Ad Hoc Networks 9 (2011) 218–227

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring

Zhi Sun [a,*], Pu Wang [a], Mehmet C. Vuran [c], Mznah A. Al-Rodhaan [b], Abdullah M. Al-Dhelaan [b], Ian F. Akyildiz [a,b]

[a] Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States
[b] College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia
[c] Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, United States

ARTICLE INFO

Article history:
Received 30 September 2010
Accepted 6 October 2010
Available online 20 October 2010

Keywords:
Underground pipelines
Leakage detection and localization
Wireless sensor networks
Magnetic induction (MI) communications

ABSTRACT

Underground pipelines constitute one of the most important ways to transport large amounts of fluid (e.g. oil and water) through long distances. However, existing leakage detection techniques do not work well in monitoring the underground pipelines due to the harsh underground environmental conditions. In this paper, a new solution, the *magnetic induction* (*MI*)*-based* wireless sensor network for underground pipeline monitoring (MISE-PIPE), is introduced to provide low-cost and real-time leakage detection and localization for underground pipelines. MISE-PIPE detects and localizes leakage by jointly utilizing the measurements of different types of sensors that are located both inside and around the underground pipelines. By adopting an MI waveguide technique, the measurements of different types of the sensors throughout the pipeline network can be reported to the administration center in real-time. The system architecture and operational framework of MISE-PIPE is first developed. Based on the operational framework, research challenges and open research issues are then discussed.

1. Introduction

Nowadays, millions of kilometers of pipelines are deployed all over the world to transport vast volumes of fresh water, fuels, crude oil and natural gas. In mid-east countries, those pipelines are even regarded as the lifelines of the national economy. Among all the pipelines used for oil or water transportation, pipeline structures, which are buried underground, are generally preferred due to their advantages in terms of safety and concealment. For example, the water supply of Riyadh City, the capital of Saudi Arabia, depends on hundreds of kilometers of underground pipelines that connect the city with the Arabian Gulf and remote water wells through the desert [23,42]. Moreover, during 2007, Russia exported almost 1.3 million barrels of crude oil per day via pipelines (most are underground pipelines) to Belarus, Ukraine, Germany, Poland, and other destinations in Central and Eastern Europe [44].

Although the underground pipelines constitute the safest way to transport large amounts of fluid through long distances, the pipelines are exposed to multiple hostile environmental factors, such as extreme soil conditions, corrosion, and human malicious attacks, which may cause leakage on the pipelines. According to statistical analysis, the large pipelines will experience at least one obvious leakage every year [15]. Pipeline leakages may lead to large economic loss, combined with environmental pollution, or risk of personnel injuries. Thus, the security and maintenance of the pipeline infrastructure is one of the major concerns [26].

* Corresponding author. Tel.: +1 404 825 3971.
E-mail addresses: zsun@ece.gatech.edu (Z. Sun), pwang40@ece.gatech.edu (P. Wang), mcvuran@cse.unl.edu (M.C. Vuran), rodhaan@ksu.edu.sa (M.A. Al-Rodhaan), dhelaan@ksu.edu.sa (A.M. Al-Dhelaan), ian@ece.gatech.edu (I.F. Akyildiz).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2010.10.006

Traditional pipeline leakage detection methods depend on the periodical inspection conducted by the maintenance personnel [10,43], which requires intensive human involvement. Moreover, the periodical inspection does not provide real-time monitoring of the pipelines. Consequently, a leakage may not be detected in time and may cause much larger economic loss and environmental pollution. Real-time pipeline monitoring systems based on wired or wireless sensors have been developed in [8,14,31]. The wire-based techniques connect the sensors along the pipelines with wires. Measurements from each sensor are transmitted to the remote monitoring center through these wires. However, the wire-based monitoring systems suffer from damages within any part of the network and the deployment in underground settings is highly costly. Wireless sensor networks [2], on the other hand, are much more robust and efficient to monitor the aboveground pipelines. However, terrestrial wireless sensor networks cannot be used to monitor the underground pipelines, since the traditional electromagnetic (EM) wave-based signal propagation techniques encounter problems of high path loss and dynamic channel condition in the underground environments [3,4,20,27–29,35,39]. To the best of our knowledge, a robust and efficient solution for underground pipeline monitoring has yet to be realized.

In this paper, we introduce *MISE-PIPE: Magnetic induction (MI)-based wireless sensor network for underground pipeline monitoring*, which provides a low-cost solution for effective real-time leakage detection and localization of underground pipelines. MISE-PIPE consists of two types of sensors based on their deployment, i.e. inside or outside the pipeline.

- Sensors, which are inside the pipelines, measure the pressure and the velocity of the oil/water flow, as well as the acoustic vibrations caused by the leakages. Since the inside sensors are deployed at the checkpoints or pump stations of the pipelines, they are resource-rich, high-power devices with higher processing capabilities. Therefore, the inside sensors also act as local processing hubs of MISE-PIPE.
- Sensors, which are outside the pipelines, measure the temperature, humidity, and properties of the soil around the underground pipelines. The outside sensors are densely buried underground along the pipelines hence can provide high granularity for leakage detection and localization.

The inside and the outside sensors have different detection/localization accuracy, system lifetime, and cost, while their measurements are complementary to each other. By coordinating these two types of sensors, MISE-PIPE provides both accurate real-time leakage detection/localization results and long system operation lifetime with low-cost for underground pipelines.

The measurements taken by the outside sensors along the pipelines are transmitted wirelessly using the MI waveguide technique to closeby processing hubs for in-network processing. Then the detection and localization results are transmitted through aboveground wireless communication techniques (such as sittlight communications) to a remote administrator center. The MI waveguide technique provides efficient and reliable communication in underground environments [32,33]. Since the MI channel is not affected by the properties of the soil medium, the channel conditions remain constant for MISE-PIPE. Moreover, by tuning the relay coils of the MI waveguide, the MI waveguide system achieves very low path loss in soil medium in long term operation. The details of the MI waveguide system are introduced in Section 4.

In the following, the system architecture and operational framework of MISE-PIPE is described. Based on the architecture and framework, the research challenges and open research issues are discussed. In particular, the remainder of this paper is organized as follows: The existing pipeline leakage detection techniques are summarized in Section 2. The system architecture and operational framework for the MISE-PIPE system are presented in Section 3. Then, in Section 4, the signal propagation techniques based on MI waveguide and corresponding deployment strategies are described. The research challenges are discussed in Section 5. Finally, the paper is concluded in Section 6.

2. Existing pipeline monitoring techniques

Existing pipeline monitoring techniques can be divided into two categories based on the positions of the sensors, i.e., inside or outside the pipeline.

2.1. Sensors outside pipelines

2.1.1. Visual inspection

Traditional monitoring techniques for aboveground pipelines utilize image/video sensors to monitor the area around the pipelines [41]. The image/video sensors have large sensing ranges if visibility is good. Any leakage or other abnormity status along the pipelines can be detected and localized by the image/video sensors. However, this technique cannot be used to monitor underground pipelines.

2.1.2. Ground penetrating radar (GPR)

To detect the leakage of underground pipelines, the ground penetrating radar (GPR) is adopted in [6,12,13,25]. GPR can accurately pinpoint buried pipeline leaks without digging. The GPR can be integrated to portable devices and can be carried by maintenance people. Although this method is able to cover several miles pipeline per day, it requires intensive human involvement. Moreover, the monitoring is not real-time. Hence, a leakage may not be detected in time.

2.1.3. Soil properties sensors

Since the fluid leaked from the pipelines may cause the changes of soil properties around the underground pipelines, the leakage can be detected through the identification of abnormal value of the soil properties. The type of sensors to be utilized is determined by the transported fluid of the monitored pipelines. For example, temperature sensors can be used to detect hot liquid leaks as the surrounding temperature increases after a leak develops [36,40]. Soil humidity sensors can be used to detect water leakage [8,41]. Hydrocarbon vapour sensors can be used to detect the leakage of pipeline transporting liquefied natural gas [30]. Soil dielectric property sensors can be used to detect the leakage of crude oil pipelines [8,41].

The monitoring system based on soil property sensors provides accurate and real-time leakage detection and localization. However, currently the wire-based communication system is used to transmit the measurements derived by the underground soil property sensors to remote administration center [41]. The deployment cost of the wire-based system is extremely high for underground pipeline monitoring. Moreover, the system is not robust since the communication is compromised if any one point on the wire is damaged. Although the wireless sensor networks has been introduced for aboveground pipeline monitoring [14], this terrestrial wireless sensor network does not work well in underground environments since the EM wave propagation suffers from the problems of high path loss and dynamic channel conditions in underground soil medium [3,4,20,27–29,35,39]. To solve the above problems, the underground sensor can be connected to an aboveground antenna through a cable. Then the sensor can communicate wirelessly using EM waves through the air. However, for underground pipeline monitoring, it is unfavorable to connect every underground sensor to an aboveground antenna due to the deployment difficulty and the large number of underground sensors.

2.2. Monitoring techniques based on sensors inside pipelines

Intensive inside measurements are not favorable for the underground pipelines since deployment of sensors inside the pipelines requires to set junctions between two adjacent pipes. In underground pipelines, high densities of junctions increase the leakage possibility. Therefore, the inside sensors can be only deployed inside the pipeline at the checkpoints or the pump stations. Consequently, the density of the inside sensors cannot be very high. Current inside leakage detection sensors are explained as follows.

2.2.1. Acoustic devices

Small leakage from pipelines can generate high frequency oscillations in the pipe wall as the fluid escapes from the pipeline. The acoustic transducers are widely used to trace the vibration data to its source to detect and localize the leakage [1,18,19,36]. Due to the limitation of the detection range, it is usually necessary to install a high density of acoustic sensors inside the pipeline to cover the whole pipeline network, which is impossible for underground pipelines due to the deployment and maintenance difficulties. Moreover, the acoustic sensors are insensitive to large leaks as they do not generate vibrations in the characteristic high frequencies [7]. Therefore, the acoustic sensors is only suitable to accurately detect the small leakages on the underground pipelines near the checkpoints or pump stations.

2.2.2. Mass balance methods

A leakage may cause an abnormal change in the difference between an upstream and down stream flow. Therefore, the leakage can be detected by monitoring the flow difference based on flow sensors inside the pipelines [22,24]. The cost of mass balance method is very small. Moreover, this method can detect small leaks which do not generate a high rate of change in flow pressure. However, the detection false alarm rate is high because the change of flow difference can be caused by many other factors, such as the blockage/roughness inside the pipes and the temperature/density of the transported fluid. Furthermore, the mass balance method cannot accurately localize the position of the leakage.

2.2.3. Transient-based methods

Recently, transient-based methods have been intensively analyzed by the research community [5,7,11,21,37]. The transient-based leakage detection methods can be accomplished in four steps:

- An artificial transient event, such as opening/closing a valve or starting-up or shutting down a pump, is triggered in the pipeline network.
- Pressure sensors deployed at checkpoints of the pipeline network measure the pressure during the transient event.
- The measurements are transmitted to a processing center.
- A transient simulation model of the pipeline network is calibrated according to the measurements.

The presence, size, and location of the leakage can be identified in the calibration process. Since the pressure sensors can be only deployed in limited number of locations, the transient-based methods cannot provide enough leakage detection and localization accuracy.

3. System architecture and operational framework for MISE-PIPE

As discussed in Section 2, current leakage detection techniques have different detection accuracies, applicable environments, and costs. However, none of these techniques, alone, can provide accurate detection/localization and system longevity with low-cost for underground pipelines. Moreover, transmitting measurements from underground sensors to remote administration centers in a reliable and efficient way is still an open research issue. As introduced in Section 1, MISE-PIPE utilize sensors both inside and outside the pipelines to cooperatively detect and localize leakages. Accurate detection and localization can be achieved with minimum cost and energy consumption. The measurements taken by the underground sensors outside the pipelines are transmitted using the magnetic induction (MI)-based wireless underground sensor networks [32,33], which provide both robust and efficient wireless communication in underground environments. The detailed system architecture of MISE-PIPE is described as follows.

3.1. System architecture of MISE-PIPE

MISE-PIPE has a clustered architecture of heterogeneous sensors, which consists of two layers: the hub layer and the in-soil sensor layer, as illustrated in Fig. 1. The hub layer consists of the pressure sensors and acoustic sensors that are deployed inside the pipeline at the checkpoints or the pump stations. The in-soil sensor layer consists of different types of soil property sensors that are deployed along the underground pipelines. The long pipelines are divided into multiple pipeline sections by the checkpoints or pump stations. Each pipeline section has two checkpoints or pump stations at the two terminals, as shown in Fig. 1. In each pipeline section, a cluster of heterogeneous sensors is formed, which consists of the pressure/acoustic sensors at the two checkpoints or pump stations and the soil property sensors along this pipeline section. The pressure/acoustic sensors at the checkpoints or pump stations act as the cluster heads (processing hubs). The soil property sensors along the pipeline section act as cluster members and transmit their measurements wirelessly to the cluster heads at the checkpoints or pump stations. The cluster heads conduct in-network processing of all the measurements and send the preprocessed data to a remote administration center, which is located in the near city or town. Specifically,

- At the hub layer, pressure sensors and acoustic sensors are deployed inside the pipelines at the checkpoints and pump stations. The pressure sensors utilize the transient-based method to identify the areas where the pipelines are likely to have leakages. Acoustic sensors can be utilized as a complement to the pressure sensors to accurately detect the small leakages on the pipelines near the checkpoints or pump stations. Those inside sensors are equipped with magnetic induction transceivers to communicate with the soil property sensors buried along the underground pipelines. Since the checkpoint and the pump stations of the underground pipelines usually have the aboveground parts for maintenance purposes, the inside sensors at each checkpoint or pump station are connected to an aboveground gateway wirelessly or through wire, as shown in Fig. 1. The aboveground gateways send the measurements of the pressure and acoustic sensors wirelessly in a multi-hop fashion or through satellite communications to the remote administrator center. Since the inside sensors are deployed in the checkpoints or the pump stations, they are resource-rich, high-power devices with higher processing capabilities. As a result, these components are also in charge of performing intensive detection and localization processing on the measurements. However, due to the limited number of checkpoints and pump stations, the acoustic sensors can only accurately detect the pipeline sections near the checkpoints and pump stations, and the pressure sensors cannot provide enough leakage detection and localization accuracy.
- At the in-soil sensor layer, the wireless soil property sensors are deployed along the underground pipelines to provide higher granularity to solve the small monitoring range problem of the acoustic sensors and the low accuracy problem of the pressure sensors at the hub layer. Based on the type of fluid transported in the monitored pipelines, the sensors are designed to sense at least soil properties. The soil property sensors collaboratively process the measured data, and transmit the data wirelessly in a multi-hop fashion along the underground pipelines to the processing hubs located at the checkpoints and pump stations. MISE-PIPE employs magnetic induction techniques for wireless communication [32,33], which is further explained in Section 4. Since the wireless sensors buried in underground are powered by batteries, the energy consumption of those sensors should be limited to prolong the system lifetime.

3.2. Operational framework of MISE-PIPE

Based on the system architecture, the operational framework of MISE-PIPE is described in this subsection to realize the basic functionalities of leakage detection and localization for underground pipelines. According to the system architecture, the acoustic sensors provide continuously leakage monitoring for the pipeline sections that are near the checkpoints and pump stations. The leakage mon-

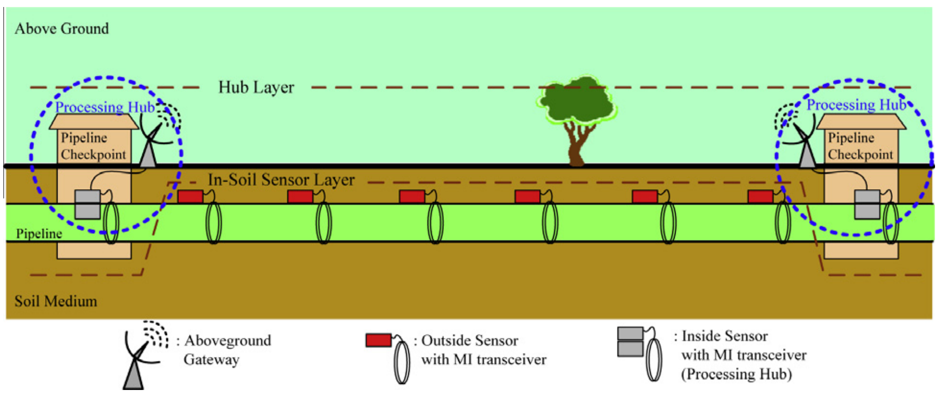


Fig. 1. System architecture of MISE-PIPE.

itoring of all other parts of the pipelines are accomplished by utilizing the soil property sensors and pressure sensors. The two types of measurement (soil property and flow pressure) are complementary to each other. On the one hand, the pressure sensors at the checkpoints and pump stations are resource-rich and thus, can monitor the pipeline continuously. However, the leakage detection and localization are not accurate due to the limited density of the pressure sensors. On the other hand, the soil property sensors densely deployed along the pipelines can provide much more accurate leakage detection and localization results. However, due to the constraint battery energy, the soil property sensors are not desired to continuously make and transmit the soil property measurements.

In MISE-PIPE, to accurately detect and localize possible leakage while achieving long system operation lifetime, a three-phase collaborative detection strategy is adopted:

- In the first-phase, the transient-based leakage detection method [5,7,11,21,37] is applied in the pipeline networks. The pressure sensors measure the flow pressure during the transient event and send the measurements to the remote administrator center. By calibrating the transient simulation model of the pipeline network based on the pressure measurements, the administrator center can identify some suspicious areas where the pipelines are possible to have leakages.
- In the second phase, the administrator center notifies the pressure sensors of the pipelines in the suspicious areas. The pressure sensors send out data requests to the soil property sensors along the pipelines that are suspicious to have leakages. Before receiving the data request, those soil property sensors keep in sleep mode to save battery energy. The soil property sensors are activated from the sleep mode by the data requests and measure the required soil properties. The measurements are aggregated while being transmitted. The aggregated measurements are then sent to the pressure sensors (processing hubs) through a multi-hop fashion. The data transmission along the pipelines in soil medium is accomplished by the magnetic induction techniques [32,33].
- In the third phase, after receiving the soil property measurements along each suspicious pipelines, adjacent processing hubs exchange those high resolution measurements through aboveground wireless channels. The adjacent processing hubs collaboratively determine whether there is a leakage or not in the suspicious pipelines by in-network processing. The location of the leakage is determined at the same time. After the processing hubs confirm a leakage detection, they report the detection results as well as the leakage position to the remote administration center and inform pipeline reparation personnel to fix the leakage in time.

4. Magnetic Induction-Based Underground Communication for MISE-PIPE

According to the system architecture and operational framework described in Section 3, the functionality of the MISE-PIPE highly depends on two types of wireless communication needs: the communication between soil property sensors and the processing hubs, and the communication between the processing hubs and the remote administration center. The communication between the processing hubs and the remote administration center can be established through existing wireless communication techniques, including the satellite communication, the cellular networks, the ad-hoc networks, and mesh networks. However, a reliable and efficient wireless underground communication technique has yet to be developed to realize the wireless communication between soil property sensors and processing hubs.

Traditional signal propagation techniques using electromagnetic (EM) waves encounter two major problems in soil medium: (1) high levels of attenuation due to absorption by soil, rock, and water in the underground; and (2) dynamic channel conditions depending on numerous soil properties such as water content, soil makeup (sand, silt, or clay) and density [4,20,27–29,39]. To guarantee the network connectivity, high density of underground sensors is required, which may induce high deployment and maintenance cost [35].

The magnetic induction (MI)-based communication is a promising signal propagation technique in soil medium, since the dense soil medium does not cause higher attenuation rate of magnetic fields than the rate in the air and the MI channel conditions do not dramatically vary as the soil properties change [32,33]. The MI communication is accomplished with the use of a coil of wire, as shown in Fig. 2. Those coils can be winded on the pipelines in MISE-PIPE. The signal in the transmitter coil is modulated by a sinusoidal current, which produces a time-varying magnetic field in the near field of the transmitter. The time-varying magnetic field induces another sinusoidal current in the receiver, which accomplishes the communication.

4.1. MI Waveguide

Despite the potential advantages of MI communication, the path loss of MI transceivers are still high since the magnetic field strength falls off much faster than the EM waves ($1/r^3$ vs. $1/r$). Motivated by this fact, we developed the MI waveguide technique in [32,33] to reduce the path loss and extend the transmission range for the MI communication in underground environments. In particular, relay points between the transmitter and the receiver are employed. Different from the relay points using the EM wave technique, the MI relay point is just a simple coil without any energy source or processing device. The sinusoidal current in the transmitter coil induces a sinusoidal current in

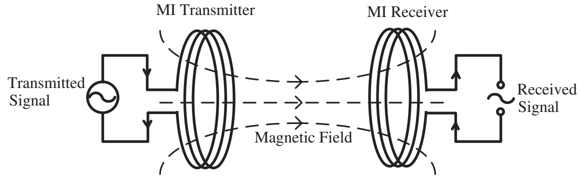


Fig. 2. MI-based wireless communications.

the first relay point. This sinusoidal current in the relay coil then induces another sinusoidal current in the second relay point, and so on and so forth. Those relay coils form an MI waveguide in underground environments, which acts as a waveguide that guides the so-called MI waves, as shown in Fig. 3. It should be noted that if the pipeline is made of metal, no (or very few) relay coils are needed since the metal pipeline itself acts as the magnetic core of the MI waveguide. The relay coils are needed only if the pipeline is made of non-metal materials, such as PVC pipelines. It is only required to deploy one relay coil that is around 5 m [32–34] apart from each other. The underground pipeline is the perfect core to wind those coils. The cost of the deployment of the coils is small if they are mounted on the pipeline during deployment.

The MI waveguide has four advantages in underground communications for MISE-PIPE:

- Based on our preliminary analysis in [32,33], by using the MI waveguides, the required number of underground sensors is possible to be significantly reduced. Specifically, by appropriately designing the waveguide parameters, the total path loss can be greatly reduced. The maximum communication range between two transceivers can achieve more than 100 m.
- Unlike the sensor devices, the relay coils do not require additional maintenance once they are buried. Even if some of the coils are damaged in extreme circumstances, the remaining coils still provide robust network operation. Hence the MI waveguide is robust and easy to deploy and maintain.
- The relay coils do not consume energy and the unit cost is very small. Therefore, the MI waveguide is ideal for the underground pipeline monitoring system.
- The system lifetime can be greatly prolonged, since it is possible to use the MI waveguide to recharge the underground sensors using the inductive charging technique [17].

4.2. Deployment of MI waveguide in MISE-PIPE

Although the MI waveguide technique is favorable in underground communications for MISE-PIPE, the deployment strategy of the relay coils to connect the soil property sensors along the pipelines needs to be developed due to the following reason. On the one hand, large number of relay coils are required to guarantee the network connectivity and robustness. On the other hand, the intensive deployment of the coils along pipelines cost a un-negligible amount of labor. Therefore the optimal number of relay coils needs to be found out. In this subsection, the relay coil deployment strategy for the one-dimensional (1D) network along the underground pipelines in MISE-PIPE is provided according to our previous analysis [34]. The optimal number of relay coils between two soil property sensors is analyzed according to the required bandwidth and the distance between two sensors.

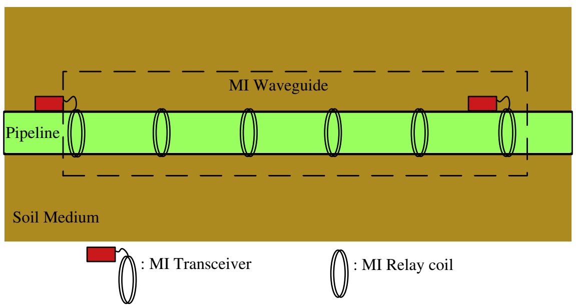


Fig. 3. MI waveguide structure in MISE-PIPE.

The goal of the optimal deployment of the MI waveguide in MISE-PIPE is to use as few relay coils as possible to connect the two adjacent soil property sensors. The optimal number of relay coils for each link is determined by the length of the link and the required bandwidth.

Assuming that the length of a link is d. The required bandwidth is B. An MI waveguide with $n-1$ relay coils is deployed along the link to connect the two sensors. Therefore the interval r between two adjacent relay coil is $r = d/n$. Assuming that the angle frequency of the transmitting signal is ω, and the center frequency of the signal is ω_0. According to [32,33], the path loss of the MI waveguide can be expressed as,

$$L_{MI}(d,n,\omega) \simeq 6.02 + 20\lg\zeta\left(\frac{Z}{\omega M}, n\right), \tag{1}$$

where M is the mutual induction between the adjacent coils; Z is the self impedance of one relay coil; and $\zeta(\frac{Z}{\omega M}, n)$ is the n order polynomial of $\frac{Z}{\omega M}$. The self impedance of a coil Z is designed to be resonant at the center frequency ω_0. When $\omega = \omega_0$, Z becomes pure resistance R, which is the coil wire resistance. The polynomial $\zeta(x,n)$ can be developed as

$$\zeta(x,1) = x, \quad \zeta(x,2) = x^2 + 1, \ldots, \\ \zeta(x,n) = x \cdot \zeta(x,n-1) + \zeta(x,n-2). \tag{2}$$

Then, the mutual induction M can be deduced by the magnetic potential of the magnetic dipole:

$$M \simeq \frac{\mu\pi N^2 a^4}{2r^3} = \frac{\mu\pi N^2 a^4}{2\left(\frac{d}{n}\right)^3}, \tag{3}$$

where μ is the permeability of the pipeline; N is the number of turns of the wire on the coils; and a is the coil radius.

According to (1), the path loss increases monotonically when the signal frequency deviates from the central frequency ω_0. Therefore, if the signal with frequency $\omega = \omega_0 + 0.5B$ is correctly received, a communication channel with bandwidth of B is established between the two sensors. Assuming that transmission power is P_t and the minimum power for correct demodulation a signal is P_{th}. Using the path loss given in (1), the received power is derived. Then the optimal number of relay coils for this link is:

$$n_{opt}(d,B) = \arg\min_n \{P_t - L_{MI}(d,n,\omega_0 + 0.5B) \geqslant P_{th}\}. \tag{4}$$

According to (4), the optimal number of relay coils is a function of the link length and the required bandwidth. Since the required bandwidth can be viewed as a constant, it is the link length that determines the optimal number of relay coil.

By using the parameters of the MI waveguide developed in [32,33], we can numerically analyze the optimal number of relay coils with different link length. In the following analysis, $P_t = 4$ dBm (2.5 mW) and $P_{th} = -80$ dBm. Due to the resonant characteristics of the MI waveguide, the bandwidth of the system is much smaller than the terrestrial wireless networks. However, the small bandwidth is acceptable for MISE-PIPE since the reporting the soil property measurements do not require very high data rate [3]. Therefore, the bandwidth of the MI waveguide is set to be 1 KHz. The operating frequency is 10 MHz. The relay coils have the same radius of 0.15 m and the number of turns is 20. The coil is made of copper wire with a 1.45 mm diameter. The cost and weight of coils made of this kind of wire is neglectable. The wire resistance of unit length is 0.01 Ω/m. This relatively high wire resistance also effectively mitigates the in-band signal fluctuation. The permeability of the underground soil medium is a constant and is similar to the permeability of the air, since most soil in the nature does not contain magnetite. Therefore, $\mu = 4\pi \times 10^{-7}$ H/m. The soil moisture and the soil composition do not affect the MI communication according to the analysis in [32,33].

In Fig. 4, the received power of the 10 MHz + 0.5 KHz signal using MI waveguides with different numbers of relay coils is shown as a function of the link length d. The axial communication range of a MI waveguide with a certain number of relay coils is shown as the intersection point of the received power and the −80 dBm threshold. Fig. 4 shows that the axial communication range increases as the number of relay coils increases. However, the increment of the communication range caused by additional relay coils decreases as the number of relay coils increases. For example, the axial communication range of a MI transceiver pair can be increased by 36 m by adding the first 10 relay coils but can be only increased by 27 m by adding another 10 relay coils. This phenomenon is due to the fact that the coils relay the signal in a passive way and there is no extra power added at each relay coil. According to (4), the optimal number of relay coils for the link with a certain length can be read from Fig. 4 by finding out the curve with the minimum number of relay coils that has the axial communication range larger than the link length.

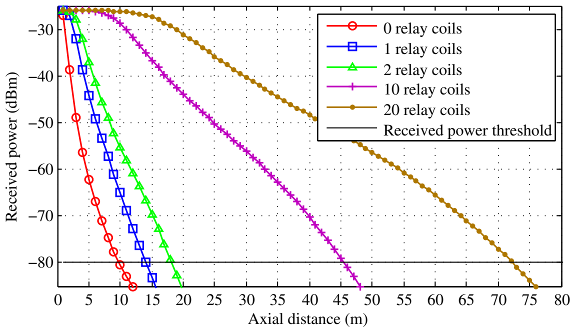


Fig. 4. Received power of MI waveguides with different numbers of relay coils.

It should be noted that the numerical results shown in Fig. 4 is based on the assumption that the pipeline is made of non-metal material. If the metal pipelines (e.g. cast iron pipelines) are used, the required number of relay coils can be greatly reduced since the metal pipeline acts as a perfect core of the magnetic induction system. Moreover, as the radius of the pipelines increases, the required number of relay coils also dramatically decreases since the radius of the relay coils also increases.

5. Research challenges

Based on the system architecture and operational framework of MISE-PIPE, the following research thrusts need to be investigated.

5.1. Optimal deployment strategies

As discussed in the introduction, the MISE-PIPE should cover underground pipelines for hundreds of kilometers long. On the one hand, to accurately detect and localize the pipeline leakages, the adjacent soil property sensors cannot be deployed too far from each other. Thus, a large number of soil property sensors are expected to fulfill the coverage requirement. Moreover, the first-phase leakage detection using the transient-based method in the MISE-PIPE operational framework are dependent on the number and locations of the inside pressure sensors [16,38]. On the other hand, different types of devices, e.g., soil property sensors, MI transceivers and relay coils, inside pressure sensors and acoustic sensors, and aboveground gateways are characterized by different cost and deployment/maintenance complexity. Thus, an optimal deployment strategy is required to determine the number and locations of different devices. Accordingly, the deployment and operational cost can be minimized while maintaining the highest leakage detection accuracy.

5.2. Collaborative leakage detection and localization

MISE-PIPE depends on the information from multiple sources including the acoustic vibration measurements, soil property measurements, and the flow pressure measurements to make the leakage detection decisions. Specifically, in the third phase of the MISE-PIPE operational framework, the soil property measurements of all the sensors along the suspicious pipelines, as well as the inside flow pressure measurements and the acoustic vibration measurements at the two terminals of those pipelines, are available at the processing hubs. These three types of measurements should be processed together in the transient simulation model. The relationship between the measured soil properties and the potential leakage should also be analyzed. Based on the above analysis, a collaborative leakage detection and localization algorithm is to be developed.

5.3. In-network processing and lightweight protocols

Due to the limited power and computation capacity of the underground soil property sensors, low-complexity communication protocols are desired for extended lifetime and high system efficiency in the distributed networks. In addition, the bandwidth of the MI channel is limited and in-network data processing is required. Moreover, the leakage detection and localization algorithms demand strict requirements in terms of accuracy and timeliness with these low-end devices. Thus, the design of low-complexity and high-efficiency protocols is challenging. Moreover, MISE-PIPE requires in-network processing scheme and lightweight protocols that support the resource-constraint MI transceivers along the long pipelines so that the integrated traffic can be timely, reliably, and efficiently delivered to administrator center.

5.4. Adaptive equalization of the MI transceiver

According to our previous analysis [32,33], the MI channel experiences frequency selective fading when the coil wire resistance is small. To guarantee the low path loss of the MI channel, the coil wire resistance cannot be very high. Consequently, the frequency selectivity of the MI channel is unavoidable. Due to the frequency selectivity of the MI channel, adaptive equalization is mandatory. Several existing equalization strategies need be investigated for the MI waveguide channel, which include linear equalization (LE), decision feedback equalization (DFE) and Tomlinson Harashima precoding (THP), and trellisbased equalization [9].

5.5. Inductive charging-based energy harvest for underground sensors

To further prolong the system lifetime of MISE-PIPE, the inductive charging-based maintenance strategy is adopted. Inductive charging [17] uses the magnetic field to transfer energy between two objects. In MISE-PIPE, the communications between underground soil property sensors are accomplished by magnetic induction. In the similar way, a charging station set at pipeline checkpoints or pump stations is possible to send energy through inductive coupling to the underground soil property sensors, which can store the energy in the batteries. However, since there is a nontrivial interval between each MI relay coils, the energy transferring efficiency is very low in current MISE-PIPE architecture. More efficient inductive charging techniques are expected to solve the problem of the current techniques.

5.6. Testbed and performance evaluation

Although the theoretical analysis shows that MISE-PIPE is very promising, the practical performance of MISE-PIPE in real applications still need to be evaluated. A testbed of MISE-PIPE needs to be setup at large-scale underground pipeline sites and the monitoring system needs be showcased to detect and localize leakages. The testbed of MISE-PIPE consists of sensors both inside and outside the pipelines, where multiple commercial off the shelf devices can be utilized. However, there is no product on the market to test the underground MI communication part in MISE-PIPE, since the MI waveguide technique for communications is newly developed at our lab.

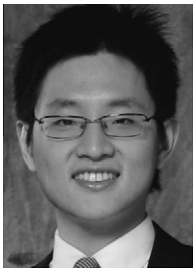
6. Conclusion

In this paper, we introduce a magnetic induction-based wireless sensor network architecture for underground pipeline monitoring (MISE-PIPE) for detecting and localizing leakages in underground pipelines. MISE-PIPE utilize sensors both inside and outside the pipelines, including the pressure sensors, the acoustic sensors, and soil property sensors. Those sensors cooperatively detect and localize the leakage on the underground pipelines. The new magnetic induction technique is utilized to provide efficient and robust wireless communications for the underground sensors. Compared to the existing underground pipeline monitoring system, MISE-PIPE provides both accurate real-time leakage detection and localization results and long system operating lifetime in the harsh underground environments. Beyond the system architecture and operational framework introduced in this paper, much work needs to be done to deploy MISE-PIPE in real life applications. More specifically, comprehensive simulation evaluations should be performed to test the feasibility and efficiency of the concept of MISE-PIPE. In addition, based on the theoretical and simulation analysis, we plan to build a testbed for MISE-PIPE based on *Crossbow Mica2 mote* to conduct field experiments to test its performance of leakage detection and localization for real underground pipelines.

References

[1] M. Ahadi, M.S. Bakhtiar, Leak detection in water-filled plastic pipes through the application of tuned wavelet transforms to acoustic emission signals, Applied Acoustics 71 (March) (2010) 634–639.
[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Computer Networks Journal 38 (4) (2002) 393–422.
[3] I.F. Akyildiz, E.P. Stuntebeck, Wireless underground sensor networks: research challenges, Ad Hoc Networks Journal 4 (July) (2006) 669–686.
[4] I.F. Akyildiz, Z. Sun, M.C. Vuran, Signal propagation techniques for wireless underground communication networks, Physical Communication Journal 2 (3) (2009) 167–183.
[5] L. Berardi, O. Giustolisi, D.A. Savic, Z. Kapelan, An effective multi-objective approach to prioritisation of sewer pipe inspection, Water Science and Technology, WST 60 (4) (2009) 841–850.
[6] M. Bimpas, A. Amditis, N. Uzunoglu, Detection of water leaks in supply pipes using continuous wave sensor operating at 2.45 GHz, Journal of Applied Geophysics 70 (March) (2010) 226–236.
[7] A.F. Colombo, P. Lee, B.W. Karney, A selective literature review of transient-based leak detection methods, Journal of Hydro-environment Research 2 (April) (2009) 212–227.
[8] B.C. David, E.S. Alan, State of the Art for Pipe and Leak Detection, US Department of Energy Report, 2001.
[9] Z. Ding, Y. Li, Blind Equalization and Identification, CRC Press, 2001.
[10] H. Duvoisin, Detection of subsurface facilities including non-metallic pipe, Final Technical Report, DOE Cooperative Agreement, DE-FC26-01NT41315, 2003.
[11] O. Giustolisi, D. Savic, Z. Kapelan, Pressure-driven demand and leakage simulation for water distribution networks, Journal of Hydraulic Engineering 134 (5) (2008) 625–635.
[12] F.L. Graf, Using ground-penetrating radar to pinpoint pipeline leaks, Materials Performance 29 (4) (1990) 27–29.
[13] G.W. Hennigar, Leak detection: new technology that works, Gas Industries 37 (January) (1993) 16–18.
[14] I. Jawhar, N. Mohamed, K. Shuaib, A Framework for Pipeline Infrastructure Monitoring using Wireless Sensor Networks, in Wireless Telecommunications Symposium 2007, Pomona, CA, USA, April 2007.

[15] C.A.V. Junior, J.L.D. Medeiros, O.D.Q.F. Araujo, ARX modeling approach to leak detection and diagnosis, Journal of Loss Prevention in the Process Industries 23 (May) (2010) 462–475.
[16] Z.S. Kapelan, D.A. Savic, G.A. Walters, Multiobjective sampling design for water distribution model calibration, Journal of Water Resources Planning and Management 129 (6) (2003) 466–479.
[17] A. Karalis, J.D. Joannopoulos, M. Soljacic, Efficient wireless non-radiative mid-range energy transfer, Annals of Physics 323 (1) (2008) 34–48.
[18] W.R. Klein, Acoustic Leak Detection, vol. 55, American Society of Mechanical Engineers, Petroleum Division, 1993. pp. 57–61,.
[19] J.P. Kurmer, S.A. Kingsley, J.S. Laudo, S.J. Krak, Applicability of a novel distributed fibre optic acoustic sensor for leak detection, in Proceedings of SPIE, vol. 1797, pp. 63–71, March 1993.
[20] L. Li, M.C. Vuran, I.F. Akyildiz, Characteristics of underground channel for wireless underground sensor networks, in: Proceedings of the IFIP Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net '07), Corfu, Greece, June 2007.
[21] J.A. Liggett, L. Chen, Inverse transient analysis in pipe networks, Journal of Hydraulic Engineering 120 (8) (1994) 934–955.
[22] C.P. Liou, Pipeline leak detection based on mass balance, in: Proceedings of the International Conference, ASCE, Seattle, USA, May 1993.
[23] A.U. Malik, A Survey of Product Water Transmission Lines in the Kingdom of Saudi Arabia, Technical Report, Saline Water Conversion Corporation, 1991.
[24] J.C. Martins, P. Seleghim Jr, Assessment of the performance of acoustic and mass balance methods for leak detection in pipelines for transporting liquids, Journal of Fluids Engineering 132 (January) (2010).
[25] D. Moodie, L. Costello, D. McStay, Optoelectronic leak detection system for monitoring subsea structures, in: Proceedings of the SPIE, Vol. 7726, Brussels, Belgium, April 2010.
[26] A. Ostfeld et al., The battle of the water sensor networks (BWSN): a design challenge for engineers and algorithms, Journal of Water Resources Planning and Management (November/December) (2008) 556–568.
[27] A.R. Silva, M.C. Vuran, Empirical evaluation of wireless underground-to-underground communication in wireless underground sensor networks, In: Proceedings of the IEEE DCOSS '09, Marina Del Rey, CA, June 2009.
[28] A.R. Silva, M.C. Vuran, Commmunication with aboveground devices in wireless underground sensor networks: an empirical study, in: Proceedings of the IEEE ICC '10, Cape Town, South Africa, May 2010.
[29] A.R. Silva, M.C. Vuran, Development of a Testbed for Wireless Underground Sensor Networks, to appear in EURASIP Journal on Wireless Communications and Networking special issue on Simulators and Experimental Testbeds Design and Development for Wireless Networks, 2010.
[30] J.L. Sperl, System pinpoints leaks on Point Arguello offshore line, Oil and Gas Journal 89 (36) (1991) 47–52.
[31] I. Stoianov, L. Nachman, S. Madden, PIPENET: a wireless sensor network for pipeline monitoring, in: Proceedings of the IPSN '07, Cambridge, MA, USA, April 2007.
[32] Z. Sun and I.F. Akyildiz, Underground wireless communication using magnetic induction, in: Proceedings of the IEEE ICC 2009, Dresden, Germany, June 2009.
[33] Z. Sun, I.F. Akyildiz, Magnetic induction communications for wireless underground sensor networks, IEEE Transactions on Antenna and Propagation 58 (7) (2010) 2426–2435.
[34] Z. Sun, I.F. Akyildiz, Deployment Algorithms for wireless underground sensor networks using magnetic induction, in: Proceedings of the IEEE GLOBECOM 2010, Miami, USA, December 2010.
[35] Z. Sun, I.F. Akyildiz, Connectivity in Wireless Underground Sensor Networks, in: Proceedings of the IEEE SECON '10, Boston, MA, USA, June 2010.
[36] N.C. Turner, Hardware and software techniques for pipeline integrity and leak detection monitoring, in: Proceedings of Offshore Europe '91, Aberdeen, Scotland, 1991.
[37] J.P. Vitkovsky, M.F. Lambert, A.R. Simpson, J.A. Liggett, Experimental observation and analysis of inverse transients for pipeline leak detection, Journal of Water Resources Planning and Management 133 (6) (2007) 519530.
[38] J.P. Vitkovsky, J.A. Liggett, A.R. Simpson, M.F. Lambert, Optimal measurement site locations for inverse transient analysis in pipe networks, Journal of Water Resources Planning and Management 129 (6) (2003) 480492.
[39] M.C. Vuran, I.F. Akyildiz, A.M. Al-Dhelaan, Channel modeling and analysis for wireless underground sensor networks in soil medium, Physical Communication Journal, in press.
[40] G.J. Weil, Non contact, remote sensing of buried water pipeline leaks using infrared thermography, in: Proceedings of the International Conference, ASCE, Seattle, USA, May 1993.
[41] J. Zhang, Designing a cost effective and reliable pipeline leak detection system, in: Proceedings of Pipeline Reliability Conference, Houston, USA, November 1996.
[42] Kingdom of Saudi Arabia Water Projects, Opportunities, Water Resources Equipment/Services (WRE) 2006, Technical Report, Royal Netherlands Embassy Riyadh, Economic and Commercial Department, 2006.
[43] Technical Review of Leak Detection Technologies, vol. I: Crude Oil Transmission Pipelines, Technical Report, Alaska Department of Environmental Conservation, 1999.
[44] Russia Energy Data, Statistics and Analysis – Oil, Gas, Electricity, Coal, Report of US Energy Information Administraion, 2008, <http://www.eia.doe.gov/cabs/Russia/pdf.pdf>.



Zhi Sun received the B.S. degree in communication engineering from Beijing University of Posts and Telecommunications (BUPT), and the M.S. degree in electronic engineering from Tsinghua University, Beijing, China in 2004 and 2007, respectively. Currently, he is a graduate research assistant in Broadband Wireless Networking Laboratory (BWN Lab), School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA. He is pursuing Ph.D. degree under the supervision of Prof. Ian F. Akyildiz. His current research interests are in wireless underground networks, mobile ad-hoc networks, and wireless sensor networks. He received the Best Paper Award in IEEE GLOBECOM 2010.

Pu Wang received the B.S. degree in electrical engineering from the Beijing Institute of Technology, Beijing, China, in 2003 and the M.Eng. degree in computer engineering from the Memorial University of Newfoundland, St. John's, NL, Canada, in 2008. Currently, he is a graduate research assistant in Broadband Wireless Networking Laboratory (BWN Lab), School of Electrical and Computer Engineering, Georgia Institute of Technology. He is currently working toward the Ph.D. degree in electrical engineering under the supervision of Prof. Ian F. Akyildiz. His research interests include wireless sensor networks and mobile ad-hoc networks, with emphasis on traffic modeling, node clustering, data aggregation, and network coding.

Mehmet C. Vuran received his B.Sc. degree in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2002. He received his M.S. and Ph.D. degrees in electrical and computer engineering from Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, under the supervision of Prof. Ian F. Akyildiz in 2004 and 2007, respectively.

Currently, he is an Assistant Professor in the Department of Computer Science and Engineering at the University of Nebraska-Lincoln and director of Cyber-Physical Networking Laboratory. Dr. Vuran received the NSF CAREER award in 2010. He has received numerous academic honors, including the 2010 Maude Hammond Fling Faculty Interdisciplinary Research Fellowship from the UNL Research Council and the 2007 ECE Graduate Research Assistant Excellence Award from Georgia Tech's School of Electrical and Computer Engineering. He is an associate editor of Computer Networks

Journal and Journal of Sensors. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and the IEEE Communication Society. His current research interests include cross-layer design and analysis, wireless sensor networks, underground sensor networks, cognitive radio networks, and deep space communication networks.

Mznah Al-Rodhaan has received BS in Computer Applications (Hon) and MS in Computer Science both from King Saud University, in 1999 and 2003 respectively. In 2009, she received her Ph.D. in Computer Science from the University of Glasgow in Scotland. She is currently working as Assistant Professor in the College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia. Moreover, she has participated in several international conferences and chaired some technical sessions. She is currently on the editorial board of the Ad Hoc Networks Journal (Elsevier). Her current research interest includes: Mobile Ad Hoc Networks, Wireless Sensor Networks, Cognitive Networks, Network Security, and High Performance Computing. The photo of the author is not available.

Abdullah M. Al-Dhelaan has received B.S. in Statistics (Hon) from King Saud University, in 1982, and the MS and Ph.D. in Computer Science from Oregon State University on 1986 and 1989 respectively. He is currently Associate Professor of Computer Science, Chairman of the join Ph.D. program, and Director General for the Center for International Collaboration and Visiting Professors, College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia. He has guest edited several special issues for the Telecommunication Journal (Springer) , and the International Journal for Computers and their applications. Moreover, he is currently on the editorial boards for several journals such and Computer Network (Elsevier) and The International Journal of Computers and their applications. His current research interest includes: Mobile Ad Hoc Networks, Sensor Networks, Cognitive Networks, Network Security, and High Performance Computing.

Ian F. Akyildiz received the B.S., M.S., and Ph.D. degrees in Computer Engineering from the University of Erlangen-Nurnberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, the Director of Broadband Wireless Networking Laboratory and Chair of the Telecommunication Group at Georgia Tech. His current research interests are in nanonetworks, cognitive radio networks and wireless sensor networks.

He is an Honorary Professor with the School of Electrical Engineering at Universitat Politecnica de Catalunya (UPC), Barcelona, Spain, since June 2008. Since March 2009, he is an Honorary Professor with the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria, South Africa. He is also a Visiting Professor at the King Saud University in Riyadh, Saudi Arabia, since January 2010.

He is the Editor-in-Chief of Computer Networks (Elsevier) Journal, and the founding Editor-in-Chief of the Ad Hoc Networks (Elsevier) Journal, the Physical Communication (Elsevier) Journal and the Nano Communication Networks (Elsevier) Journal. Dr. Akyildiz serves on the advisory boards of several research centers, journals, conferences and publication companies.

He is an IEEE FELLOW (1996) and an ACM FELLOW (1997). He has received numerous awards from IEEE and ACM. He received the "Don Federico Santa Maria Medal" for his services to the Universidad of Federico Santa Maria, in 1986. From 1989 to 1998, he served as a National Lecturer for ACM and received the ACM Outstanding Distinguished Lecturer Award in 1994. He received the 1997 IEEE Leonard G. Abraham Prize Award (IEEE Communications Society) for his paper entitled "Multimedia Group Synchronization Protocols for Integrated Services Architectures" published in the IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS (JSAC) in January 1996. He received the 2002 IEEE Harry M. Goode Memorial Award (IEEE Computer Society) with the citation "for significant and pioneering contributions to advanced architectures and protocols for wireless and satellite networking." He received the 2003 IEEE Best Tutorial Award (IEEE Communication Society) for his paper entitled "A Survey on Sensor Networks," published in IEEE COMMUNICATIONS MAGAZINE, in August 2002. He received the 2003 ACM Sigmobile Outstanding Contribution Award with the citation "for pioneering contributions in the area of mobility and resource management for wireless communication networks". In 2010, he received the IEEE Communications Society Ad Hoc and Sensor Networks Technical Committee (AHSN TC) Technical Recognition Award with the citation "for pioneering contributions to wireless sensor networks and wireless mesh networks." He also supervised and co-authored papers that received the Best Paper Award in IEEE ICC 2009 and IEEE GLOBECOM 2010, respectively.

He received the 2004 Georgia Tech Faculty Research Author Award for his "outstanding record of publications of papers between 1999 and 2003". He received the 2005 Distinguished Faculty Achievement Award from School of ECE, Georgia Tech. In 2009, he received the Georgia Tech Outstanding Doctoral Thesis Advisor Award for his 20+ years service and dedication to Georgia Tech and producing outstanding Ph.D. students. He also received the 2009 ECE Distinguished Mentor Award from the School of Electrical and Computer Engineering Faculty Honors Committee, Georgia Tech.