitoring using Acoustic Signal Propagation along the Pipe.* Ph.D. Thesis. University of Birmingham.

Farai, O., Metje, N., Anthony, C. and Chapman, D., 2023. Analysis of Acoustic Signal Propagation for Reliable Digital Communication along Exposed and Buried Water Pipes. *Applied Sciences*, *13*(7), p.4611.

Guo, H., Prince, M., Ramsey, J., Turner, J., Allen, M., Samuels, C. and Nuako, J.A. (2023) 'A Low-cost Through-metal Communication System for Sensors in Metallic Pipes', *IEEE Sensors Journal 23(8)*, pp. 8952-8960.

Hao, T., Rogers, C.D.F., Metje, N., Chapman, D.N., Muggleton, J.M., Foo, K.Y., Wang, P., Pennock, S.R., Atkins, P.R., Swingler, S.G., Parker, J., Costello, S.B., Burrow, M.P.N., Anspach, J.H., Armitage, R.J., Cohn, A.G., Goddard, K., Lewin, P.L., Orlando, G., Redfern, M.A., Royal, A.C.D., Saul, A.J. (2012) 'Condition assessment of the buried utility service infrastructure', *Tunnelling and Underground Space Technology*, 28 (2012), pp. 331-344.

Jin, Y., Ying, Y. and Zhao, D. (2013) 'Data communications using guided elastic waves by time reversal pulse position modulation: Experimental study', *Sensors*, 13(7), pp. 8352-8376.

Johnson, M., Healy, M., Van de Ven, P., Hayes, M.J., Nelson, J., Newe, T. and Lewis, E. (2009) 'A comparative review of wireless sensor network mote technologies' *IEEE Sensors 2009 Conference,* Christchurch*,* CAN, New Zealand, 25-28 October 2009.

Joseph, K.M., Watteyne, T. and Kerkez, B. (2018) 'Awa: Using water distribution systems to transmit data', *Transactions on Emerging Telecommunications Technologies*, 29(1), pp. 1-14.

Kokossalakis, G. (2006). *Acoustic data communication system for in-pipe wireless sensor networks.* Ph.D. Thesis. Massachusetts Institute of Technology. Available at: https://dspace.mit.edu/handle/1721.1/34379 (Accessed: 1 July 2014).

Lee, A. (2017). Condition assessment technologies for water transmission and sewage conveyance systems. Available at: https://www.sustain.ubc.ca/sites/default/files/2017-20_Condition%20Assessment%20-%20Water%20Distribution%20%26%20Sewage%20Conveyance_Lee.pdf (Accessed: 1 June 2020).

Lee, K.B. (2011). *Principles of microelectromechanical systems*. Hoboken, N.J: Wiley.

Lin, K., López, O.L.A., Alves, H., Chapman, D., Metje, N., Zhao, G. and Hao, T. (2022) 'Throughput optimization in backscatter-assisted wireless-powered underground sensor networks for smart agriculture', *Internet of Things*, 20, p.100637.

Linear Technology (1983). *LT1001 precision operational amplifier.* Available at: https://www.analog.com/media/en/technical-documentation/data-sheets/LT1001.pdf (Accessed: 1 February 2017).

Li, L., Vuran, M.C. and Akyildiz, I.F. (2007) 'Characteristics of underground channel for wireless underground sensor networks' *Proc. Med-Hoc-Net*, Corfu, Greece, June 2007.

Liu, B.H., Fu, T.H. and Wang, Y.B. (2021) 'Research on the model and characteristics of underground magnetic induction communication channel', *Progress In Electromagnetics Research M*, 101, pp. 89-100.

Liu, Z. and Kleiner, Y. (2013) 'State of the art review of inspection technologies for condition assessment of water pipes', *Measurement*, 46(1), pp. 1-15.

Long, R., Cawley, P., and Lowe, M. (2003) 'Acoustic wave propagation in buried iron water pipes', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 459(2039), pp. 2749–2770.

Makar, J.M. and Kleiner, Y. (2000) 'Maintaining water pipeline integrity' *AWWA Infrastructure Conference and Exhibition*, Baltimore, Maryland, USA, 12 March 2000.

Metje, N., Chapman, D.N., Walton, R., Sadeghioon, A.M. and Ward, M. (2012) 'Real time condition monitoring of buried water pipes', *Tunnelling and Underground Space Technology*, 28(2012), pp. 315-320.

Misiunas, D. (2005) *Failure Monitoring and Asset Condition Assessment in Water Supply Systems*. Ph.D. Thesis. Lund University. Available at: https://www.iea.lth.se/publications/Theses/LTH-IEA-1048.pdf (Accessed: 1 July 2016).

Misiunas, D., (2008) 'Failure Monitoring and Asset Condition Assessment in Water Supply Systems' *The 7th International Conference*, Faculty of Environmental Engineering Vilnius Gediminas Technical University, Vilnius, Lithuania, 22nd to 23rd May 2008.

Muggleton, J. M., Brennan, M. J., and Pinnington, R. J. (2002) 'Wavenumber Prediction of Waves in Buried Pipes for Water Leak Detection', *Journal of Sound and Vibration* 249(5), pp. 939-954.

Muggleton, J.M. and Yan, J. (2013) 'Wavenumber prediction and measurement of axisymmetric waves in buried fluid-filled pipes: Inclusion of shear coupling at a lubricated pipe/soil interface', *Journal of Sound and Vibration*, 332(5), pp.1216-1230.

Mutagi, R.N. (2012) Digital Communications: Theory, Techniques, and Applications. Oxford: Oxford University Press.

National Instruments (2009) 'DAQ M Series: NI USB-621x user manual'. Available at: https://www.ni.com/pdf/manuals/371931f.pdf (Accessed: 1 May 2015).

NXP (2016) 'UM10360. LPC176x/5x User Manual. Rev. 4'. Available at: https://www.nxp.com/docs/en/user-guide/UM10360.pdf (Accessed: 30 January 2017)

Pal, M. (2008) *Leak detection and location in polyethylene pipes.* Ph.D. Thesis. Loughborough University. Available at: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.603092 (Accessed: 1 September 2017).

Pal, A., Guo, H., Yang, S., Akkas, M.A. and Zhang, X. (2020) 'Taking Wireless Underground: A Comprehensive Summary', *ACM Transactions on Sensor Networks,* pp.1-42

Pons, J. L. (2005) *Emerging Actuator Technologies: A Micromechatronic Approach*. Hoboken, N.J: Wiley.

Precision Microdrives (2015) 'Product Data Sheet. Uni Vibe. 8mm Vibration Motor' Available at: https://www.precisionmicrodrives.com/product/datasheet/308-103-8mm-vibration-motor-20mm-type-datasheet.pdf (Accessed: 30 January 2015).

Proakis, J.G. & Salehi, M. (2008) *Digital Communications*. 5th edn. New York, N.Y: McGraw-Hill.

Rajani, B. and Kleiner, Y., (2004) 'Non-destructive Inspection Techniques to Determine Structural Distress Indicators in Water Mains' *Evaluation and Control of Water Loss in Urban Water Networks*, Valencia, Spain, 21 to 25 June 2004.

Rajeev, P., Kodikara, J., Robert, D., Zeman, P. and Rajani, B. (2014) 'Factors contributing to large diameter water pipe failure', *Water Asset Management International, 10(3)* pp. 9-14.

Rogers, C.D.F., Hao, T., Costello, S.B., Burrow, M.P.N., Metje, N., Chapman, D.N., Parker, J., Armitage, R.J., Anspach, J.H., Muggleton, J.M., Foo, K.Y., Wang, P., Pennock, S.R., Atkins, P.R., Swingler, S.G., Cohn, A.G., Goddard, K., Lewin, P.L., Orlando, G., Redfern, M.A., Royal, A.C.D. and Saul, A.J. (2012) 'Condition assessment of the surface and buried infrastructure–A proposal for integration', *Tunnelling and Underground Space Technology, 28(1)*, pp. 202-211.

Rose, J.L. (2014). *Ultrasonic guided waves in solid media.* Cambridge: Cambridge University Press.

Rose, J.L., Mu, J. and Cho, Y. (2008) 'Recent advances on guided waves in pipe inspection', *Proceedings of the 17th World Conference on Non-Destructive Testing*, Shanghai, China, 25 to 28 October 2008.

Sadeghioon, A. (2014) *Design and Development of Wireless Underground Sensor Networks for Pipeline Monitoring*. Ph.D. Thesis. University of Birmingham. Available at: https://etheses.bham.ac.uk/id/eprint/5947/1/MollazadehSadeghioon15PhD.pdf (Accessed: 1 March 2015).

Severn Trent (2019) 'Summary of Charges 2019-2020: A householder's guide to how we calculate your bill'. Available at: https://www.stwater.co.uk/content/dam/stw/my-account/our-charges/stw-summary-of-charges-2019-20.pdf (Accessed: 1 April 2021).

Smart Material (2015) 'Macro Fibre Composite – MFC'. Available at: https://www.smart-material.com/media/Datasheets/MFC_V2.3-Web-full-brochure.pdf (Accessed 10 March 2016).

Sun, Z. and Akyildiz, I.F. (2010) 'Magnetic induction communications for wireless underground sensor networks' *IEEE transactions on antennas and propagation, 58(7),* pp. 2426-2435.

Texas Instruments (2014) 'LM567x Tone Decoder'. Available at: http://www.ti.com/lit/ds/symlink/lm567c.pdf (Accessed: 1 October 2016).

Texas Instruments (2016) 'Quadruple Half-H Drivers'. Available at: http://www.ti.com/lit/ds/symlink/l293.pdf (Accessed: 1 April 2016).

Vuran, M.C. and Silva, A.R. (2009). *Sensor Networks: Where Theory Meets Practice*. Edited by Ferrari, Gianluigi. Berlin: Hiedelberg.

Walton, R., Sadeghioon, A.M., Metje, N., Chapman, C. and Ward, M. (2011) 'Smart Pipes: The future for proactive asset management' *International Conference on Pipelines and Trenchless Technology 2011*, Beijing, China, 26-29 October 2011.

Water UK (2020) 'Water companies record lowest leakage levels from pipes'. Available at https://www.water.org.uk/news-item/water-companies-record-lowest-leakage-levels-from-pipes/ (Accessed: 1 June 2021).

Whittle, A.J., Allen, M., Preis, A. and Iqbal, M. (2013) 'Sensor networks for monitoring and control of water distribution systems' *6th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII 2013),* Hong Kong, 9 to 11 December 2013.

Zhao, G., Lin, K., Chapman, D., Metje, N. and Hao, T. (2023) 'Optimizing energy efficiency of LoRaWAN-based wireless underground sensor networks: A multi-agent reinforcement learning approach' *Internet of Things*, 22, p.100776.

IJPCC05-2022-0179.R1 - RESPONSE TO REVIEWER COMMENTS

We wish to thank the reviewer for the valuable and constructive comments on our paper. We have addressed all the comments as outlined in this document and believe the paper has improved because of this. The issues raised are addressed under Reviewer 1 comments. We have added our response in italic and any new text, based on the reviewer's comment, is shown in blue. Tracked changes have also been used in the manuscript to indicate the changes.

Reviewer 1 comments

Comment 1: It would be better to discuss why we need such kind of communication. The application scenario can be better discussed.

Response: *We agree with the reviewer that a better discussion of the need for such a communication system should be included in the paper. We have addressed this by including additional text in the introduction to draw out existing limitations of buried pipe inspection technologies including limited sensor coverage which can become cost prohibitive for monitoring large areas of buried water pipe network.*

1 Introduction

There are two fundamentally different approaches to proactive pipe deterioration monitoring. Repeat surveys using pipeline inspection gauges, surface geophysics or temporary sensors (e.g., Lee, 2017; Datta & Sarkar, 2016; Liu and Kleiner, 2013). A common drawback, however, is the need for on-site technical personnel and equipment deployment to successfully run inspection operations. An alternative is to use permanently installed sensors, which enable continuous monitoring. Here, the most critical aspect is reliable communication between sensors or to the ground surface enabling data processing for further decision making by the utility owner (Makar & Kleiner, 2000). However, existing sensing technologies which use underground wireless communication for data transmission have limited range (less than a few metres) in the underground environment (e.g., Akyildiz and Stuntebeck, 2006). While the range could be extended using higher powered sensors, this is not unproblematic either due to the limited power sources below the ground surface and the inability to regularly change e.g., batteries. Such short-range sensor deployment can quickly become cost prohibitive for buried water pipe monitoring over an extended network, especially when the sensors are installed retrospectively on legacy assets, where the cost of digging the whole to the pipe itself is a major contributor to the overall costs. With the cost of water itself being low in many countries, it would make the sensor network uneconomical. Another option for longer range inspection (at least tens of metres) is guided wave testing (GWT) (e.g., Rose, 2014; Rose et al., 2008) but as noted by Liu et al. (2012), this technique requires significant labour and equipment costs (which can reach thousands of pounds) for each inspection operation. Long-term continuous monitoring of the buried pipeline asset, with cost-effective underground sensor deployment is therefore an attractive proposition for proactive buried water pipe monitoring.

Long-term continuous monitoring of the buried pipeline asset, with cost-effective underground sensor deployment is therefore an attractive proposition for proactive buried water pipe monitoring.

Comment 2: Most of the references are before 2020. It would be better to discuss more recent works on underground communication and pipeline monitoring. It would be better to discuss the unique advantages of this work compared to other pipeline communication solutions such as the magnetic communication.

[1] Amitangshu Pal, Hongzhi Guo, Sijung Yang, Mustafa Alper Akkas, and Xufeng Zhang. 2023. Taking Wireless Underground: A Comprehensive Summary. ACM Trans. Sen. Netw (March 2023).

[2] Guo, Hongzhi, et al. "A Low-cost Through-metal Communication System for Sensors in Metallic Pipes." IEEE Sensors Journal (2023).

Response: *We have included additional references after 2020 to better reflect more recent work on wireless underground communication for buried pipeline monitoring. We have also added more text to further discuss the unique advantages of this work compared to other buried pipeline communication solutions such as magnetic induction communication.*

1 Introduction

Another option for wireless underground communication which has been investigated in the literature is magnetic induction (MI) communication. Guo et al. (2023), for example, proposed a through-metal magnetic induction communication system for metallic pipe monitoring using off-the-shelf electronic components. Although a data rate of up to 500 bits per second (bps) was reported, the communication system was limited to a data transmission range of less than 4 cm. Sun & Akyldiz (2010) and Akyldiz et al., (2009) also proposed an MI waveguide technique in response to the limited radio signal propagation range within an underground soil environment. The MI waveguide method relies on mutual magnetic induction between electrical coil pairs for signal transmission along a buried water pipe. A magnetic field, unlike an electromagnetic field, shows little variation in air, water, or soil (due to the similar magnetic permeabilities of air, water, and most types of soil) and so MI-based signal transmission would be largely unaffected by the presence of underground soil or water (Liu et al., 2021; Sun & Akyldiz, 2010; Akyldiz et al., 2009). However, the MI signal path loss within a waveguide system depends on the radius (and electrical parameters such as coil resistance and capacitance) of the MI relay coils wrapped around the pipe. Maintaining a signal transmission range within tens of metres will therefore necessitate bespoke electrical coil designs for buried pipes of different diameters which is not only challenging but also cost intensive for deployment along a buried pipeline network.

A separate (i.e., non-electromagnetic or magnetic induction based) approach for enabling wireless underground communication through soil is achieved by using the buried water pipe as an acoustic waveguide.

Comment 3: A shortcoming of this work is the low data rate which may limit the application. It would be better to discuss more on this. Power consumption can be another important issue considering the devices are buried underground. It is not easy to supply power.

Response: *We agree with the reviewer to include a better discussion of the communication system low data rate, as well as the issue of power management within the communication system. Additional text has been added to the results and discussion section to address this comment.*

3 Results and discussion

As discussed in the introduction, proactive buried water pipe monitoring is advantageous for continuous monitoring since the cost implications of a complete pipe failure can be largely avoided with this approach. A potential application of the digital communication system described in this paper is to facilitate data communication of early warning signs of pipe deterioration within continuous pipeline monitoring framework. Since the deterioration processes of buried pipes are slow (Rajani & Kleiner, 2004), i.e., often months and years, a real-time data communication strategy for continuously monitoring should focus on capturing changes in baseline data using two-state logic to capture changes in the pipeline baseline data as determined by a preconfigured threshold at the sensor level. Therefore, during regular data transmission, measured data above a preconfigured threshold can be flagged as an alarm indicating a potential onset of pipe deterioration. Furthermore, data transmission can occur within a fixed time window (e.g., for 10 minutes every 24 hours or even weekly) to conserve limited underground power supply within the communication system thereby extending the operational life of the sensors. Data transmission can also be executed during periods of low environmental activity (e.g., 2am – 4am) to reduce potential communication interference by environmental noise. With this approach, even with a low data rate of at least 1 bps, the communication system described in this paper could be deployed for continuous, proactive buried water pipe monitoring.

Comment 4: Authors are suggested to provide a clean copy of the paper for better readability. Some figures are blurry.

Response: *The paper has been reviewed and thoroughly cleaned for better readability while all blurry figures have been corrected for better presentation.*