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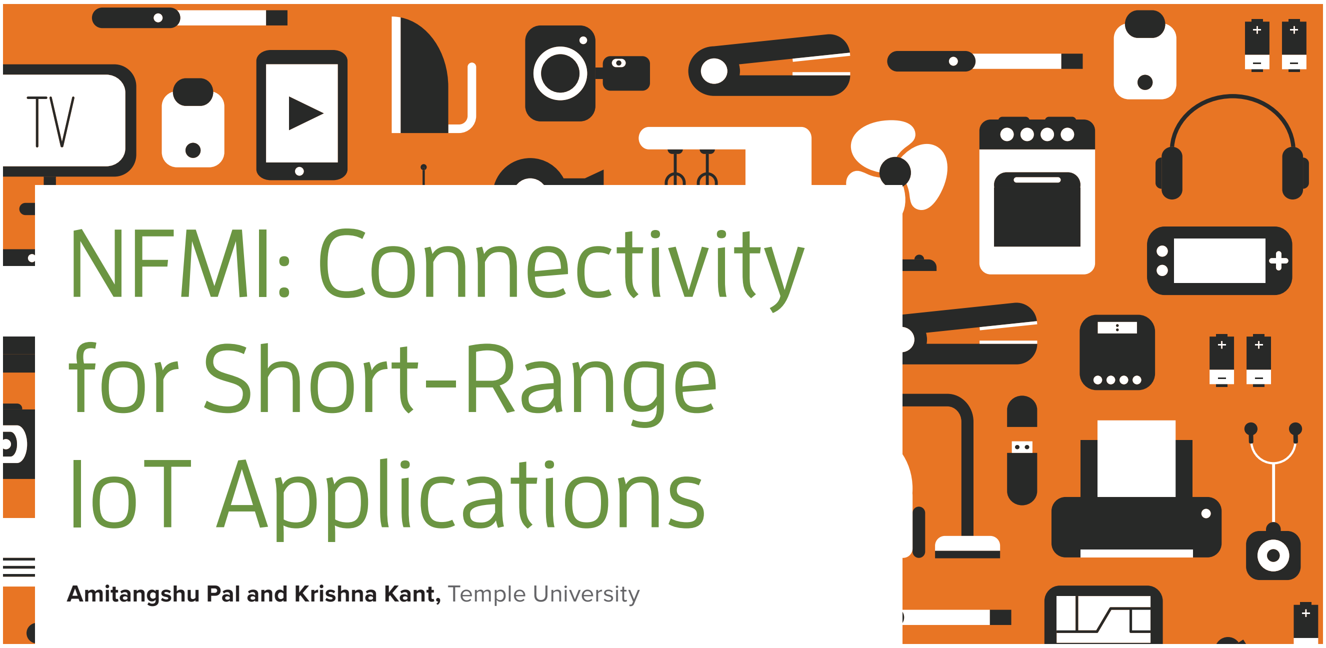

NFMI: Connectivity for Short-Range IoT Applications

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Magnetic-induction-based near-field communication is an emerging technology that is used for short-range, Internet-of-Things applications requiring high security, human safety, and low power; it operates in harsh environments, withstanding the presence of water, soil, and metals.

Electromagnetic waves are composed of mutually orthogonal electric and magnetic fields. Typical RF-based communication involves the propagation of such waves, as governed by Maxwell's equations. In free space, RF signal strength falls off at $1/r^2$ with distance r, although in cluttered environments, the fall-off is often somewhat faster. In contrast, near-field magnetic induction (NFMI) transmits data through a modulated alternating magnetic field that induces a current in a receiver coil. The transmitter generates this magnetic field by modulating an alternating current in its own transmit coil. At first glance, this coupling has entirely different physics than that of propagating electromagnetic waves. The induction is a near field (NF) phenomenon that applies to distances of less than $\lambda/2\pi$, where λ is the wavelength of the transmit-side current.

NFMI communication is based on the principle of resonant inductive coupling (RIC), which involves two matched coils, each forming an LC circuit with the same resonance frequency. RIC is commonly used in wireless power transfer and has numerous applications. For example, smartphone charging pads and the charging of moving electric cars' batteries operate on the same principle. NFMI communication modulates the magnetic field and forms the basis of near-field communications (NFCs) among NFMI devices. Because the electric field plays no role in this communication, the signal is almost purely magnetic and thus does not suffer from the usual fading and diffraction associated with electromagnetic waves.

Consider a pair of transmit-and-receive magnetic coils, with K_t and K_r turns and radii of ρ_t and ρ_r, respectively, separated by distance r. Suppose that the coils are immersed in a medium that features a relative permeability of μ (note: $\mu = 1$ for air). Suppose that the receiver coil is oriented orthogonal to the line passing through the centers of the two coils. Then, if the transmit coil has current I_t flowing through it, the induced current in the receiver coil, that is, I_r, is given by

Digital Object Identifier 10.1109/MC.2019.2892862
Date of publication: 22 March 2019

FROM THE EDITOR

The Internet of Things (IoT) extends traditional computing by making use of the spatial arrangement of computing nodes to achieve many of its goals. Whether this is a heating, ventilation, or air-conditioning system in a home or nodes in an automated factory line, spatial- and proximity-based data exchange is a key tool that enables the desired operation. In this article, the authors discuss using NFMI to support short-range IoT communication.

Passing the Torch

I would like to take this opportunity to thank all of the contributors to and readers of the "IOT Connections" column. I have served as department editor for three years, and in April, I will be passing the torch to Trevor Pering (Google, Inc.). Trevor has extensive publishing experience in the areas of mobile and pervasive computing and is currently working on IoT systems in industry. This gives him a fresh perspective on the kind of articles that will add value to the department and the discussions that need to occur to move IoT system design forward.—*Roy Want*

$$I_r \propto I_t f_{\text{res}} \frac{\pi K_t K_r \rho_t^2 \rho_r^2}{2r^3},$$

where f_{res} is the operating (resonance) frequency. We can draw several conclusions from this.

1. Since the power is proportional to I_r^2, the induced power decays as $1/r^6$ with distance r. This makes the technology inherently short range and, therefore, suitable for small personal area networks (PANs). Fortunately, the very rapid decay means that it is not possible to snoop on the signal beyond a certain range.
2. The current is directly proportional to the product of transmit-and-receive coil areas ($\rho_t^2 \times \rho_r^2$) and the number of turns for each of them ($K_t \times K_r$). In other words, to transfer higher power, one must choose larger-sized coils and more turns. This provides a very flexible control on power for NFMI; however, it may also limit miniaturization when the size is crucial.
3. Because the induced current is proportional to the frequency f_{res}, the induced power is proportional to f_{res}^2. This means a higher power transfer can be achieved by increasing the frequency, but at the cost of decreasing the maximum range of $c/(2\pi f_{\text{res}})$, where c is the speed of light.
4. If the receive coil is not aligned as indicated, the induced current will be less, but this aspect is omitted for simplicity.

Recognizing the potential of NFMI communications, IEEE finalized the 1902.1 standard in 2009, which specifies an NF magnetic communication protocol called *RuBee*.[9] RuBee operates in the lower frequency range of 30–900 KHz, and its purpose is to support low data-rate applications with coin-size batteries that last 5–10 years. Visible Assets, Inc. has introduced RuBee tags that operate at below 450 kHz (it typically operates at 131 kHz), which is compatible with low-frequency RFID. At 131 KHz, NF conditions occur for up to approximately 364 m, which is very long; however, because of low power and small coil antennas, the actual range is only a few tens of meters.

In a higher NFMI frequency range, 13.56 MHz is very popular because it is the same frequency used by high-frequency RFID[1] and is employed for personal products, such as audio headphones from NXP[6] and Freelinc.[7] At this frequency, the NFMI range is only 3.5 m, which is adequate for body area network (BAN) applications but not for more general home automation. The higher frequency helps in terms of higher power transfer with tiny antennas.

LOW-POWER BLUETOOTH AND RELATED TECHNOLOGIES

Bluetooth (BT) is an RF-based wireless technology standard for exchanging data over short distances (typically 10 m for class 2 devices) using ultra-high frequency (UHF) radio waves in the 2.4-GHz Industry, Science, Medicine (ISM) band. It is mainly used for communicating among a few devices in PANs. Bluetooth Low Energy (BTLE) is a slightly modified version of BT that features short connection times and devices that largely remain in sleep mode, which is of primary interest here. Zigbee is another similar technology designed to be at lower power and lower speed than BTLE and operates at lower frequencies. RF-based NFC is another relevant technology although it's designed for operation over very short distances. Table 1 shows a comparison of the three technologies.

These technologies are well established and work extremely well in open, uncluttered environments but do not work well in the presence of aqueous or plant/animal tissue media, which cause high signal absorption; or metallic clutter that causes diffraction or shielding of the signals; or underground/underwater operation that results in an extremely complex communications channel. Reducing absorption by choosing lower frequencies helps in attenuation; however, bigger antennas are required, which introduces the problem of undesirable size and potentially severe interference with nearby radios. For this reason, BTLE devices cannot be deeply implanted in the human body.

BTLE devices coexist with other products that use different protocols, such as Wi-Fi or Zigbee, but operate in the ISM 2.4-GHz band and thus may experience high interference. Additionally, RF radios consume more power because of the high sleep-mode power consumption. Because of the characteristics of far-field (FF) transmissions, the BTLE signals can be intercepted and decrypted by a remote eavesdropper. For this reason, the NSA has restricted its use in the U.S. Armed Forces.[2] Furthermore, in the context of BANs, the use of BTLE has already raised serious concerns. BTLE-equipped implantable defibrillators, insulin pumps, and infusion pumps have all been hacked.[3]

TABLE 1. A comparison of NFC, Zigbee, and BTLE.

Aspect	NFC	Zigbee	BTLE
Standardization body	International Organization for Standardization (ISO)/International Electrotechnical Commission	Zigbee Alliance	Bluetooth Special Interest Group
Network standard	ISO 13157, and so on	IEEE 802.15.4	IEEE 802.15.1
Network type	Point-to-point	WPAN	WPAN
Cryptography	Not with RFID	Available	Available
Range	<0.2 m	10–20 m	50 m
Frequency	13.56 MHz	2,400/915/868 MHz	2.4–2.5 GHz
Bit rate	106/212/424 Kb/s	110 Kb/s	1 Mb/s
Setup time	<0.1 s	<6 s	<0.006 s
Peak current draw[11]	50 mA	30 mA	13 mA

WPAN: wireless personal area network.

OPPORTUNITIES FOR NFMI

The key benefit of NFMI is its better penetration performance (i.e., lower absorption) than RF through materials that are challenging for RF, such as underwater environments and communications through water-rich media such as the human body, fresh produce, meats, and so on. The reason for this is that water and most other water-rich materials have magnetic permeability similar to that of air. In other words, the relative magnetic permeability of most such materials is 1.0, which also includes austenitic stainless steel.[12] This is demonstrated by tests conducted by the U.S. Department of Energy in which one NFMI radio is kept inside a sealed stainless steel drum and one remains outside.[3] Furthermore, a sheet of mild steel or other form of iron placed in close proximity to an NFMI radio essentially acts like a mirror and strengthens the signal.[4] Because magnetic signals are not affected by an aqueous or tissue medium, NFMI works well for communication with deeply implanted medical devices. NFMI communication protocols, including RuBee, have been certified by the U.S. Food and Drug Administration as a nonsignificant risk technology suitable for human use.[1,2]

Because NFMI operates in a low-frequency band, it significantly reduces RF absorption by biological tissues. The amount of RF absorption in the human body is often measured by the specific absorption rate (SAR), which is the power absorbed per mass of tissue, measured in units of watts per kilogram (W/kg). In the United States, the U.S. Federal Communications Commission requires mobile phones to have a SAR limit of at or below 1.6 W/kg. Similarly, the European Union has made the SAR limit 2 W/kg. The emissions from NFMI are far less than this specified limit. RuBee produces 40 nW of RF power compared to 4 W for UHF RFID systems, i.e., RuBee produces roughly 1-quadrillion (15 zeros) less RF power than UHF RFID.[8]

The power consumption of NFMI is generally lower than that of BTLE. As reported in Abrams,[1] the current NFMI battery-powered earpieces can operate for roughly 20 hours, as opposed to 3–4 hours in the case of BTLE. Aura Communications, Inc. has developed a system-on-chip magnetic communication system named *LibertyLink*, which draws 7 mA at 2.2 V to transmit full-duplex voice or data across a 1-m link, whereas typical RF solutions require at least 10 times that amount of power.[11]

The received power of the NFMI signal falls off as $1/r^6$ of the distance r, or 60 dB/decade between coils (instead of $1/r^2$ or 20 dB/decade for NFC RF). Figure 1 shows the propagation characteristics of NFMI (at 13.56 MHz) and BTLE (at 2.4 GHz) signals, which indicates the dual slope of NFMI communication and represents a simultaneous decay of the magnetic and electric waves. At 13.56 MHz, the NFMI signal has a wavelength of $\lambda = 22.1$ m; thus the crossover point between NF and FF occurs at approximately $(\lambda/2\pi) \sim 3.5$ m. Beyond this point, it rolls off at 20 dB/decade (just like the FF propagation characteristics), as observed in Figure 1. With NFMI, the signal crosses the noise floor at approximately 3 m, as opposed to 20 km with BTLE. In the case of NFMI, this results in very little leakage outside of the intended range. The communication is invisible outside this range and thus adds a high level of security. Additionally, NFMI communication does not cause interference with other wireless networks such as Wi-Fi and BTLE. Because of its short range, the same frequency can be reused for other NFMI communications. Thus, in an overcrowded area, using an NFMI-based PAN is more efficient than using BTLE.

Given that NFMI transmission through the body is safe and no different than

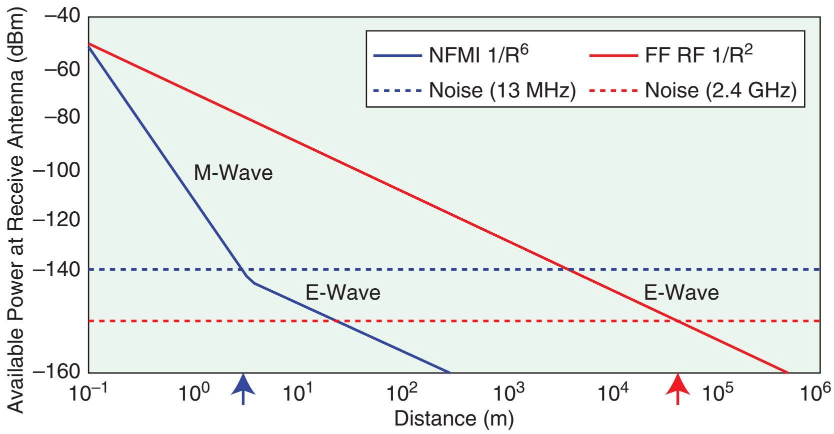

Figure 1. The signal propagation characteristics of NFMI versus BTLE. M-Wave: magnetic wave; E-Wave: electronic wave; FF: far field. (Source: Audio Express[13], used with permission.)

transmission through the air, the technology provides the tantalizing possibility of secure, through-the-body-communications. In other words, if all of the devices worn by a person are shielded to remove any through-the-air communication, all communications will be through the body and thus free from any interference or tampering. To enable these devices to communicate with another external device, the person would have to touch the device (with mutual authentication procedures used to prevent unwanted communication). One such scenario is that of a patient securely transferring medical data to a health-care worker via a physical touch, such as shaking hands. This applies to a wide range of bodily data collection and transfer, e.g., from routine data given to a trainer to data given to a doctor during a hospital round.

HURDLES OF NFMI

The magnetic field induced by an NFMI coil is necessarily orthogonal to the coil, and the field strength falls off as the cosine of the angle in other directions. This means that, to generate an omnidirectional signal, one would need three orthogonal coils, placed either concentrically or in close proximity to each other. The third dimension can be challenging in many applications where a thin, surface-mounted device is highly desirable (e.g., a wearable device such as a wristwatch or heart-rate monitor).

Another issue with magnetic communication is its small transmission range (a few meters) and much lower data rates than RF (400 Kb/s at 13.56 MHz, as opposed to a few megabits per second). The latter can be addressed to some extent by using multiple-input, multiple-output techniques, which essentially amount to using multiple coils operating on different channels. Increasing the range requires overcoming two limitations: 1) the need to keep the range below $\lambda / 2\pi$ to maintain NFC communication and 2) fast decay of the induced signal from a distance.

The problem of a low transmission range can be addressed by simply choosing a low-operating frequency, for example, lowering the frequency from 13 to 1.3 MHz increases the range from 3.5 to 35 m, which is adequate for most applications. However, this frequency reduction would also decrease the induced current by a factor of 10, and to compensate for this decrease, we would need to increase the coil diameter, and/or the number of turns. This may be reasonable for many large form-factor IoT devices but may be problematic for small embedded devices.

A team from the National Institute of Standards and Technology has proposed very low-frequency (VLF) magnetic communication using an ultrasensitive magnetic receiver based on emerging quantum magnetometer technology.[5] This work suggests that "The best magnetic field sensitivity is obtained using quantum sensors." This technology will improve the receiver's ability to pick up VLF signals far beyond the range of conventional RF receivers. As a result, the team demonstrated sending a digitally encoded dc magnetic signal in the sub-kHz frequency band and detecting this faint signal at one pico-tesla magnetic field strength (i.e., one-millionth of Earth's magnetic field strength) across a distance of tens of meters in a magnetically noisy indoor environment. This is achieved by using an "optically pumped," highly sensitive magnetometer that relies on the quantum properties of rubidium atoms. The novel magnetometer uses polarized light as a detector to measure the "spin" of the rubidium atoms induced by the magnetic fields. The team also believes that its range can be further improved to hundreds of meters in a less noisy environment using improved sensor technology and signal modulation schemes.

NFMI technology provides some unique advantages that can be exploited in several emerging IoT applications where many small IoT devices must operate in close proximity in a rather harsh environment. However, NFMI technology is still not as well explored as RF, and we expect many challenges with using the technology reliably and integrating it with other wireless technologies. We hope that this article will inspire greater interest in examining and applying this technology to a wider set of emerging IoT applications.

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