Vol. 5(16) Jul. 2015, PP. 2229-2238

Contents list available at IJMEC

International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)

Journal Homepage: www.aeuso.org

PISSN: 2411-6173 - EISSN: 2305-0543

Modelling of Wireless Acoustic In-Pipe Robot Communication Through the Steel Pipeline

Fadi N. Sibai*

Computer Operations Department, Saudi Aramco, Dhahran 31311, Kingdom of Saudi Arabia

***Corresponding Author's E-mail:** fadi.sibai@aramco.com*

Abstract

Communication from within the steel pipeline by inspecting or sensing tools or robots is usually performed via a cable. As the length of the tether restricts the communication distance and as the cable may encumber the tool's movement, we explore the feasibility of acoustic communication from within the liquid-filled pipe to an external sink through the steel pipe walls. The paper derives the sound signal attenuation resulting from the combination of the liquid content and metal wall acoustic channels. Results show that for 4" to 40" diameter steel pipes, acoustic communication of only a few hundred Hertz may be possible with low data rates, but multimedia communication prospects are weak. The paper also explores other wireless communication methods.

Keywords: *acoustic communication, liquid and metal channel acoustic models, in-pipe robot communication and steel pipelines.*

1. Introduction

Aging pipelines carrying hydrocarbon products have to be regularly inspected to extend their reliabilities and prevent environmental and/or safety incidents and avoid costly disruption times. Tools or robots for monitoring, inspecting and sensing the inner environment of conventional steel pipelines often communicate with the outside via a tether. In such an operational environment with liquid or gas flow, despite its many uses including supporting power delivery and data communication and pulling tools for retrieval after mission completion, a cable is not desirable as the cable length limits the reach distance of the tool, and the cable itself may restrict the movement of the tool. In-line instruments for inspection record sensed data on-board and data is retrieved following the exit of the instrument from the pipe. Such an approach however prevents real time communication with the instrument while in operation. Researchers [1] have demonstrated two other techniques for communication from within the pipe to an external sink. One employs communication by signal injection on the steel tube using the pipe's steel walls as a conductor. The other employs electromagnetic (EM) transmission using the empty pipe as a waveguide. Wi-Fi communication for up to 6GHz frequencies with proper amplification was demonstrated on a 24" diameter pipe with approximately 1 mile length and this range can be extended with the latest Wi-Fi technology; however, when the pipe is filled with liquid, the transmission range is expected to be drastically reduced. Signal injection on the steel tube for up to 60 KHz frequencies was shown to be feasible but this technique employs 2 orders of magnitude more power than using the pipe as waveguide technique, reducing its appeal. Moreover, in the flammable and explosive environment of a live pipe, signal injection on the tube and high power may introduce safety risks. For these reasons, we explore acoustic communication feasibility from within the steel pipeline to an external sink through the pipe steel walls. Despite its immunity to noise, acoustic communication is the preferred

Article History:

Received Date: Mar. 14, 2015

Accepted Date: Jun. 28, 2015

Available Online: Jul. 01, 2015

method of communication in seawater due to low attenuation of sound in seawater [2]. At a speed of 1500m/s increasing with temperature, it is 5 orders of magnitude slower than EM communication, possibly causing time dispersion of sound signals leading to severe symbol interference. Lower wave frequencies lead to lower data rates. Yet, sound waves travel further in seawater than EM or optical waves. EM waves do not travel well in salty water, their operating frequency in seawater should be low (1-20MHz) to reduce absorptive loss of EM waves. Free-space optical waves (blue-green wavelengths) also travel in seawater very short distances because of severe water absorption and strong backscatter from suspending particles. Their power loss is proportional to the liquid's turbidity, reducing the range to virtually nothing in dark liquids such as crude oil. Optical communication in water also requires precise placement of hardware. Another disadvantage of EM and free-space optical waves in seawater is that their antenna complexity is higher than for sound waves.

In this paper, we investigate the feasibility of acoustic communication from the within a water-filled pipe through the steel pipe walls to an external sink. We use a key part of the undersea water channel model [3] to model the liquid channel inside the water-filled pipe and add it to the metal channel model [4] to derive an estimate of the total sound wave attenuation in the water-filled steel pipe.

Section 2 reviews background information and related work. Section 3 describes the acoustic metal-channel model across the pipe's steel tube. Section 4 describes the acoustic liquid-channel model. In Section 5, we derive the total signal attenuation resulting from combining both acoustic channel models. Section 6 explores other tetherless communication methods. We conclude the paper in the last Section.

2. Background

Erikson et al. [1] investigated two communication techniques in empty gas-transporting steel pipes which they found to be feasible: (1) pipeline as a microwave waveguide of commercial wireless modems; and (2) pipeline as a signal conductor. In the pipeline as a waveguide method, three different experiments were conducted on various gas pipes.

a. Transmission line technique mimicking the coaxial cable by setting the ratio of the radius of outer pipe cylinder to the radius of inner copper pipe cylinder to 2.6 to create a 50 ohm impedance. Researchers used a cone shaped copper section to launch an EM wave on one end of the pipe to diverge the signal and another cone shaped copper section at the other end of the pipe to converge the EM signal. The two corners of the cone shaped sections were joined to a network analyzer to measure signal attenuation. Signal attenuation was found to increase with frequency A large loss (3 db for frequencies higher than 3 GHz) was measured in the short 3.5 m pipe but communication is possible.

b. Resonance cavity method: Both ends of the pipe were tightly sealed with two copper plates to convert the space inside the pipe to a resonant cavity. An EM wave was generated by a dipole inside the cavity and the number of times the wave bounces inside the cavity before it disappears was measured. For a resonant frequency of 1.11 GHz, pipe diameter of 0.15 m and pipe length of 3.5 m long, researchers concluded that this technique can be used to transmit a few frequencies of a few GHz.

c. Wireless 802.11b communication was successful when one modem used a horn antenna and the other used the dish/feed antenna, or when both receiver and sender antennas were 8 dBi collinear antennas oriented vertically. The tested 0.9 mile pipe showed less attenuation for frequencies around 5 GHz. New wireless communication technologies are expected to improve the transmission range.

In the pipeline as a conductor method, experiments were conducted on a 6" diameter steel pipe loop, where a signal generator is attached to the steel pipe and grounded at one end and a voltmeter is attached to the other/receiving pipe end. Experimental results revealed that the tube can be used to transmit a signal in the 10 KHz to 60 KHz range. The pipe diameter and wall thickness had negligible effect on attenuation. Skin effect is more pronounced with pipes made of ferroelectric material and at the higher communication frequencies. Transmission is mainly affected by the Earth resistivity, frequency, and pipe material. Little attenuation was recorded for frequencies below 1KHz no matter the Earth's resistivity. Signal attenuation was lower for higher Earth resistivity. Unburied pipe (little contact with Earth, higher outside pipe resistivity) showed little attenuation while mostly buried pipe had large attenuation at 10 KHz to 60 KHz, but not large enough to prevent Wi-Fi communication with sufficient amplification at the receiver.

The above results are in an empty pipe in the absence of any liquid. Liu, Zhou and Cui [2] investigated underwater communication involving the transmission of information in the form of sound, EM or optical waves. Acoustic communication is most widely used underwater but high frequency bands (>50KHz) can only be used over short distances. For moderate distances, frequency range 20 KHz to 50 KHz is used, and for tens of km of distance, low frequency waves (<10 KHz) are used. Acoustic communication bandwidth is limited to a few KHz up to tens of KHz. The slow speed of sound wave in sea water causes severe inter-symbol interference due to multipath and large channel delay spread. Also slow propagation in motion environments causes a large Doppler spread or shifts. Due to conducting nature of seawater, EM must work in power-limited region with low frequencies to avoid large EM signal attenuation. In seawater, 1-20 MHz radio waves were able to propagate over distances of up to 100 m using dipole radiation with transmission power of 100 W. Optical communication enables data rates above 1 Gbps but highly depends on liquid turbidity. Free-space optical (FSO) waves used as wireless communication carries are limited to very short distances because of severe water absorption at the optical frequency band and strong backscatter from suspending particles. Yet, FSO, particularly in blue-green wavelengths, offer high bandwidth (10-150 Mbps) over moderate ranges (10-100 m) of sea communication. Also fiber optic communication over an optical fiber can extend to very long distances.

Verzijlenberg and Jenkin [5] investigated human-robot communication in deep sea. Low bandwidth (~19Kb/s) acoustic modems are available for underwater applications, and high bandwidth (~20Mb/s) optical modems have been shown to be effective for short range communication with underwater robots; however, their sizes and weights are large, occupying one quarter of the underwater vehicle size, impractical for small diameter steel pipes. Also in hydrocarbon transport, these optical modems do not function due to high liquid turbidity.

Acousto-optical hybrid techniques have been devised whereby a laser beam creates temperature fluctuations which produce volume expansion and contraction creating a propagating pressure wave with the acoustic characteristics of the laser modulation signal. Wild and Hinckley [6] investigated electro-acoustic and acousto-optic communication (wireless) channels used by robotic agents in the non-destructive evaluation of structures. Results with a 1 MHz square wave carrier reveal that the electro-acoustic communications channel with piezoelectric sensors gave a data rate of 200 kbps. When applied to communicate acoustically across a human arm, the electro-acoustic communication method's data rate with piezoelectric transducers went down to 40 kbps [7].

In the pipe, optical communication over fiber optic cable may be undesirable due to the cost, and inconvenience of tethered communication in a live pipe environment. FSO modems also do not function in high turbidity hydrocarbon flow; therefore in a pipe environment, acoustic and EM communication methods may be most suitable. Ultrasonic communication through a water tank was tested with amplitude modulation and demodulation communication circuits and ultrasonic transducers. A 7.5 V peak 1000 Hz square wave input signal was modulated with a 2 MHz 10 V peak carrier, amplified and then transmitted via an ultrasonic transducer. The acoustic signal traverses a water tank and is received and converted by an ultrasonic transducer to an electric signal (in the mV range) which is fed to an amplification circuit, followed by an AM demodulation circuit.

3. Ultrasonic Metal Channel Model

To model acoustic metal channel communication through the steel tube, we use Primerano' s acoustic metal channel model [4] consisting of a ¼" thick steel plate sandwiched by two 6 MHz ¼" contact transducers, a transmitting transducer on one side of the metal plate, and a receiving transducer on the other side, precisely positioned over each other. The transducers are needed as radio signals do not propagate across metal channels. One transducer converts electrical signals to acoustic ones while the other makes the reverse conversion. The transducer relates the voltage and current of its electrical signal at one port to the force and velocity of its sound signal at the other port. Due to media impedance mismatches, acoustic echoes are reflected by incident acoustic signals in the metal channel causing inter-symbol interference and necessitating the placement of an equalization filter in series with the transducer. This equalization filter cancels these reflected echoes.

The basic (non-equalized) metal channel model is based on primary (P(z)) and echo (E(z)) transfer functions as shown in Fig. 1, where E(z) represents the echo portion of the transient response.

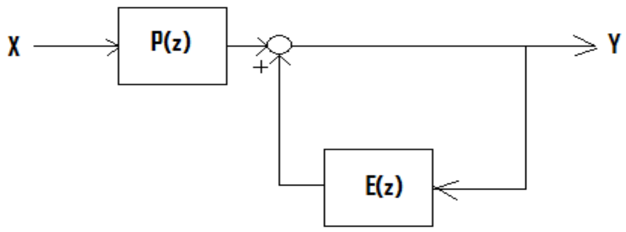
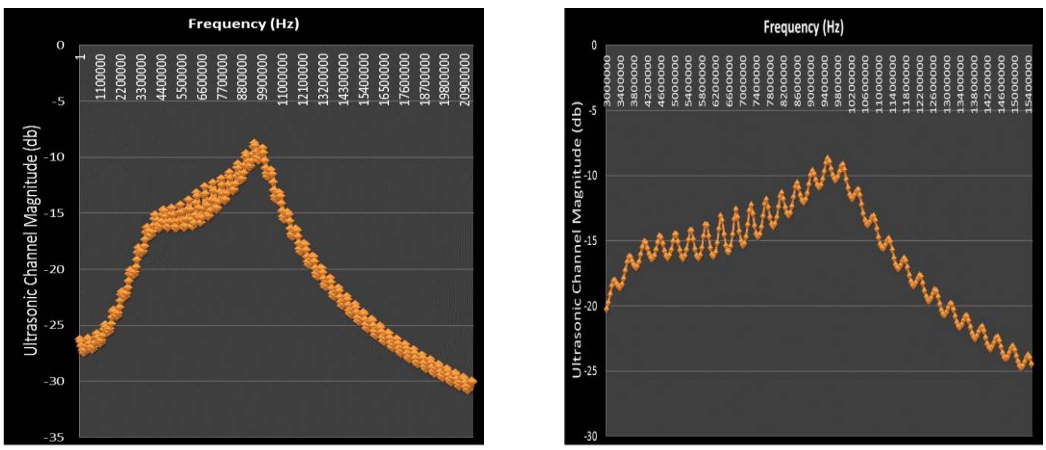
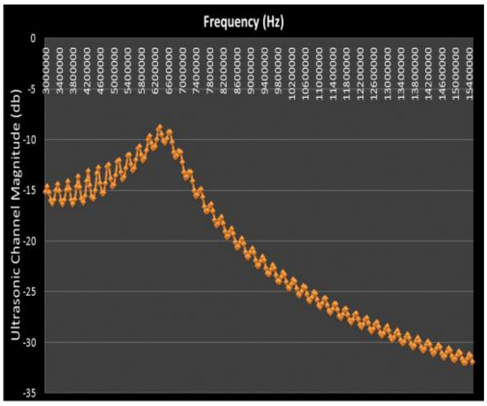


Figure 1: Acoustic Metal Channel Block Diagram

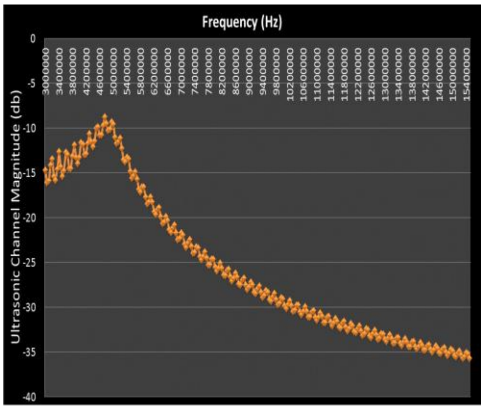
The metal channel frequency response is plotted in Figs. 2a and 2b, assuming a sampling period of 10 ns and a peak sound wave amplitude of 1. The signal plus noise power over noise power ratio was empirically measured by [3] to be close to 210. With the 3 db bandwidth near 2.5 MHz, the maximum metal channel capacity is thus about 2.5 x $\log_2(2^{10})$= 25Mbps. When the sampling period is increased to 15 ns and then 20 ns, the peak response shifts to the left to a lower frequency as shown in Figs. 2c and 2d. When the sampling period is decreased to 7.5 ns and then 5ns, the peak response shifts to the right to a higher frequency as shown in Figures 2e and 2f. After the sampling period is reduced to 4 ns and below, the



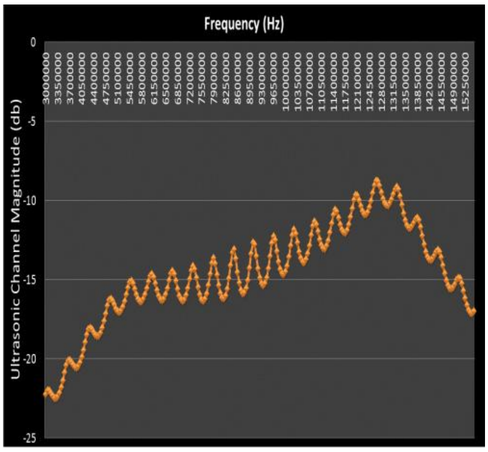
a. Over 1 MHz to 20 MHz range **b. Over 3 MHz to 15 MHz range**



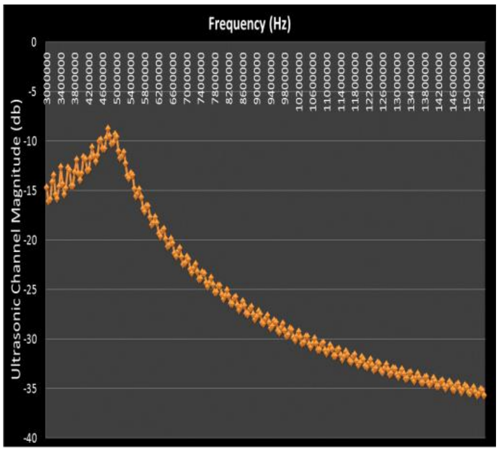
c. After increasing sampling period by 50% to 15 ns



d. After increasing sampling period by 100% to 20 ns



e. After decreasing sampling period by 25% to 7.5 ns



f. After decreasing sampling period by 50% to 5 ns

Figure 2: Frequency response of acoustic metal channel

Frequency response magnitude drops further. So the best sampling period resulting for the highest magnitude for the highest frequency is around 5 ns. We will assume a 10 ns sampling period in the rest of the paper.

4. Acoustic Liquid Channel Model

Before discussing the acoustic water channel, we will review a few properties of sound. Sound travels faster in solids, than in liquids, and air. The velocity of sound is 1,430 m/s in fresh water, dropping to 1,330 m/s in petroleum, about one-fourth its speed of 5,900 m/s in steel. It is proportional to the acoustic impedance. Acoustic impedance impacts the magnitude of reflected echoes and is given by

$$Z = \rho c \tag{1}$$

where c is the velocity of the sound wave, and ρ is the channel material density. The acoustic impedance is 47.6 x 106, 1.43 x 106, 0.93 x 106, 430 Pa s/m while the density is 7.85, 1, 0.7, 0.001205 gm/cm^3, for steel, fresh water, petroleum, and air, respectively [9].

When the sound wave originates in some material 1 and hits an interface between the two types of materials 1 and 2 with impedances Z_1 and Z_2, respectively, part of the beam is reflected (back to material 1, and is detected as echo, and another part is transmitted through material 2. If E_i is the incident beam's energy, the reflected beam energy (E_r) and transmitted beam energy (E_t) are given by

$$E_r = E_i (Z_1 - Z_2)^2 / (Z_1 + Z_2)^2$$
$$E_t = E_i \ (2 Z_2)^2 / (Z_1 + Z_2)^2 \tag{2}$$

The above energy expressions imply that if a wave travels from a high impedance medium to a low impedance medium, most of it will be reflected. As the acoustic impedance of air is much smaller than other media, a big fraction of the wave is reflected when crossing some medium to air interface, e.g., necessitating the use of transducers in the metal channel model of the previous Section. As to the sound speed in liquids, it increases with reductions in temperature or increases in pressure.

We assume an acoustic water-channel model similar to the seawater channel model and assume cylindrical wave spreading in the pipe. The acoustic water-channel attenuation loss is expressed as the sum of the spreading loss and the absorption loss. This path loss represents the decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source and is given by

$$PL= n \log r + 1000\, \alpha\, r \tag{3}$$

where n is the spreading loss factor which equals 1 for transmission caused by cylindrical spreading; α represents the absorption coefficient (in db/km) which is detailed below; and r represents the range in meters. Thorp's expression of α (in db/Km), for a few hundred Hz is given by [3, 10, 11]

$$\alpha = 0.11\, f^2/(1+f^2) + 44\, f^2/(4100+f^2) + 2.75\, 10^{-4}\, f^2 + 0.003 \tag{4}$$

where frequency f is expressed in KHz. Assuming that the robot or tool conservatively transmits from the bottom of the pipe to its top (longest distance within the cross section area), the range r equals d, the pipe's diameter. Thereby, the path loss equation is reduced to

$$PL= \log d + 1000\, d\, (0.11\, f^2/(1+f^2) + 44\, f^2/(4100+f^2) + 2.75\, 10^{-4}\, f^2 + 0.003) \tag{5}$$

Adding the path loss of the water channel to the attenuation over the metallic channel gives us a good estimate of the comprehensive attenuation loss of an acoustic wave transmitted from the bottom of the pipe and received outside the pipe at the external transducer attached to the external pipe wall. For the acoustic metal-channel loss represented by the frequency response, we consider five types of sound waveforms: sinusoid, 1-sample long pulse, 3-sample long pulse, 8-sample long pulse, and step input, where the sampling period is 10 ns. The 1-sample long pulse is of length equal to 1 cycle. The 8-sample long pulse is eight times longer.

5. Total Attenuation

As an ultrasound beam goes through a medium, it loses energy and intensity (power per area) and experiences a reduction in amplitude determined by the characteristics of the medium. Thereby attenuation determines the penetration of a wave in a medium. Excluding noises in the pipeline environment, results of the total attenuation in db combining both metal channel and water channel path losses are plotted in Figures 3 to 6 for pipe diameters of 4" (0.1 m), 12" (0.3 m), 20" (0.5 m), and 40" (1 m), respectively. In Figures 3 to 6, negative numbers in the Y axis represent signal losses or attenuations, while positive numbers represent gains. Acoustic signal attenuation increases with increasing pipeline diameters and frequencies. Note that a 10db (20db) attenuation represents a 10x (100x) attenuation. By increasing the sound wave peak amplitude to a (from 1), the attenuations in Figs. 3 to 6 are pushed up by $10 \log_{10} a$.

As indicated by Fig. 3, for small diameter pipes of 4" diameter, acoustic communication is not feasible beyond 500 Hz without high signal magnitudes or amplification. For a sinusoidal tone (1 sample-long pulse), the water channel path loss exceeds the metal channel path loss for f>=4,500 Hz (3,900 Hz). Longer pulses are attenuated less than shorter pulses or sinusoidal tone. As indicated by Fig. 4, for pipes of 12" diameter, acoustic communication is not feasible beyond 300Hz without high signal magnitudes or amplification. For a sinusoidal tone (1 sample-long pulse of 1 cycle length), the water channel path loss exceeds the metal channel path loss for f>=1,500 Hz (1,300 Hz).

International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)
Universal Scientific Organization, www.aeuso.org
PISSN: 2411-6173, EISSN: 2305-0543

For pipes of 20” diameter and as shown by Fig. 5, acoustic communication is not feasible beyond 200Hz without high signal magnitudes or amplification. For a sinusoidal tone (1 sample-long pulse), the water channel path loss exceeds the metal channel path loss for f>=900 Hz (800 Hz). For larger 40” diameter pipes and as shown by Fig. 6, acoustic communication is not feasible beyond 100 Hz without high signal magnitudes or amplification. For a sinusoidal tone (1 sample-long pulse), the water channel path loss exceeds the metal channel path loss for f>=550 Hz (500 Hz).

The results (not shown in Figures. 3-6 which sum path losses through water and metal channels but do not show the breakup) show large signal attenuations in the water-filled pipeline due to the liquid content and the pipe metal walls allowing acoustic communication with only a few hundred Hz frequencies possible. The low frequencies result in low data rates, which make multimedia communication from within the pipe very difficult. It should be noted that the total path loss does not change much if we shorten the range r, and assume that the robot communication originates from the center of the pipe rather than the bottom of the pipe.

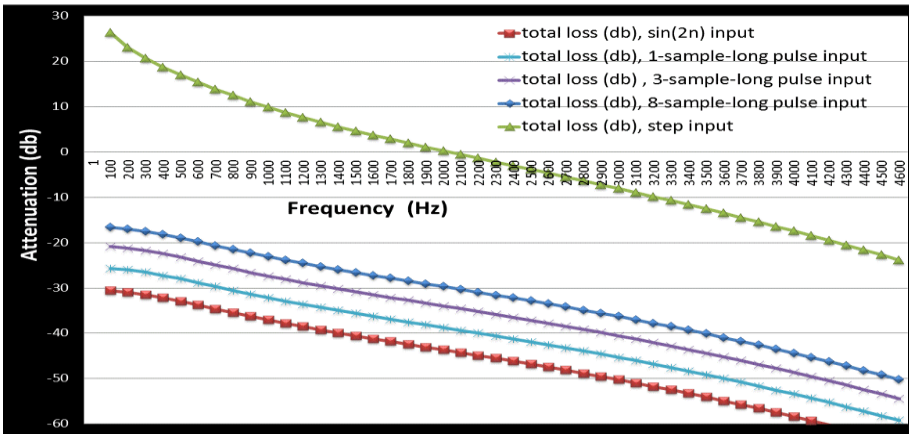


Figure 3: Total attenuation (db) vs. frequency (Hz) for 4” diameter pipes

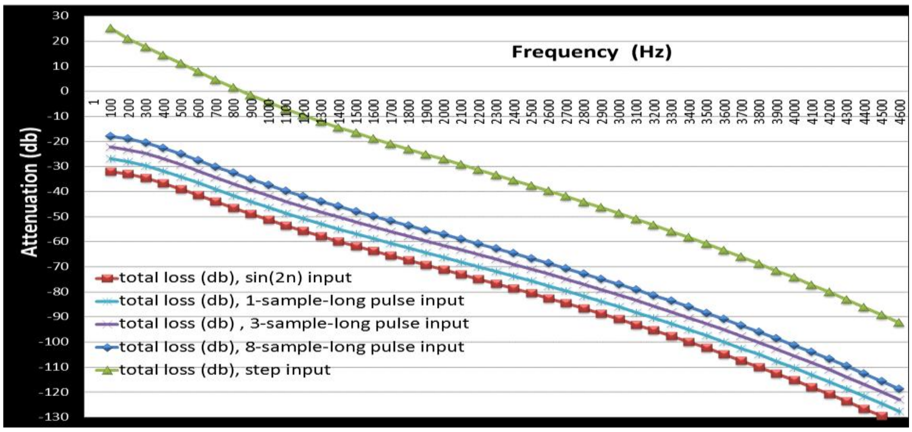


Figure 4: Total attenuation (db) vs. frequency (Hz) for 12” diameter pipes

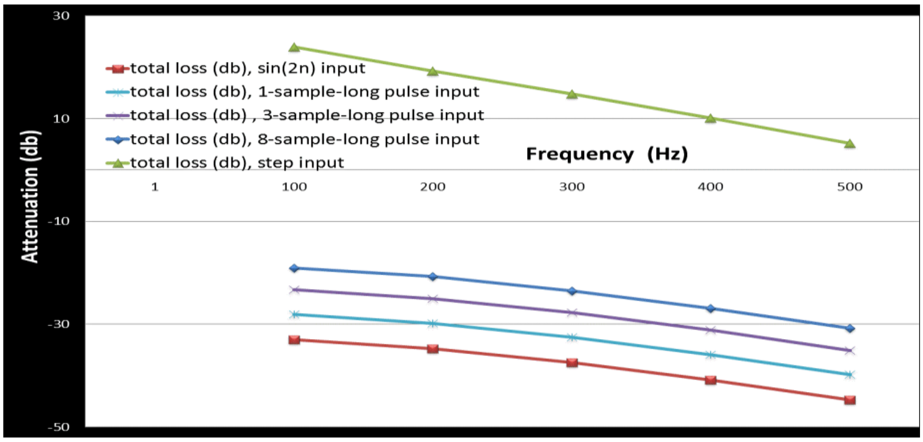


Figure 5: Total attenuation (db) vs. frequency (Hz) for 20” diameter pipes

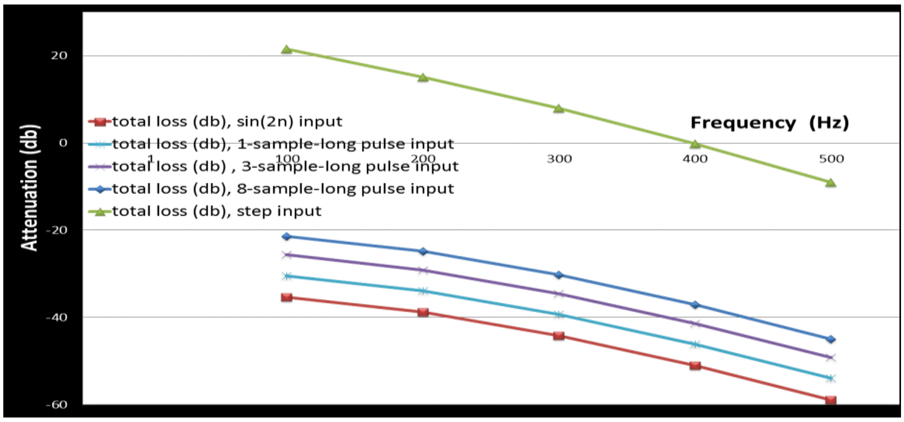


Figure 6: Total attenuation (db) vs. frequency (Hz) for 40” diameter pipes

6. Other Tetherless Communication Methods

One major inconvenience of the above acoustic method is the requirement for placing transducers on each side of the pipe precisely positioned on top of each other. To avoid such requirement and to transmit for long distances, an inspecting robot or instrument equipped with acoustic receiver (hydrophone) and transmitter (e.g. air-gun) can communicate acoustically with an acoustic transceiver placed on the inner pipe wall as shown in Fig. 7. The acoustic transceiver then injects electrical signal on the steel tube, which is picked by a sensor node placed on the external pipe wall which reads and transmits this signal electromagnetically via Wi-Fi or radio frequency. Sensor nodes have been previously used to monitor pipelines [12]. In PIPENET [12], the sensor nodes also perform the processing, such as detecting pressure pulses, and localization of leaks. In our application, the sensor nodes serve as communication relays only.

Again, the placement of the acoustic transceiver on the inner pipe wall is inconvenient and can be avoided by the communication method of Fig. 8. In Fig. 8, the in-pipe robot or instrument equipped with an on-board acoustic transceiver transmits an acoustic signal picked by a sensor node equipped with a sensitive microphone/air-gun and an EM transceiver. The placement of the sensor node is critical with respect to the inspecting tool’s position to be contained within the acoustic coverage range. More sensor nodes may be equidistantly placed on the outside of the pipeline to cover longer communication ranges. As acoustic communication from within the liquid filled pipe and across the pipe’s metal walls is too slow, alternative communications methods may be investigated. The communication method of Fig. 9 features an in-pipe robot with metallic communication tips, which make electric contact with the pipe tubing. Such communication contacts can be engulfed in cups for water-proofing. This way the in-pipe robot or inspecting instrument communicates with the sensor node by injecting and reading electric signals traveling on the steel tube. The tips of the communication whisker contacts could be metallic wheels for easy sliding. One drawback of such an approach is its larger power requirements, while another advantage of such a method is that communication on the steel tube was already demonstrated for frequencies as large as 60 KHz.

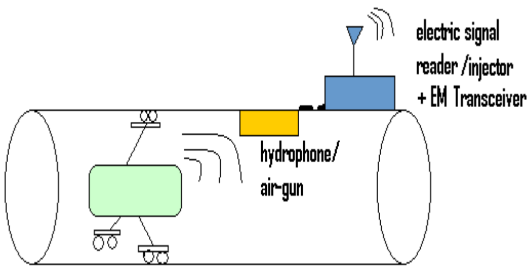


Figure 7: Acoustic transceiver relaying node in between the robot and the external sensor node.

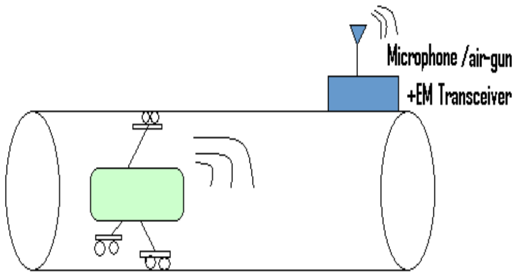


Figure 8: Direct communication between the robot and the external sensor node.

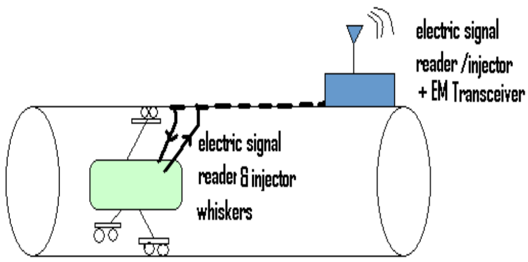


Figure 9: Signal Injection on the Tube with EM Communication.

Conclusion

We explore the feasibility of acoustic communication from an inspecting in-pipe robot or instrument in a liquid-filled steel pipe to an external sink by combining the water channel and metal channel acoustic models. Results indicate that low-throughput acoustic communication through the steel pipe is possible for up to a few hundred Hz but multimedia communication is difficult. Also, the slow speed of sound inside the pipe content presents a barrier to long distance real-time communication exchanges. Underwater radio frequency wireless communication may be also feasible in this environment as reported [13] and is under future investigation. It works well and is immune to liquid color and turbidity, acoustic noise, or waves while enabling high bandwidths. Underwater EM wave propagation distances and EM data rates decrease with increasing frequencies. At lower distance ranges, changes in propagation velocity are higher with changes in frequency than at higher distance ranges, necessitating bandwidth reductions at low distance ranges. Because of EM communication's limited range in liquid, a combination of wireless EM and other communication technologies may work best. As to future work, we may investigate dust cleaning options for PV modules and compare them based on output power performance, water requirements, and initial and long term costs.

Acknowledgment
We thank Saudi Aramco Management for authorizing the publication of this work.

References
[1] K. Erickson, A. Miller, E. Stanek, C. Wu, and S. Dunn-Norman, "Pipelines as Communication Network Links," Technical Report, University of Missouri Rolla, 2005.
[2] L. Liu, S. Zhou, and J. Cui, "Prospects and problems of wireless communication for underwater sensor networks," Wireless Communications and Mobile Computing, special issue on Underwater Sensor Networks, J. Wiley, 2008.
[3] M. Stojanovic, Underwater Communications, http://rpsea.org /forums/auto_stojanovic.pdf
[4] R. Primerano, "High Bit-rate Digital Communication Through Metal Channels," Ph.D.Thesis, Drexel Univ., 2010.
[5] B. Verzijlenberg, and M. Jenkin, "Swimming with robots," Proc. IEEE/RSJ Conf. on Robotics & Intelligent Systems (IROS), Taiwan, 2010.
[6] G. Wild, and S. Hinckley, "Electro-acoustic and acousto-optic communications for robotic agents in smart structures," Proc. SPIE, vol. 6414, 2006.
[7] G. Wild, and S. Hinckley, "Wireless acoustic communications and power supply for in vivo biomedical devices," Proc. IEEE Ultrasonics Symposium, 2010.
[8] G. Saulnier, et al, "Through-wall communication of low-rate digital data using ultrasound," Proc. IEEE Ultrasonics Symposium, Vancouver, 2006.
[9] V. Rudraraju, "Ultrasonic Data Communication Through Petroleum," MS Thesis, Dept. of Electrical Engineering, The University of Akron, 2010.
[10] W. Thorp, "Analytic description of low-frequency attenuation coefficient," Journal of Acoustical Society of America, vol. 42, no. 1, 1967.
[11] J. Ulrick, Principles of Underwater Sound, 3rd edition, McGraw-Hill, NY, NY, 1983.
[12] I. Stoianov, L. Nachman, and S. Madden, "PIPENET: A wireless sensor network for pipeline monitoring", Proc. ACM Info. Processing in Sensor Networks, MA, 2007.
X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong, "Re-evaluation of RF electromagnetic communication in underwater sensor networks," IEEE Communications Magazine, vol. 42, no. 12, 2010.

Authors

Dr. Fadi Sibai has been working for Saudi Aramco since 2011 where he currently focuses on data center performance management and analysis. Prior to that he worked in Saudi Aramco's Process and Control Dept., and Research and Development Center. Between 2006-2011, he directed the Computer Systems Design program and IBM-funded Cell Center of Competency at the UAE University. Between 1996-2006, he managed performance benchmarking and system validation teams at Intel Corporation, USA. Between 1990-1996, he worked as professor of electrical engineering at the University of Akron, USA. He received the PhD degree in Electrical Engineering from Texas A&M University. Dr. Sibai has authored above 180 technical publications and reports, and served on the Organizing or Program Committees of over 20 International Conferences. He is the recipient of competitive IBM and Intel awards. He is a senior member of the IEEE, and a member of Eta Kappa Nu.