Internet of Things in Extreme Environments using Low-power Long-range Near Field Communication

Hongzhi Guo, *Member, IEEE,* and Albert A. Ofori, *Student Member, IEEE*

Abstract

Internet of Things (IoT) in extreme environments, such as underground and underwater, is an essential technology to monitor the status and exploit resources therein. Existing solutions using active UHF radios experience high power consumption and high signal propagation losses which increase the cost of maintenance. In this article, a low-power IoT technology using passive sensors and near field communication (NFC) is introduced. Existing magnetic induction-based NFC and other communication protocols are reviewed and their advantages and limitations are identified. Then, the system framework, key technologies, and research challenges of the low-power long-range NFC-based passive sensing system are discussed. This system can enable ubiquitous sensing and computing in various inhomogeneous extreme environments. Its applications in precision agriculture, road infrastructure monitoring, and water quality monitoring are presented.

Index Terms

Extreme environments, internet of things, low-power, magnetic induction, near field communication.

I. Introduction

Internet of things (IoT) has dramatically changed the way we monitor and interact with the physical world. Deploying wireless sensors in extreme environments, such as soil, water, and the human body, enables a large number of important applications for precision agriculture, water quality monitoring, and health status monitoring, respectively. Various low-power and low-cost sensors have been designed to collect critical information in extreme environments. Most of these sensors are intrusive and they are directly deployed inside extreme environments. To communicate with them, the wireless IoT solution is always preferable compared with its wired counterpart since it creates minimal environmental damages and requires less infrastructure support. Moreover, it is more cost-effective to employ wireless IoT solutions to design large-scale networks to support ubiquitous sensing and computing.

However, it is not trivial to build and maintain wireless IoT networks in extreme environments. First, existing wireless IoT solutions such as Zigbee and LoRaWAN require high-cost maintenance. Wireless sensors and LoRaWAN devices are supported by batteries which increase the device size and require frequent battery replacement or wireless recharging due to the high power consumption, especially in the standby mode. Also, a low-quality battery may create environmental contamination owing to chemical leakages. Second, the UHF (300 MHz to 3 GHz) signals suffer from strong reflections from media boundaries and high propagation losses due to the conductivity and short skin depths in extreme environments. Third, it is not economical to deploy large-scale IoT networks by using high-cost UHF radios. For example, a microcontroller with soil sensors and radios costs more than $40 [1]. The cost will be prohibitive if we deploy an IoT network with thousands of sensors.

Consider the precision agriculture as an example, which requires not only aboveground information but also underground information. In addition to existing terrestrial wireless sensor networks that can monitor the aboveground environment, the wireless underground sensor networks have to be adopted to extend the sensing capability to the soil medium to form heterogeneous wireless sensor networks. Recent studies show that one of the key factors that prevent farmers from adopting precision agriculture is the revenue [2]. Although farm yields can be increased by adopting precision agriculture, the high cost of equipment reduces farmers' revenue. Existing wireless sensors are equipped with standard radios, memory, sensors, and microcontrollers, which are not only expensive but also power-hungry [3]. It is challenging, if not impossible, for farmers to purchase, deploy, and maintain (e.g., recharge) a large number of such devices on their farms. Due to this reason, wireless underground sensor networks for precision agriculture have been proposed for more than a decade, but they are not widely adopted. Today's precision agriculture calls for a low-cost, low-profile, energy-efficient, and easy-to-maintain solution.

Near Field Communication (NFC) using magnetic induction to transmit signals has been widely used for IoT applications with high requirements in security and privacy. It demonstrates a short communication range, e.g., 0.1 m to 0.2 m, which creates a secure bubble and any attackers outside of this range cannot detect NFC signals. Moreover, NFC uses the near field HF band (3 MHz - 30 MHz) signals which can penetrate through most nonmagnetic materials with negligible penetration losses. Also, NFC tags consume near-zero power which significantly reduces the standby power consumption and it has much lower overall power consumption than many other options such as Zigbee and WiFi. Thus, due to these properties, NFC is desirable for IoT applications in inhomogeneous extreme environments. However, the short communication range significantly limits NFC's applications since most practical applications demand a communication range that is longer than 0.2 m.

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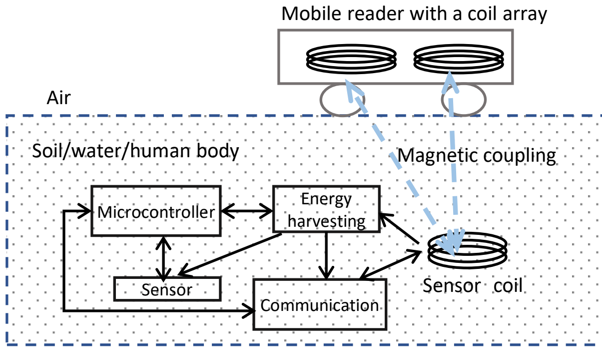


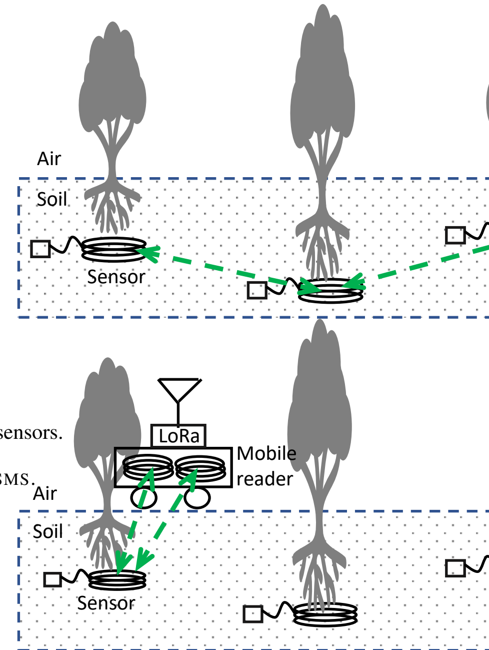


Fig. 1. Architecture of the autonomous data collection system using a mobile reader and low-power NFC passive sensors.

TABLE I
CHARACTERISTICS OF MAGNETIC INDUCTION COMMUNICATION MECHANISMS.

	Ref.	Range	Coil radius	Sensor power consumption	Maintenance cost
NFC Forum	[5]	$<$ 0.2 m in the air	0.025 m	Low	Low
Point-to-point MI	[4]	around 3 m in the soil	0.15 m	Medium	Medium
MI waveguide	[4]	$>$ 100 m in the soil	0.15 m	Medium	High

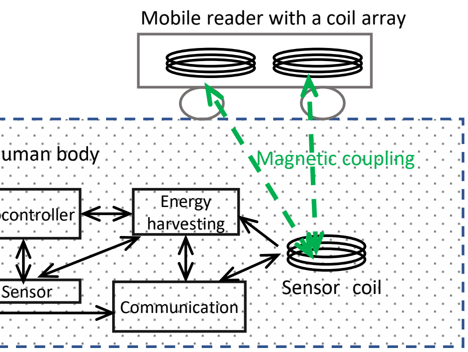
In this article, we introduce a low-power IoT solution in extreme environments, as shown in Fig. 1, where a mobile reader is used to communicate with a passive sensor using NFC in the unseen extreme environment. The sensor has energy harvesting units that can harvest electromagnetic energy from the reader. The harvested energy is used for sensing and communication. Instead of building a fully connected sensor network in the unseen media [4], we use a mobile reader to visit each *in situ* sensor to reduce the communication range and power consumption. The NFC communication range is so short that it cannot support such an application. We present potential solutions that can extend NFC's communication range to around 1 m. First, we review the NFC theories, protocols, and recent development in IoT. Then, we identify its limitations. After that, we provide an overview of the key technologies that can enable low-power long-range NFC. Lastly, we discuss the research challenges and show two appealing IoT applications using NFC for road monitoring and water quality monitoring.

II. Near Field Communication: Protocols and Limitations

Although Sony and Phillips started to specify the NFC protocols in 2002, the magnetic induction (MI) communication, which is the foundation of NFC, has been used in military and civilian applications for about a century. MI communication uses the magnetic coupling between two coils to transmit signals. As shown in Fig. 1, Alternating Currents (AC) in one of the reader's coils can induce currents in the sensor's coil, which can be used to transmit information and energy. The two coils can be regarded as loosely coupled transformers. Data are transmitted by modulating AC's frequency, phase, or/and amplitude. MI communication was originally used for underwater communication and through-the-earth communication with giant antennas.

Although NFC and MI communication are used interchangeably, MI communication is more general which includes all communication protocols using magnetic induction, while, usually, NFC is used to represent the technologies that are adopted by the NFC forum [5], who develops the NFC technical specifications to unlocking full capabilities of the NFC technology. NFC forum develops NFC systems and network stacks to meet the needs of today's IoT applications by following international standards such as the ISO/IEC 18092 and ISO/IEC 14443, and including novel features. In addition to NFC forum specifications, the NFC-assisted wireless energy transfer (WET) also received wide acceptance, where NFC and WET share the same coil and NFC is used to transmit energy/power-related information for WET. This is also considered as an operation mode in the NFC forum specifications. The last and more recent MI communication application is for wireless sensor networks in extreme environments. In this case, the point-to-point MI communication can connect wireless sensors that are separated by a short distance and the MI waveguide can connect widely separated wireless sensors. Larger coils are used, i.e., 0.15 m in radius, to extend the point-to-point communication range to around 3 m. A summary of the NFC forum specifications, point-to-point MI communication, and MI waveguide communication is given in Table I.

NFC forum protocols offer a low-power and low-cost sensing approach by using passive tags, which is similar to the RFID at 13.56 MHz. However, they are rarely used for wireless sensing in extreme environments due to the short communication



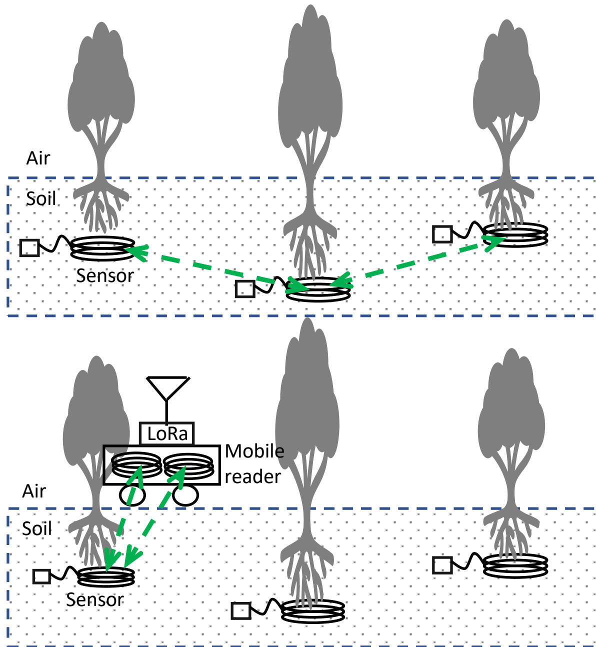


Fig. 2. Illustrations of a fully underground MI sensor network (upper) and a mobile reader-assisted underground NFC sensor network (lower).

range. On the contrary, the point-to-point MI communication and MI waveguide have received wide acceptance since they have much longer communication ranges. As shown in the upper part in Fig. 2, sensors are connected using point-to-point MI communication. If the distance between two sensors is beyond the communication range of the point-to-point MI communication, MI waveguide can be employed. This solution is analogous to the terrestrial wireless sensor networks in the sense that all sensors have active radios and they can communicate with each other.

However, it is not simple to deploy wireless sensor networks in extreme environments due to the following challenges. First, it is not cost-effective to deploy a wireless sensor network fully in the unseen extreme environments. For example, although a fully underground sensor network does not affect aboveground farming activities, it increases the propagation loss and the overall power consumption. Second, sensors' batteries need to be recharged or replaced. This is not trivial since sensors are buried in unseen media. Third, when we deploy MI waveguides, a large number of passive coils have to be buried. This is a labor-intensive task because we cannot simply place a coil at the desired location; we need to dig into the unseen media, avoid existing underground infrastructures, and bury sensors. Next, we introduce a novel solution using NFC and passive sensors, which is a low-power technology with low maintenance cost.

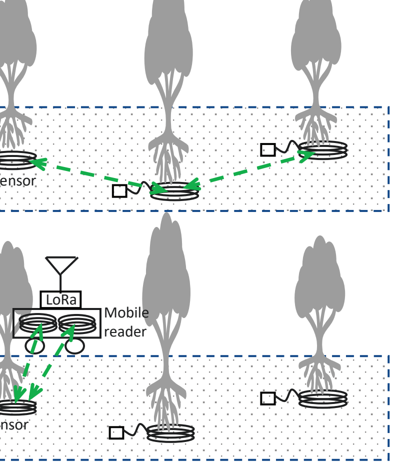
III. Low-power Long-range Near Field Communication

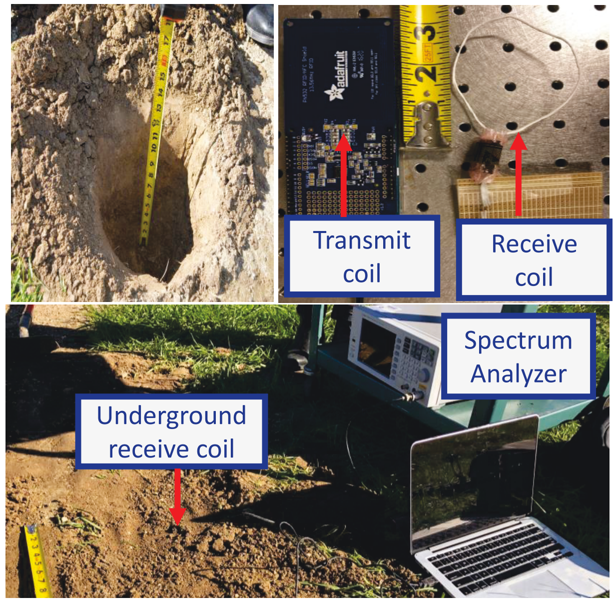
In this section, without loss of generality, we consider the unseen extreme environment as the underground and the IoT application is the plant monitoring.

Instead of using fully connected wireless underground sensor networks, a mobile reader is employed to collect data from sensors. The mobile reader has been widely used for Unmanned Aerial Vehicle (UAV) assisted wireless sensor networks and RFID networks to collect data. Although wireless sensors may not be fully connected, the mobile reader can physically visit each sensor to obtain sensing data.

A. System Framework

As shown in Fig. 1 and the lower part of Fig. 2, the mobile reader can collect sensing data from underground sensors by using the long-range NFC. The sensor is buried in the soil and it is analogous to the traditional NFC tags with an additional sensing unit. A sensor transmits data by modulating its impedance. In the near field there is almost no propagating wave and the scattering effect is weak, and thus this communication mechanism is not backscatter rigorously. However, the concept is the same as backscatter communications. In this system, sensors are not required to communicate with each other—this not only reduces their burden on power consumption but also reduces their coil sizes. Since most agricultural activities are within 0.5 m depth in the soil, the horizontal communication range between sensors is much longer than the vertical communication range between a sensor and a reader. Replacing the sensor-to-sensor communication with reader-to-sensor communication is more power-efficient. Also, this system does not require aboveground infrastructure support. The reader is mobile and it is easy to maintain. In addition, most rural areas have poor wireless connectivity. The reader can save sensing data and then upload it to a server when it returns, or it can use the LoRaWAN [6] to send the data to a gateway. Since the sensor in the unseen medium is passive, its power consumption is extremely low and it is easy to maintain [7].





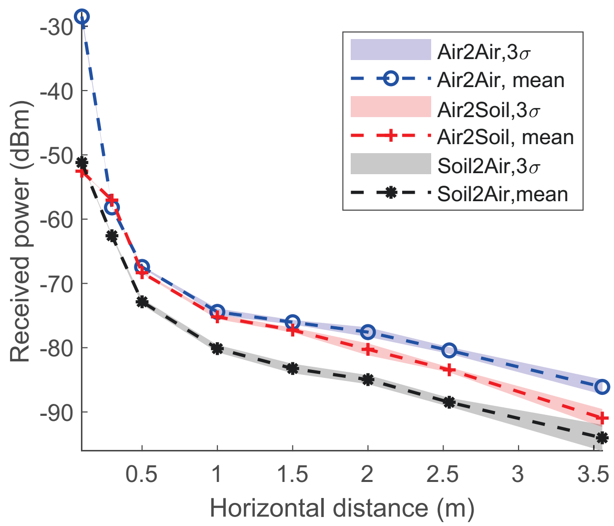
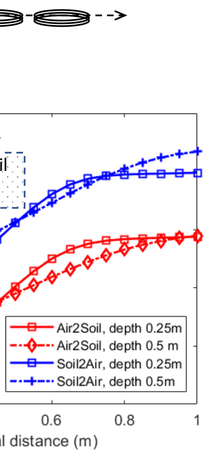


Fig. 4. Received power for Air2Air channel (both the transmitter and the receiver are aboveground with 10 cm height), Air2Soil channel (the transmitter is aboveground with 10 cm height and the receiver is underground with 30 cm depth), and Soil2Air channel (the transmitter is underground with 30 cm depth and the receiver is aboveground with 10 cm height). At each distance, 10 data points were collected and the mean value and the 3 times of the standard deviation (σ) are plotted.

However, as shown in Table I, the NFC communication range is short. It is a great challenge to realize the system without using active MI radios. To understand NFC communication channel in the underground environment, we measured the active Air2Air channel, where the transmitter and the receiver are aboveground with 10 cm height, the Soil2Air channel, where the transmitter is underground with 30 cm depth and the receiver is aboveground with 10 cm height, and the Air2Soil channel, where the transmitter is aboveground with 10 cm height and the receiver is underground with 30 cm depth. The measurements were collected on the farm owned by Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA, USA, on 12/03/2020. The transmitter is an Arduino DUE with Adafruit PN532 RFID/NFC breakout and shield, which implements the ISO/IEC 14443 standard and the carrier frequency is 13.56 MHz. The receiver coil is the ANT-1356M by RF Solutions with 6.5 cm diameter and 2 turns. The received signal is measured using Agilent N9320A spectrum analyzer with 0 dB attenuation and an internal preamplifier. In Fig. 4, the relation between the received power and the horizontal distance between the transmitter and the receiver is shown. We have the following three observations. First, the channel is not reciprocal and the Air2Soil channel experiences less path loss than the Soil2Air channel. The Air2Air channel has the highest received power



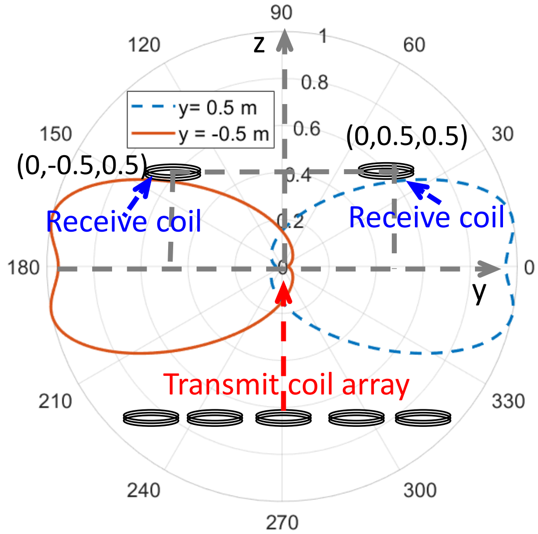


Fig. 5. Magnetic beamforming using a coil array with 5 elements. The plotted curve shows the superposition of normalized magnetic fields generated by the coil array. Their currents are designed by using the magnetic beamforming algorithm in [10]. The algorithm can steer the magnetic fields toward the receiver. The receiver orientation is facing the z axis and it is located at $y = 0.5$ m (0, 0.5, 0.5) and $y = -0.5$ m (0, -0.5, 0.5) with the same height $z = 0.5$ m. Both the transmitting coil array and the receiver are placed in the air.

because the signal propagates in the air. Second, the received power decreases fast within the first 0.5 m due to the near-field effect. As the distance increases, the far-field component is more dominant which decreases slower. Third, the channel is very stable in the near-field (within 0.5 m) and the standard deviation of our measurements is almost 0. A comprehensive theoretical channel model with detailed analyses is given in [8]. For an NFC backscatter channel, the path loss can be approximated by the addition of Air2Soil and Soil2Air path losses. As we can see, when the horizontal distance is around 0.5 m, the overall path loss for NFC backscatter communication is around 100 dB (including forward and backward path losses; the estimated transmission power is around -20 dBm). This suggests that the NFC backscatter communication is feasible by using a powerful spectrum analyzer as the receiver but the path loss has to be further reduced for commercial NFC devices to enable reliable and high-speed communication. Next, we introduce several recent advancements that can support the mobile reader-assisted underground NFC sensor network.

B. Key Technologies

1) Magnetic Beamforming: Magnetic beamforming uses a coil array to improve the received signal strength at the receiver. The idea is similar to that for terrestrial transmitter-side beamforming using antenna arrays, i.e., by tuning the phases and magnitudes of signals that are transmitted by different antennas, we can obtain constructive superposition at a receiver. The channel quality for NFC is indicated by the mutual inductance between two coils. For magnetic beamforming, a reader with knowledge of the mutual inductance between its coils and the sensor's coil can optimally allocate transmission power and choose the optimal phases to generate constructive superposition at the sensor's coil. This can improve the sensor's signal strength to allow it to backscatter strong signals. More importantly, it can increase the communication range.

Besides a planar array, the tri-axis coil with three mutually perpendicular unidirectional coils is another option to improve the received signal strength [9]. It is particularly efficient in reducing orientation losses. For example, sensor coils may have random orientations due to underground dynamics such as the growth of plants. It is hard to align them especially when their sizes are small. The orientation loss can be significant when coils are misaligned. The tri-axis coil provides orientation diversity and it can optimally control the phases and magnitudes of currents to maximize the induced voltage in a sensor's coil.

In Fig. 5, we show an example of magnetic beamforming using the algorithm that was developed in [10]. All the coils in the array are identical with radius 0.05 m. The interval between two adjacent coils' center is 0.1 m. A receiving coil facing the z axis is placed at two different locations, with coordinates (x, y, z) being $(0, 0.5, 0.5)$ m and $(0, -0.5, 0.5)$ m, respectively, to show the beam steering. The center of the transmit coil array is at the origin of the Cartesian coordinate system. As shown in the figure, by using a coil array with five elements, we can adjust the phase and magnitude of the current in each coil to steer the superposition magnetic fields towards left or right depending on the location of the receiver. Although we can improve the magnetic field intensity at the receiver, the leakages to other directions are also significant. This can be leveraged to charge nearby sensors.

2) Metamaterials: Metamaterials are engineered resonance structures that demonstrate extraordinary properties such as negative dielectric parameters. Small coils can be placed regularly to form a passive antenna array to enhance the electromagnetic fields that are generated by an active coil. For NFC, an array of passive coils can be placed between the active transmit coil and the receive coil. Together, these passive coils form artificial metamaterials. Metamaterials have been used to enhance magnetic coupling for wireless communications and wireless energy transfer [11], [12]. The metamaterial shell designed in [11] can enhance magnetic fields generated by coils inside it.

In magnetic beamforming, the coil array consists of active coils and the amplitude and phase in each coil can be controlled. On the contrary, metamaterials consist of passive coils and we cannot control the currents in each coil. However, we can carefully design the regular structure of metamaterials to obtain resonances to enhance the magnetic coupling and extend the communication range.

3) NFC Sensor: The success of the WISP project [13] has proven the feasibility of integrating sensors and RFID tags at the UHF frequency band to enable low-power sensing and computing. This idea can be leveraged to integrate the NFC tags and sensors. The NFC sensor has the following unparalleled advantages. First, the wireless charging and NFC can share the same coil and frequency, i.e., 13.56 MHz. Therefore, a reader can use the same channel state information for wireless information and wireless energy beamforming which saves resources for channel estimation. Second, sensors can harvest sufficient energy from a reader by using dedicated wireless charging to support sensing functions at various power-consumption levels. Since NFC has a wireless energy transfer mode and the range is small, its energy harvesting efficiency is much higher than the RFID tag. Lastly, a coil itself can be a sensor and the reader can obtain soil parameters based on the magnetic signals that are backscattered by the coil. For example, the magnetic coil-based sensors have been used in soil sensing [14].

4) LoRaWAN: To maintain a real-time connection with the mobile reader, long-range wireless communication technologies have to be employed because rural areas may not be well covered by cellular networks. LoRaWAN [6], as an IoT wide area technology, can achieve kilometer level communication range and support real-time communication with the mobile reader. The mobile reader collects data and then sends it to a management center for processing. Also, the mobile reader can cooperate with actuators to intelligently control farming activities. For example, based on the data collected by a mobile reader, machine learning algorithms can be used to provide suggestions such as the use of pesticides. This information can be sent via LoRaWAN to an actuator to use the exact amount of pesticide to minimize environmental contamination and improve farm yields.

C. Research Challenges and Potential Solutions

Despite these long-range and low-power solutions, the design of NFC-based sensing system in extreme environments still faces several difficult challenges.

1) Trade-off between Wireless Charging and NFC: The trade-off between wireless charging and wireless communication has been a longstanding problem and various solutions have been developed. The magnetic induction-based wireless charging requires an extremely narrow bandwidth of a coil to achieve high efficiency, while the NFC requires a broad bandwidth to transmit signals. The intuitive solution is to find a balance between these two technologies. For NFC at 13.56 MHz, a significant advantage is that we can use direct antenna modulation due to the relatively low-frequency [15]. This technique has not been extensively studied. Since we can directly modulate signals on the antenna, the requirement of the antenna bandwidth is relaxed and we may achieve a better trade-off between the wireless charging and wireless communication.

2) Dynamic Environment: The communication channel is affected by environmental changes. For example, irrigation and precipitation have strong impacts on the soil water volume content, which change the dielectric parameters of soil and thus the wireless channel. Different from UHF signals, NFC has a longer wavelength and the impact of the dynamic environmental change is much weaker. However, we still cannot neglect this effect since it may impact the wireless charging efficiency and localization accuracy. Adaptive transmission policies along with machine learning algorithms are promising solutions. Based on previous sensing data, machine learning algorithms can be used to predict the current wireless channel and the NFC reader can adaptively change its transmission policies to ensure the efficient usage of power.

3) Blind Beamforming: When a mobile reader initiates the communication with a sensor in the unseen environment, it has to wirelessly charge the sensor and provide sufficient energy to power it up. However, the mobile reader may not have the knowledge of the sensor location. Also, without channel estimation, the magnetic beamforming cannot be used to efficiently charge and communicate with the sensor. On the other hand, without magnetic beamforming, the sensor may not receive sufficient voltage to charge itself and it will remain silent. Blind beamforming without the knowledge of mutual inductance will play an important role in solving this problem. Magnetic fields generated by a reader's coil array are often added constructively at a sensor's coil due to the long wavelength and short communication range. However, the sensor coil orientation is a critical issue. If a sensor coil has significant orientation loss due to the misalignment with the reader's coils, only a small voltage can be induced in its coil. To this end, the blind beamforming which can rotate the generated magnetic field direction to improve the induced voltage in a sensor coil will be highly desirable. This can be achieved by adjusting the current phases and magnitudes in the reader's coils.

4) Mobile Reader Path Planning: The mobile reader collects data from sensors, which can be forwarded to a data management center using long-range communication technologies. The coverage of the long-range communication network such as LoRaWAN is not homogeneous. Thus, the mobile reader can plan its path and motion by considering the quality of the communication channel. When the channel quality is good the mobile reader tries to send more data, while when the channel quality is poor the mobile reader tends to save the data and send them later. A rigorous algorithm is needed to guide the mobile reader's motion and data transmission.

IV. Applications

In the preceding sections, we use precision agriculture as an example to introduce the mobile reader-assisted underground NFC sensor network. Since this framework is universal for IoT in extreme environments, we can also employ it for many other environmental sensing applications. Next, we introduce its application in road infrastructure monitoring and water quality monitoring.

Road infrastructure monitoring is becoming more and more important as the era of autonomous driving approaches. Autonomous vehicles can look ahead to avoid collisions with other vehicles and blockages, but they rarely take into account the road quality which may cause accidents as well. To monitor the road quality, sensors can be buried under roads. A mobile reader can be installed on a road sweeper truck. The data collected by the truck are published online which can be accessed by autonomous vehicles. Also, machine learning algorithms can be used to assess road quality, predict potential road damages, and make suggestions for stakeholders.

Water quality monitoring is an important task, especially drinking water. However, using wireless sensors with batteries may create hazardous leakages that cause unintended contamination. The battery-free sensors are more environmentally friendly and they can be placed in shallow water. A mobile reader, e.g., an autonomous ship or autonomous aerial vehicle, can be employed to interrogate with underwater sensors. However, this approach can only provide on-demand sensing rather than real-time sensing.

V. Conclusion

Internet of Things (IoT) in extreme environments faces unique challenges such as high cost of maintenance, invisible wireless devices, and high propagation loss of signals which prevent us from employing current IoT solutions directly. This article introduces a low-power solution using near field communication (NFC) and passive sensors. The communication range is a critical challenge. Existing solutions such as magnetic beamforming, metamaterials, and large coils can be used to extend NFC's communication range. Also, the sensor's power consumption can be reduced by relocating power-hungry units to the mobile reader side. The open design challenges are introduced and potential solutions are provided. The NFC-based sensors are promising candidates for other extreme environment applications such as road infrastructure monitoring and water quality monitoring.

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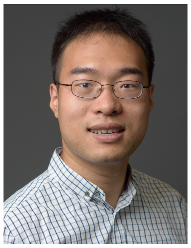

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