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RESEARCH ARTICLE

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Awa: Using water distribution systems to transmit data

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Abstract

This article presents Awa, a real-time wireless monitoring solution for urban water distribution systems (WDSs). The Awa system is composed of a distributed network of low-cost sensor nodes that can be quickly installed on water pipes. Rather than using conventional radio signals, which are attenuated in underground environments, the nodes use the actual water-filled pipe as the transmission medium to communicate with one another. This permits the use of an already existing water infrastructure in the deployment of large wireless sensor networks. We describe the development and evaluation of novel and battery-powered sensor nodes that can be magnetically clipped to valves and hard-to-access points in WDSs without requiring digging or cutting of pipes. A channel characterization is carried out and a number of data modulation schemes are evaluated across a 110-m section of pipe in an operational WDSs. We identify a near-optimal frequency (near 500 Hz) for transmitting data. We demonstrate communication at 100 bps across a real-world water pipe using amplitude modulation. Not unlike radio-frequency wireless, we also measure the highly nonstationary effects of multipath fading. The article also contains an in-depth discussion about the opportunities that this emerging communication technology offers in the context of city-wide leak detection and flow monitoring.

1 | INTRODUCTION

The roadways and buildings in the world's cities are underpinned by a complex underground infrastructure to deliver clean water to homes, schools, hospitals, businesses, and other facilities. These water distribution systems (WDSs) form a network of pipes, storage facilities, and treatment systems, whose linear length spans over 1 million km in the United States alone. Due to rapidly changing urbanization and shrinking municipal budgets, this water infrastructure is increasingly being exposed to a variety of natural and man-made stressors.

There is an urgent need to better understand and monitor aging WDSs. Perhaps the major motivating example is given by water loss in buried pipe networks, where estimates suggest 30% or more of treated water is lost due to leaks.[1,2] While the need to repair leaks is important in many "dry" regions of the world, the loss of water also results in a significant waste of energy required for treatment and conveyance. By many estimates, the energy consumption of water networks is as high as 3% of a country's total energy budget, which means that pipe leaks often have the potential to consume a large portion of a municipality's budget.[3]

Aside from leaks, the detection of accidental or malicious intrusions of contaminants, which may enter the water distribution network, is also very important.[4,5] This became evident most recently in the United States, where lead contamination of a public drinking water system caused a public health emergency.[6]

Sensors for detecting leaks and measuring water flow either exist, or are approaching the point beyond which they can be ubiquitously deployed. Commercial flow and pressure sensors are fairly common elements for use in real-time demand optimization and billing. Due to cost, the deployment of these sensors is often sparse in relation to the scale of the WDS. This is because of the need to dig out and/or cut existing pipes to install them, which induces significant personnel and equipment costs. Likewise, while recent advances in water quality sensing are permitting for the direct measurement of a number of important contaminants,[7] limited access to buried pipes and curb boxes (roadside openings) prohibits such systems from being deployed at a dense spatial resolution.

Acoustic leak detection technologies are being used extensively to localize leaks with a centimeter resolution.[8] Based mostly on the characterization of the pipe through guided mechanical waves, these approaches have shown significant promise for structural health monitoring.[9,10] However, these systems are deployed on an as-needed basis (to detect a leak in a segment of pipe, for example), and not permanently installed for long-term monitoring. In large water systems, this results in very labor-intensive manual leak detection, which imposes a significant burden on resource-constrained operators and technicians. Using leak-detection technologies on an as-needed basis often results in failure to detect leaks while they are still small. During negative pressure events, leaks that have not yet been localized may become sources of contaminant intrusion from the surrounding soil, with a significant potential to compromise the quality and health of a city's water supply.[11] There is an urgent need to develop cost-effective sensing methods to *monitor the state of buried pipe networks in real time*.

Data transmission in underground applications is, however, very challenging. This is not only true in pipe networks, but many other applications, such as deep-well drilling. While existing supervisory control and data acquisition systems are a reliable means for transmitting real-time data, they require bulky and complex installations, as well as *hardwired* communication links. Wired instrumentation has already been shown to be cost prohibitive in many industrial automation applications.[12] Wired technologies are also often logistically unfeasible for the retroactive instrumentation of hard-to-access, large-area water systems.

Since wired sensor networks are often not an option, we propose to use a wireless networking solution to interconnect the sensing devices. Furthermore, since the ability to retrofit existing pipes is a key requirement, we want to be able to install the nodes without digging out or cutting the pipes. To this end, we propose the Awa system (the Moore word for water), a solution in which nodes are non-intrusively attached to existing pipes and use the water pipe itself to communicate wirelessly. By replacing a network of wires with a network of pipes, the Awa system uses the already existing water infrastructure to enable low-cost, long-term deployments of underground wireless sensor networks. The contributions of this article are 3-fold as follows.

- A communication approach to transmit data across water systems. Rather than using traditional radio communications, our technique transmits data through the actual water-filled pipe by exciting subkilohertz acoustic waves in the water column.
- The development of the novel, battery-powered, and nonintrusive Awa sensor node that can be magnetically clipped to valves and access points, without the need to replace or retrofit existing infrastructure.
- A real-world analysis of the underground pipe transmission channel and experimental validation of the feasibility of transmitting data through an operational water system. To our knowledge, an experimental study of this type and scale has not been conducted before.

Given the use of acoustic frequencies in the field of infrastructure health monitoring, the proposed system could also be used for applications such as distributed leak detection.

The remainder of this article is organized as follows. Section 2 offers a fresh look at “wireless,” by discussing the pitfalls of radio frequency (RF) for underground communication. Section 3 lists the requirements the proposed system should satisfy in terms of transmission range, real-world retrofitting, battery lifetime, and unit cost. Section 4 presents Awa, its working principle, transducer design, and overall system architecture. Section 5 presents the results of an experimental study on a real-world water network. Section 6 goes into an in-depth discussion of the results and scalability of the Awa system. Finally, Section 7 concludes this article and lays out the future potential of the Awa system for large-scale, real-world use.

2 | RETHINKING WIRELESS

Software platforms have been developed to detect anomalous events in water systems.[13] Their real-world efficacy is, however, often limited by the fact that they are fed with sparse measurements. What is needed are data collected continuously from many locations across the WDS.

Low-power RF solutions have been proposed, in which sensors are deployed across the water system. By offering a small, battery-powered form factor, these systems can be deployed to cover large spatial extents by leveraging cellular coverage or modern, low-power mesh protocols, such as IEEE802.11 or IEEE802.15.4.[14,15] Example systems are Boston's PipeNet[16] and Singapore's WaterWiSE,[17] which have shown great promise to collect and analyze water data in real time.

However, when an RF sensor is placed on a pipe (potentially many meters below ground), the soil severely attenuates the signal, and nodes cannot communicate directly with one another or above-ground wireless infrastructure. The quality of a wireless link is guided by a number of factors, including frequency, modulation, and data rate.[18] Environmental conditions, such as soil moisture, or instances during which radio waves pass through solid or liquid media, adversely affect the quality of radio links. These absorption losses are the primary driver of signal attenuation underground and underwater,[19] which renders traditional RF communication infeasible in these environments. For example, signal attenuation underground is on the order of 100 dB/m for a 2.4-GHz electromagnetic signal due to absorption.[20]

A number of work-arounds have been proposed. Most rely an above-ground RF transmitter, connected to the sensor through a wire. Others may install several wireless repeaters at different depth to relay data from the underground sensor to the above-ground installations. Each of these options introduces constraints by requiring modifications to existing pipes and a dedicated above-ground communications infrastructure, which makes deployment and maintenance of a monitoring system very difficult. New methods are required to improve the reliability, cost, and power consumption of underground communications, with a particular emphasis on meeting the unique field conditions exhibited by WDSs.

Since a WDS is a network of pipes, could this same network be used to exchange data between sensor nodes installed throughout the system?

We are motivated by oceanic communications, in which data is exchanged by acoustic transceivers, using the surrounding water as the communication medium. However, "going acoustic" also comes with complications that make the underwater channel notoriously difficult to work with. First, ambient and site-specific acoustic noise can overpower the data signal, especially in the 3- to 30-kHz frequency band that is typically used. Second, bandwidth is very limited and depends on the transmission distance, which requires bandwidth efficient modulation methods to achieve usable data rates.[21] Third, the underwater channel is highly dependent on geometry and temperature gradients, which create multiple propagation paths or "echoes." This significantly increases susceptibility to multipath fading, in which multiple copies of the signal arrive at the receiver at various delays and strengths, possibly leading to destructive interference. Due to these challenges, underwater data transmissions and modulation schemes have been notoriously difficult to design and implement. Nonetheless, advances in state-of-the-art oceanic communication are encouraging, now enabling reliable, bandwidth efficient, and phase-coherent solutions that enable data rates of more than 1 b/s/Hz for ship, submarine, and buoy communications.[22] For example, the attenuation loss is close to 100 dB/km for an underwater acoustic signal of frequency of 500 kHz. This absorption loss coefficient increases with increasing frequency. These results are, however, difficult to generalize for underground pipe communications, since the presence of the surrounding soil medium may play a major, if not the biggest, role in attenuation.

Unfortunately, acoustic communication developed for oceanic communication does not translate directly to pipe networks. Due to ambient conditions and attenuation by soil and other surrounding media, the underwater communication models developed for oceanic communication cannot be used to describe signal propagation in pipe networks. There has, however, been developed a large body of work on underground wave propagation in piped systems for nondestructive testing, leak detection, and structural health monitoring of pipelines.[9,10] In most of these studies, guided waves (vibrations that travel through the pipe, soil, and water) are induced at 1 location via external transducers. The waves are then measured at receiving locations using laboratory-quality equipment and large, geometrically optimized sensor arrays to localize pipe damage. Typically, high frequencies (in the 70- to 100-kHz range) are used for damage detection in piped systems.[9] However, due to attenuation, these frequencies are unsuitable for long-distance (100 m+) communications. Lower frequencies (5 to 150 Hz), on the other hand, are often used in leak detection applications, where microphones or accelerometers are employed to trilaterate the location of leaks across distances of 100 m via unique frequency signatures.[23] While these studies have contributed significantly to the fundamental understanding of wave propagation in buried pipe networks, piped systems have yet to be analyzed as data transmission channels.

To our knowledge, there has only been 1 initiative on the use of the actual pipe as a transmission channel. Through laboratory experiments, bit streams were transmitted across short (1.2 m) sections of pipe using a time-reversal method and high-frequency pulsewidth modulation to compensate for signal dispersion.[24,25] The pipe used in this work was *not* buried underground, nor was it filled with water. While these studies offer invaluable insights into the nature of elastic wave communications through metal pipes, their real-world applicability is still unclear, as the high frequencies used in the study would be quickly attenuated in buried pipe networks. Furthermore, the sensitive equipment and sensors used were also not tailored to the seamless instrumentation of real-world water systems.

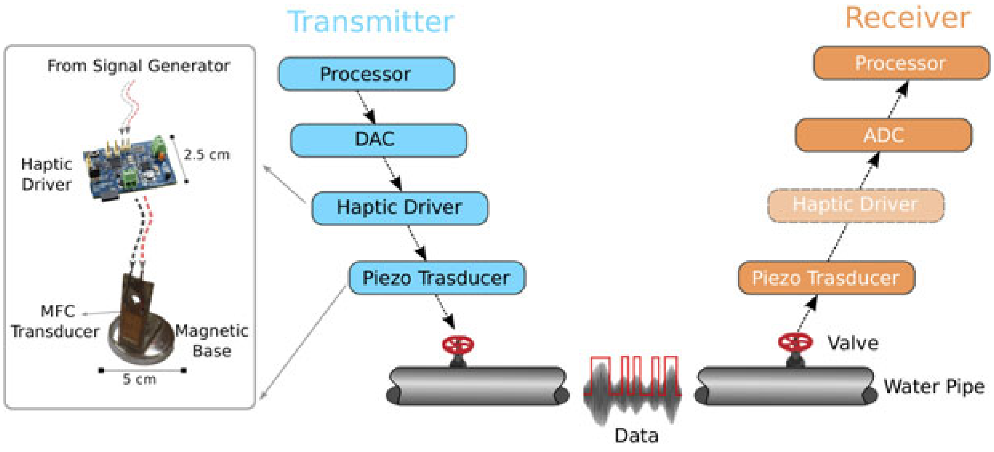

FIGURE 1 Node and system architecture. Each node switches between the transmitter (TX) and receiver (RX) modes. In transmitter mode, a digital-to-analog converter (DAC) is used to drive the transducer. In receiver mode, the haptic driver is bypassed and an analog-to-digital converter (ADC) is used to directly measure the vibrations from the receiving piezo. ADC, analog-to-digital converter; DAC, digital-to-analog converter; MFC, macrofiber composite

3 | REQUIREMENTS

To meet the needs of real-world water networks, any solution must satisfy the following requirements.

- *Retrofitting*: To enable an already installed WDS to be retrofitted with a communication network, the transmission method should not require modifications to existing infrastructure (no cutting pipes, no digging, etc). Transmitter nodes should be self-contained and resistant to harsh environments. Ideally, the unit can simply be clipped to a valve or exposed pipe segments and does not require special glues or mounting belts, as is the case with most existing guided wave technologies.
- *Communication range*: In most modern WDSs, access points (curb boxes, fire hydrants, manhole covers, etc) are typically spaced about 50 to 100 m apart to meet fire codes and water demands.[26] Thus, a practical communication range of at least 50 m is needed to ensure connectivity, assuming a multihop network topology.

Of secondary importance are power consumption and cost. Ideally, transmitter nodes should consume as little power as possible to enable years of battery lifetime. Aligned with the price of today's typical RF sensor, and given the spatial extent of typical water systems, individual nodes must be cheap (less than US $100) to enable the cost-effective instrumentation of the entire system.

4 | THE AWA SYSTEM

Figure 1 shows the Awa node. Each node is comprised of a microcontroller, a piezoelectric transducer, a haptic driver (amplifier), and a magnet for mounting.

The working principle of the node is that it magnetically clips onto a pipe or valve, and either generates an acoustic vibration (transmitter mode) or analyzes the vibration of the pipe (receiver mode). In transmitter mode, the microcontroller generates a waveform (analog voltage), which is amplified by the haptic driver and applied to the macrofiber composite (MFC) piezo. Acoustic vibrations induced by the piezo are then transferred via the magnetic resonator into the pipe or valve, and relayed through the water column to a receiving node. Every node in the system can be constructed identically. Nodes can switch between the transmitter and receiver modes. Each node costs under US $100 at unit price, addressing the requirement to keep costs low.

Each node is comprised of a small metallic body and a circular magnet (5 cm in diameter), which can be easily lowered into existing access points and clipped to valves or exposed sections of pipe.

The magnet acts as a resonator and is actuated by a MFC piezoelectric transducer.* Unlike a ceramic or crystal-based piezo, the MFC is a thin-film, small form-factor transducer that resembles a strain gauge. Compared with traditional ceramic or crystal-based piezos, the MFC transducer occupies significantly less volume and can be easily attached to the metallic body of

*M2814 P2 type, http://www.smart-material.com/

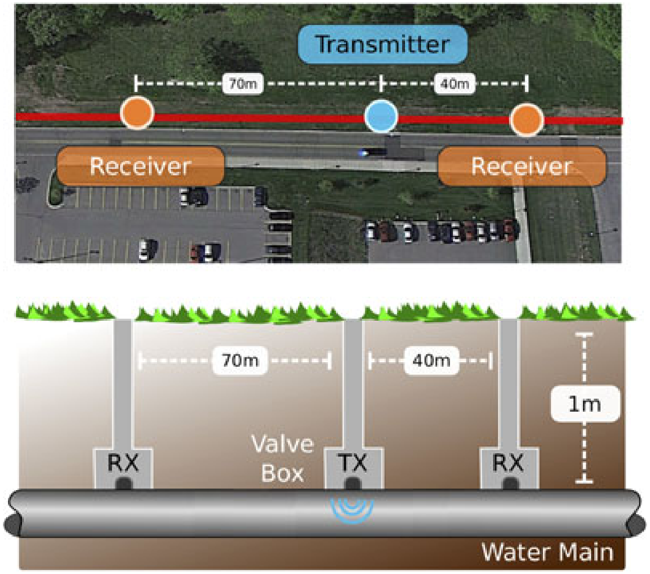

FIGURE 2 Field experiment for testing the Awa system. Signals are sent by a transmitter (TX) node and recorded by 2 receiver (RX) nodes

the node via standard strain gauge glue. The transducer has an active area of 28 × 14 mm, capacitance of 25.7 nF, free strain of −700 ppm, and blocking force of −85 N. These specifications were chosen to maximize the strain and vibrations induced in the metallic base during signal transmission. In receiver mode, vibrations are converted to an electrical signal via the MFC piezoelement and measured directly by an analog-to-digital converter.

The distance traveled by the data signal through the pipe is highly contingent upon the magnitude of induced vibrations, which are a direct result of the strain created by the MFC piezo. The MFC transducers are designed to deliver maximum strain at a peak-to-peak voltage of 200 V, which cannot be delivered by a standard microcontroller. In transmitter mode, to maximize the energy input into the pipe, a piezo haptic driver[†] is installed between the microcontroller and the piezoelement. Designed for haptic feedback in touch screen applications, this low-cost haptic chip permits low-voltage microcontroller signals to be amplified to 200-V peak-to-peak, while only requiring a 3-V battery input. Even while generating high-voltage signals, the system consumes little current (peak 100 to 200 mA measured at 3.3 V), thus ensuring operational safety and low-power consumption, which addresses one of our main requirements. This enables a very small form factor while simultaneously maximizing the strain energy input into the resonator.

To generate data packets and modulate waveforms, we use a programmable System-on-Chip (Cypress PSoC5)[‡] microcontroller. This chip features a suite of high-fidelity analog components, including a digital-to-analog converter and a 20-bit Delta-Sigma analog-to-digital converter. Signal modulation, data transmission, and demodulation are done on-board this compact chip, allowing the node to be deployed as a stand-alone, battery powered, and fully embedded unit.

Along with the node, we also designed a lab-bench setup, in which the microcontroller is replaced by a lab-bench signal generator and oscilloscope,[§] connected to a laptop. In this setup, analog waveforms can be generated in MATLAB[¶] and sent via the signal generator to the haptic driver, with modulation, demodulation, and data collection taking place on the laptop. This lab-bench setup is designed for experimental convenience while behaving exactly like the embedded node.

5 | EXPERIMENTAL RESULTS

Figure 2 shows the 110-m section of the underground, potable water pipe on which the experimental study was performed. The iron pipe is buried 1 m below the soil surface and accessible via 3 small curb boxes spaced 30 and 70 m apart. The pipe section was intentionally selected due to its proximity to a busy construction site to reflect above-average ambient noise conditions, which were anticipated to adversely affect low-frequency communications.

[†] DRV8662 from Texas Instruments, http://www.ti.com/
[‡] PSoC5 32-bit ARM Cortex-M microcontroller, http://www.cypress.com/
[§] Tie Pie Handy scope HS4, http://www.tiepie.com/
[¶] http://www.mathworks.com/

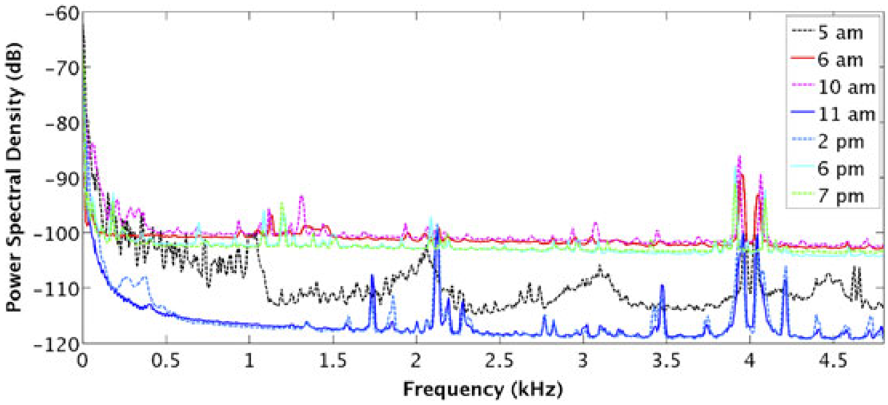

FIGURE 3 Power spectral density (PSD) of the ambient noise recorded in the pipe at different times of the day

Our experimental plan first evaluated the background noise of this real-world site (Section 5.1), after which the frequency response of the pipe channel was measured (Section 5.2). Finally, a number of modulation schemes (Section 5.3) were evaluated, and the multipath profile of the channel was quantified (Section 5.4).

5.1 | Background noise

The noise characteristics of the buried pipe channel were quantified by clipping one of the nodes onto the valve of the central curb box. The ambient noise of the pipe channel was recorded at a sampling frequency of 9765.625 Hz at different times of the day. Each waveform was compared in a normalized frequency domain using a power spectral density (PSD) transform, which computes a modified periodogram by segmenting the signal and averaging spectral densities (Welch's PSD method using a window of 1024 points[27]). The resulting PSD is shown in Figure 3.

Figure 3 shows how the ambient noise significantly changed at different times of the day. Low-frequency noise (0 to 450 Hz) was the highest in amplitude, with some high-frequency noise sources evident above 1.5 kHz. While the noise levels fluctuated significantly (within a 20 dB margin) across the span on the day, these fluctuations did not correlate with any notable events or the time of the day at which they were recorded.

5.2 | Frequency response

We evaluated the frequency response of the pipe channel by lowering 2 additional Awa nodes into the curb boxes located 40 and 70 m away from the central curb box (see Figure 1). The central node served as the transmitter; the other 2 nodes as receivers. A linear sweep from 0 to 1200 Hz spanning 120 s, was transmitted by the central node and recorded at the 2 receiving locations, after which a PSD transform was used to compare the received frequencies to those of the ambient noise (Figure 4). To isolate the frequencies most suitable for data transmission, the signal-to-noise ratio (SNR) was also calculated at the 2 receiving locations (Figure 5). To provide a performance bound, this portion of the experiment was conducted under relatively loud background noise conditions (around −100 dB).

In this experiment, the buried pipe transmission channel significantly attenuated frequencies below 400 Hz and above 600 Hz, as indicated by a comparison of the ambient noise with the sweep responses recorded at 70 and 40 m away from the transmitter (Figure 4). With the exception of a narrow band around 1.2 kHz, which was 2 dB weaker than a major band at 500 Hz, the channel was dominated by noise. In particular, the largest channel response was within a narrow 20- to 30-Hz band, centered on 500 Hz, as calculated by the SNR (Figure 5).

The background noise analysis (Section 5.1) indicated low ambient noise around 500 Hz, which also coincided with a good SNR at that frequency (Figure 5). As such, this provided a narrow band upon which data transmissions could be evaluated in the next step of the experiment.

5.3 | Modulating a data signal

We modulated a random bit-stream of length 1024 onto a carrier frequency using amplitude- (AM), frequency- (FM) and phase-modulation (PM) schemes.[18] Each bit corresponded to 5 cycles of the respective carrier frequency. In the AM scheme,

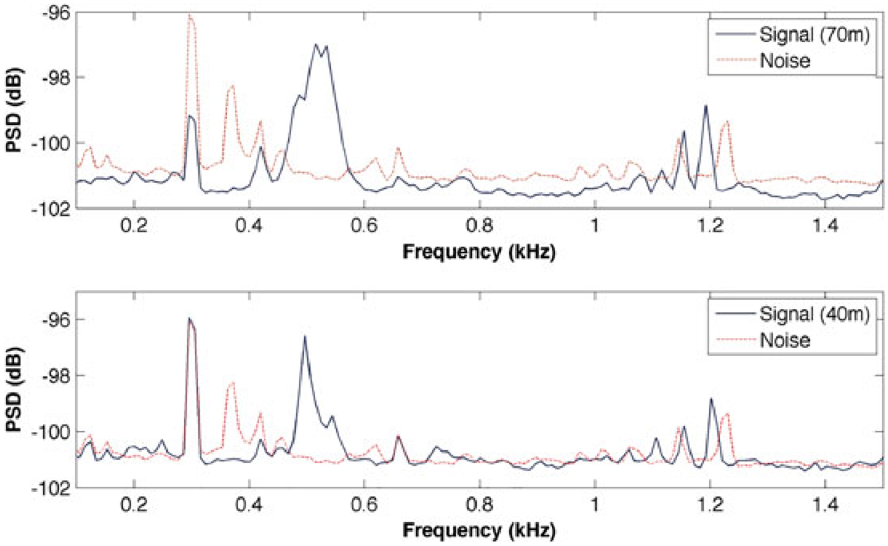

FIGURE 4 Comparison of the channel response to ambient noise at 70 m (top) 40 m (bottom). PSD, power spectral density; SNR, signal-to-noise ratio

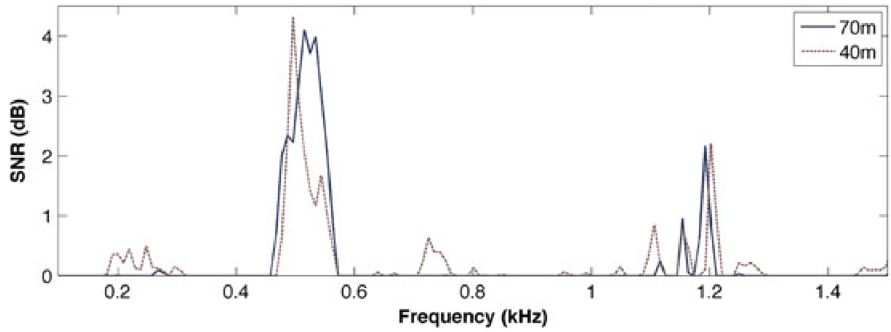

FIGURE 5 Signal-to-noise ratio (SNR), computed at 70 and 40 m

a binary one was indicated by the carrier frequency, whereas a zero corresponded with no signal. In the FM scheme, a lower frequency was used to indicate a binary one, whereas a constant frequency of 1000 Hz corresponds to a zero. In the PM scheme, ones and zeros were distinguished by a 180° phase shift of the carrier frequency. Based on the results obtained during in Sections 5.1 and 5.2, 6 carrier frequencies were evaluated, from 500 to 1000 Hz, in 100-Hz increments. While the SNR did exhibit a slightly improved value in a region near 1.2 kHz (Figure 4), the SNR on this band was nearly half that of the 500-Hz band. This coupled with our judgment that this SNR peak may have driven by a sporadic high-requency noise source (eg, pump or nearby equipment), our plan deemed the 1.2-kHz frequency inadequate for reliable modulation analysis.

Once transmitted, the waveforms were sampled at a frequency of 9.76 kHz by the receiving nodes, which is well above twice the frequency required Nyquist criterion.[28] The received signals were bandpass filtered (200 to 1200 Hz) around the carrier frequency band to remove out-of-band noise and simplify demodulation.

Analysis of the data modulation methods agreed with the results of the channel sweep analysis, showing significant attenuation for any carrier frequency other than 500 Hz. A comparison of the voltage amplitudes (as measured by the piezoelement) at the receiving nodes reveals a 2-dB attenuation for the signal at the furthest node (70 m) when compared with the closer receiving node (40 m), giving an approximate attenuation of 0.06 dB/m at 500 Hz.

The received AM signal yielded the cleanest transition between binary data (ones and zeros), when compared with the received PM and FM data (Figure 6). The binary ones in the AM bit stream are evident through a rise in received signal amplitude. The zeros in the received AM waveform did not, however, correspond to a complete absence of the 500-Hz frequency in the received signal. In most the cases, simple threshold detection identified the binary data. The threshold was based on a statistical quantile, whereby the bandpassed signal was classified into ones (upper third quantile) and zeros (remaining quantiles) based on its voltage magnitude. In a number of instances, however, 500-Hz frequencies were detected during 0 bit, which increased the complexity of classifying binary data.

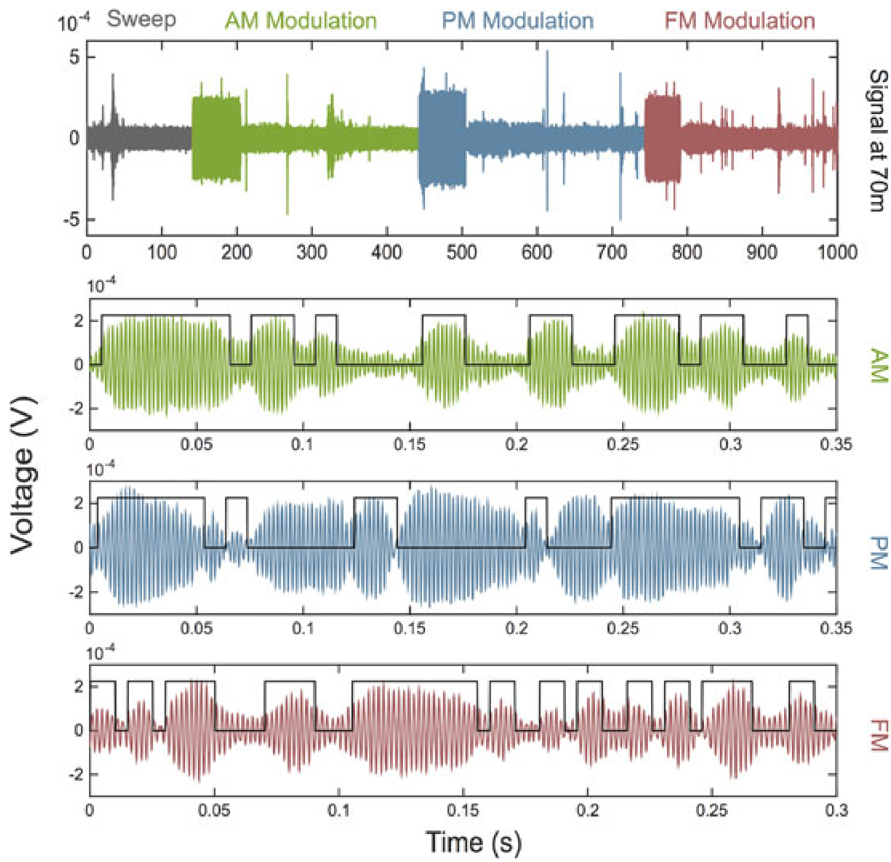

FIGURE 6 Fully measured waveform at 40 m of the entire signal (top figure), including the sweep and each modulation scheme, and segments of 500-Hz modulated signals (bottom 3 figures). Black, solid lines indicate the bits that were transmitted. AM, amplitude modulation; PM, phase modulation

Overall, a data transmission success (bit delivery) of over 70% was achieved using amplitude modulation and threshold-based demodulation. At 500 Hz, our implementation of AM achieved a data rate of 100 bps. No data could be demodulated at the other experimental frequencies, with 600 Hz being the nearest other frequency on which modulation was attempted. A finer-grained experiment around the 500-Hz band was not feasible in this study due to local security and safety protocols, which did permit additional time to access the WDS beyond that allotted to us by authorities during the initial experiment.

While the bit signal was visually evident in the received FM waveform, the higher-frequency components are almost entirely absent from the received data. In fact, a threshold-based demodulation (same as that used for the AM data) was also effective at classifying binary data.

The PM data signal was the most difficult to demodulate into a binary data stream because the phase transitions could not be extracted confidently in the received signal. The received PM signal did however exhibit significant (near complete) signal attenuation at the transition of bits (Figure 6), which could instead be used to detect bit transitions.

5.4 | Multipath intensity profile

The received signals were cross-correlated with the noise-free transmitted signals to characterize the multipath characteristics of the pipe channel. The multipath intensity profile indicated the arrival of multiple copies of the transmitted signal at varying time delays (Figure 7). When compared with the primary arrival at $t = 0$ s, a number of delayed signal copies were detected at $t = 0.030$ s (60% of primary arrival) and $t = 0.060$ s (40% of primary arrival).

6 | DISCUSSION

This article presents the Awa system, an emerging telecommunication technology for WDSs, in which the network of water pipes is used as a communication network. While the system was proven to work through an experimental study, there are a number of considerations that will underpin the generalization and scalability of the approach across larger WDSs.

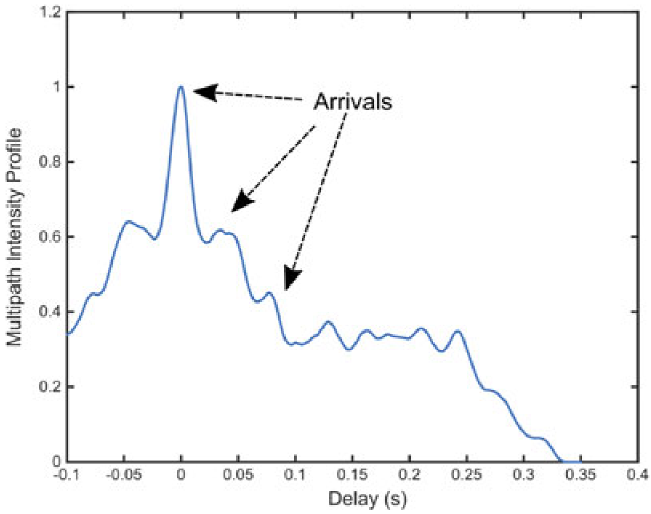

FIGURE 7 Multipath intensity profile, obtained by cross-correlating the transmitted waveform with the received waveform

6.1 | Noise

The water pipe transmission channel is highly nonstationary, as indicated by varying degrees of channel background noise (Section 5.1). While this noise did not correlate to any notable events, it can be expected that any nearby background activities, such as pump operations, vehicle traffic, or construction activities (all of which were present on our site) leaks noise into the water pipes, and, ultimately, the Awa nodes.

In general, all of the measurements shared the common property of low-frequency noise, but some hours had higher ambient noise levels than others. Since there was no direct correlation between time or ambient conditions (vehicles passing by, construction equipment, water pumps, etc) this further highlights the challenge of working on a channel with variable noise levels.

Much of this type of noise is constrained to low frequencies, which are evident in the noise spectrum below 400 Hz (Figure 3). For practical purposes, this eliminates low frequencies (<450 Hz) as a potential carrier in our proposed communication scheme, as any data signal would be overpowered by background noise. Increasing the transmission frequency appears to be the only option in combating this noise floor. In RF communication, it is well known that transmission distance decreases drastically with increasing transmission frequency (transmission distance drops off squared in proportion to increased frequency[18]). For the pipe communication channel, this is even further complicated by the fact that the channel medium is subject to a highly attenuating surroundings and wave propagation.

6.2 | α-mode propagation

When an empty pipe is subjected to an external force or impulse, guided waves are generated in the pipe. Accordingly, the pipe vibrates in a number of fundamental modes,[29] the most relevant of which are axisymmetric (L) and antisymmetric (F). While the ability of these waves to travel across long distances is governed by the surrounding soil material, the existence of pipe bend or fittings, and pipe material, it is well known that these waves do not travel across the kind of distances observed in our study. In many instances, the attenuation of these waves increases exponentially,[9] which would suggest that the waves measured by our receiver did not travel through the metal pipe or the surrounding soil. Experimental and theoretical leak detection studies have however shown that as soon as the pipe is filled with water, a new fundamental mode emerges (known as the α-mode[9,29,30]). This mode approximates a plane wave in the water. In the acoustic leak detection studies carried out by Long et al,[30] the α-mode was the only mode that was observable across large distances, with the other modes lost in the noise for distances under 10 to 15 m. Furthermore, compared with other modes, the α-mode experiences much less attenuation at lower frequencies (<800 kHz) than the other modes, further indicating that our experiment was, in effect, exciting this α-mode. Given the long distances upon which our signal was received, the α-mode is likely the only viable means by which such long distances could be achieved.

The presence of water is not only important, but vital for our approach to work. In fact, the pipe should be completely full to enable α-mode propagation and for the data transmission approach to work. This requirement is, however, very reasonable since all modern water systems have to remain pressurized and filled to maintain service to the public. While the speed of sound does change slightly under different pressure conditions, this will not impact the actual frequency of the transmitted signal. As such, only the arrival time of the transmitted signal may be offset a little if pressures fluctuate. However, since water systems are pump controlled to maintain constant pressure, we do not expect the efficacy of the proposed approach to change significantly due to water pressure.

Different pipe materials impact the attenuation and travel distance of the α-mode. For example, plastic pipes are known to attenuate vibrations more effectively than metal pipes, but as has been shown by Long et al,[31] the surrounding medium is actually the biggest factor affecting the propagation distance of the waterborne or α-mode. The more compacted and dense the soil, the larger the signal attenuation. Our experiment was carried out in a highly clay-filled soil, which is the most attenuating out of all soils. This, whoever, is encouraging, as it suggests that much longer distances could be achieved in other cities or geographic regions that have more favorable soil conditions, such as sand or gravel.

These observations significantly complicate the transmission of data through buried pipe networks, as the use of higher frequencies severely limits transmission distances, whereas lower frequencies are overpowered by background noise. To this end, a valuable discovery is the existence of a narrow transmission band near 500 Hz, which exhibits a notably higher SNR than any of the other transmission frequencies that were evaluated during our study. This suggests the presence of a near-optimal frequency for data transmission in buried pipe networks, outside of which transmissions may be difficult or unfeasible. While the existence of a near-optimal transmission frequency may in part be explained by the experiment-specific properties of our transducers and pipe system, narrow bands have also been observed in ocean communication experiments.[32]

It is feasible that this band could be widened based on the choice of a more sensitive transducer or its improved contact with the pipe. Further experimentation is required to assess how site-, and transducer-specific features may shift this transmission frequency. This shift could however not be large, as the α-mode would decay quickly for higher frequencies, while being overpowered by noise at lower frequencies. As such, the notion of a narrow-band and near-optimal transmission frequency is still expected to exist, even in variants of our study.

The number of other studies that have experimentally or theoretically quantified attenuation characteristics of buried water pipes across the frequency bands covered in our paper is limited. However, the studies that have been carried out do suggest that this the narrow band of around 500 Hz could indeed be a general feature of buried water pipes, rather than just a unique observation in our experiment. A leak-detection study carried out by Yang et al[33] exhibited a very similar channel response across a 30-m segment of pipe, showing a strong channel response near the 500-Hz band. The fact that the study was carried out in a completely different geographical region and on pipes of different physical characteristics lends argument to the claim that our results may not have been specific just to our study.

Second, a series of independent studies provide additional experimental and theoretical attenuation curves for the “alpha” or waterborne modes in buried pipes.[34-36] While the objectives of these studies did not explicitly characterize the channel, they do provide attenuation results that can be used to confirm our own experimental observations. In particular, the results from these studies can be used to estimate that an attenuation of 0.05 to 0.1 dB/m can be expected when comparing 500- to 600-Hz channel response frequencies of buried water pipes. This validates, to a large extent, the sudden attenuation that is seen in our own data when changing transmission frequencies by just 100 Hz (from 500 to 600 Hz). The fact that these studies were conducted independently, and verified both experimentally and theoretically, adds additional argument that our observations were not unique to our own experimental setup.

6.3 | Alternatives to magnets

An improved transmission performance could be obtained through the use of a more sensitive transducer that is secured via a belt or glued. Many guided wave or leak detection experiments use bonding agents and mounting belts to ensure that the energy generated by the transducer is transferred to the pipe with minimal loss. While this could have improved the transmission distance in our experiment, it is not realistic to assume that existing pipes could be readily retrofitted through such means, due to accessibility and cost. To this end, our simple, magnetically clipped nodes provided a good and working compromise between performance, cost and ease of deployment.

6.4 | Modulation

Presently, AM appears to be the most readily implementable modulation scheme for the proposed data transmission approach (Section 5.3). In part, this has to do with the computational and logistical complexity associated with implementing reliable FM and PM demodulation on a low-cost, low-power microcontroller. When calibrated, a simple threshold detection on the receiving node can be implemented to classify AM binary ones from zeros from the analog signal (Figure 6). In fact, on the microcontroller platform used for our experiment, we are able to route the threshold detector directly into a conventional communication bus (such as UART, I2C, etc). This permits for multinode communication and bitwise synchronization to be deployed with minimal effort.

While outside the scope of this paper, investigations of more complex modulation will provide insight into the robustness of pipe communications. The FM and PM demodulation was not implemented as part of this study because the transmission channel significantly limited the efficacy of both of these modulation approaches, which increased the complexity associated with demodulation. Nonetheless, the FM and PM measurements in our study offered insights into the limitations that will arise through the use of these modulation schemes for pipe-based communications.

Given the very narrow band of frequencies that were measured at the receiving nodes, a shift in frequency in FM must be carried out such that both frequencies (those representing binary ones, and those representing zeros) fall within the narrow band, which may impede their demodulation due to close proximity in the frequency band. In our case, the higher of the frequencies was attenuated almost entirely during FM, which made the received signal appear nearly identical to that AM signal. While the use of PM dominates digital data transmission for most low-power wireless networks,[18] its successful implementation in our underground communication channels would be highly dependent upon the implementation of a phase-lock loop. The detection of phase transitions was difficult to observe in our signal due to multipath interference. Phase-coherent communications have, however, been achieved in ocean communications,[32] where the transmission channel experiences very similar behavior. As such, if higher rate communications or more sophisticated modulation schemes (such as quadrature phase-shift keying) are desired, this literature should be consulted to infer the efficacy of phase-coherent communications in underground networks.

6.5 | ISI and time reversal

The pipe communication channel is highly prone to multipath fading, as indicated by the overlapping arrivals of multiple copies of the same signal at the receiving node (Figure 7). This was caused by the waves in the water being reflected on the pipe surfaces and arriving at the receiver at delayed intervals. This phase offset between arrivals may cause multiple copies of the transition to interfere destructively, effectively attenuating the received data signal. Furthermore, these multiple arrivals also cause 1 bit of data to "bleed" into another, as evident in the case of AM modulation, where smaller amplitude arrivals of 500-Hz signals were evident even during the 0 bit (Figure 6). In the communications literature, this is known as intersymbol interference (ISI) and can often lead to bits being misclassified.

In RF-based communications, multipath fading can be overcome by changing the transmission frequency. This may not be an option in pipe network given the narrow band upon which data can be transmitted. Increasing the duration of individual bits (symbols) is a common and simple means by which to reduce ISI. Increasing the duration or spacing between each bit permits the channel's bit response to settle over time, thus reducing the chance that a threshold-based algorithm misclassifies a zero as a one. This, however, reduces channel throughput, as fewer bits can be transmitted per unit time.

To reduce ISI while alleviating the need to increase bit duration, a time reversal approach, similar to that suggested in the works of Jin et al[25] and Zeng and Jiang[37] can be used. This approach takes advantage of the unique physical properties of mechanical waves. Waves in air or water are known to exhibit reciprocity, whereby a time-reversed solution of the wave is also a solution to the wave. Formally, when an impulse wave $p(t)$ is convolved with the channel response $h(t)$ it yields the channel response given in Equation 1.

$$y(t) = p(t) \times h(t). \tag{1}$$

A time-reversed waveform can then be created by flipping the reversed signal, as shown in Equation 2.

$$y(-t) = p(-t) \times h(-t). \tag{2}$$

Due to reciprocity, if the time-reversed approach is transmitted over the channel, it is effectively autocorrelated, which will focus the signal peak around its origin.[25] Practically, in this approach (Figure 8) the receiving node estimates the "bit impulse" by recording the impulse response of a single received bit. The receiving node then separates the bit impulse, which is then time inverted. This time-inverted impulse response can then be convolved with the received signal to remove unintended artifacts induced by the channel.

This method performs well at removing ISI (Figure 9). It does, however, require synchronization, so that the impulse bit can be identified, which may be achieved by using a known preamble, a common approach in digital communications. While this presents some software overhead, it may lead to significant bit classification improvements in instances where a pipe network exhibit multipath fading and time-varying channel responses.

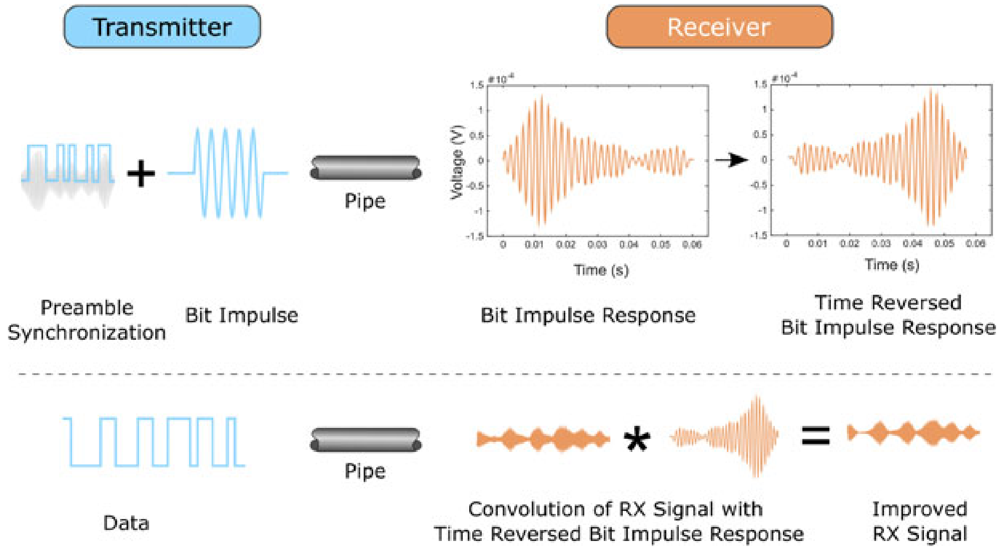

FIGURE 8 Method to improve bit classification. A received bit signal is isolated and time reversed. This time-reversed bit impulse is then convolved with the subsequently received data. RX, receiver

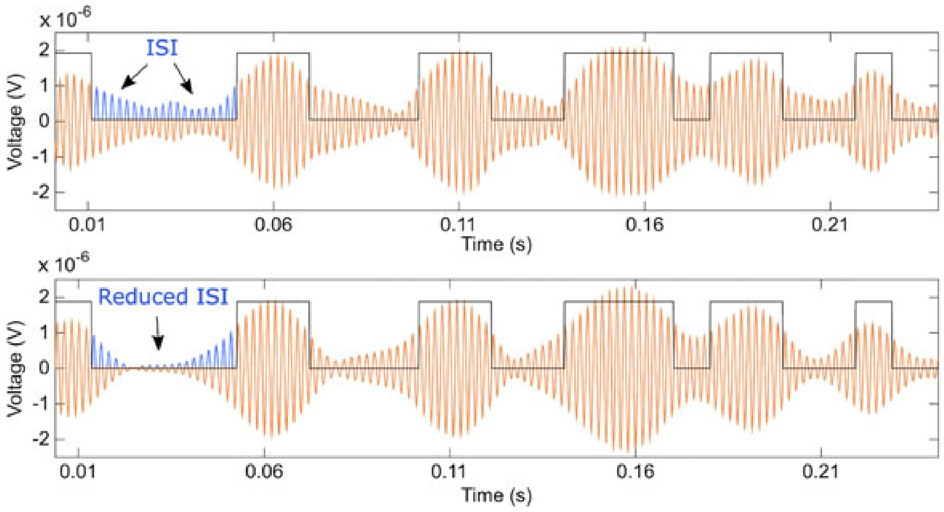

FIGURE 9 Comparison of received signal (top) and received signal convolved with reversed bit impulse response (bottom), showing improvement in bit classification and reduction in intersymbol interference (ISI)

6.6 | Practical considerations

It was shown that a simple, low-cost system, comprised of a microcontroller, piezotransducer, and magnet could be deployed quickly and without the need for complex and expensive instrumentation. While we have successfully transmitted data across distances of up to 70 m, measured attenuation characteristics suggest that distances of over 150 m may also be achieved with the same experimental nodes, well within the spacing between curb boxes and fire hydrants in most cities. The use of low carrier frequencies (500 Hz in the case of this study) limits data throughput when compared with traditional wireless RF communications, but our compact system could be useful in low data-rate applications, where data packets only need to be exchanged in daily or hourly intervals. A good example of this is leak detection, an application where data only needs to be transmitted at most hourly and where the same transducers used for leak detection could be used to transmit the readings.

The results of this experiment show significant promise toward porting the proposed techniques to long-term field deployments and large-scale, underground wireless sensor networks. The scalability of these underground sensor networks depends on a number of factors, which must still be investigated. In particular, the performance of the proposed method needs to be evaluated across varying site conditions, which include pipe flanges, bends, and joints. If, as suspected, the mode of our observed waves is, indeed, governed by the water-based α-mode,[30] then the occurrence of bends, joints and other structural should pose little or no attenuation to the transmitted wave.

The final energy consumption of such a large network will ultimately be governed by how much data needs to be transmitted. For many leak-detection applications, for example, data throughput is minimal (daily or hourly). In such instances, keeping the nodes in a low-power or "sleep" state will be critical toward conserving battery resources. Network-scale communications could simply involve a process by which a transmitting node "wakes up" a receiving node by transmitting a wake up pulse. By implementing an analog circuit filter on the receiver, which is tuned to a narrow receiving band, an incoming pulse could be used to trigger an interrupt on the receiving microcontroller to wake it up from its low-power mode. This, however, comes at the risk of internetwork interference and increased power consumption, as a transmitting node could wake up multiple nodes in its vicinity rather than just the intended receiver.

Alternatively, a more robust synchronization procedure could be achieved by implementing a time synchronized communication protocol, whereby the nodes only "wake up" according to a network-wide transmission schedule. Our nodes are already equipped with a real-time clock, which is driven by a low-cost and low-power 32-kHz crystal oscillator. The clock on each node could be set prior to deployment and its drift could be resynchronized across the network during every transmission. This would permit for network-wide communications to be scheduled, thus conserving power and reducing internetwork interference. Much of this functionality, along with more advanced multihop communications, can be ported from ongoing open-source efforts by the authors in RF sensor networks.[38]

7 | CONCLUSIONS

To our knowledge, this is the first instance of a field experiment to transmit data across an operational WDS. While wireless, our approach uses acoustic techniques as opposed to traditional RFs. The success of this approach is highly contingent upon a channel analysis, which isolated a very narrow frequency band upon which the proposed approach could be built. Outside of this band, it is likely that a combination of channel features and ambient noise will significantly attenuate the transmitted data signal.

Future extensions of this work would benefit from further analysis of various transducer technologies to improve energy transfer and transmission distance. Furthermore, phase-coherent communications should be investigated to assess the ability to implement higher order PM-based approaches, which should, similar to ocean communications,[21] improve network reliability, and throughput.

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