WIRELESS POWER TRANSFER AND APPLICATIONS TO SENSOR NETWORKS

LIGUANG XIE, YI SHI, Y. THOMAS HOU, AND WENJING LOU,
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

ABSTRACT

Energy constraints are widely regarded as a fundamental limitation of wireless and mobile devices. For sensor networks, a limited lifetime due to battery constraint poses a performance bottleneck and barrier for large scale deployment. Recently, wireless power transfer has emerged as a promising technology to address energy and lifetime bottlenecks in a sensor network. In this article, we give a review of the history of wireless power transfer and describe its recent developments. We show how such technologies can be applied to sensor networks and address their energy constraints.

INTRODUCTION

As wireless and portable mobile devices become pervasive, charging batteries for these devices has become a critical problem. Existing battery charging technologies are dominated by wired technology, which requires a wired power plug to be connected to an electrical wall outlet. This article explores recent advances in *wireless* power transfer (WPT), which achieves the same goal but without the hassle of wires. WPT technologies are revolutionizing the way energy is transferred and have the potential to make our lives truly "wireless."

To familiarize the general readers in the wireless community with the promising WPT technologies, we offer a concise review of the history of WPT and recent advances. In particular, we review inductive coupling, electromagnetic (EM) radiation, and magnetic resonant coupling. For each technology, we discuss their strengths, weaknesses and possible applications. Clearly, the impact of WPT on our lives is immense, and one can easily imagine many applications of WPT. To date, WPT technologies have already been applied to charge batteries in medical sensors and implanted devices, where battery replacement is impractical. They have also been applied to recharge mobile devices (e.g., cell phones, tablets, laptops) and electric/hybrid vehicles.

As a focus application, we will discuss how WPT technologies can help address the energy problem in wireless sensor networks (WSNs).[1] Existing WSNs are constrained by limited battery energy at a sensor node and can only remain operational for a limited amount of time. To prolong network lifetime, there have been many research efforts at all layers, from topology control, physical, MAC, and all the way up to the application layer. Despite these intensive efforts, the energy/lifetime of a WSN remains a performance bottleneck and is perhaps the key factor that hinders its wide-scale deployment. Advances in the area of WPT, especially the recent breakthrough by Kurs *et al.* [2], offer a new opportunity to prolong sensor network lifetime. In this article, we will discuss how different WPT technologies can be applied to address energy/lifetime problems in WSNs, and discuss their pros and cons.

[1] Another technology to address energy problem for a WSN is energy harvesting [1], e.g., solar, wind, vibrations, and ambient radio signals. Energy-harvesting technologies are orthogonal to WPT technologies. Due to space limitation, we only discuss one closely related energy harvesting technique that is based on ambient radio signals.

For correspondence regarding this article, please contact Prof. Tom Hou (thou@vt.edu).

WIRELESS ENERGY TRANSFER: HISTORY, CURRENT STATUS, AND RECENT ADVANCES

The vision of transferring power wirelessly can be dated back to the early 20th century (earlier than electric power grids). After the first electrical signal was sent across the Atlantic, Nikola Tesla, a pioneering electrical engineer, experimented with large scale wireless power distribution by building the world's first power station in Long Island, New York [3]. He planned to use the power station, called Wardenclyffe Tower (Fig. 1), to transmit not only signals but also wireless electricity. Unfortunately, due to its large electric fields, which significantly diminished the power transfer efficiency, Tesla's invention was not successful and was never put into practical use.

In the late 20th century, the need for WPT re-emerged when mobile electronic devices (e.g. laptops, cell phones, PDAs, tablets) became popular. Further, the rapid development of electric and plug-in hybrid vehicles in the auto industry also contributed to the need for WPT. Due to these demands, there have been many active efforts to develop efficient technologies for WPT. Recently, the Wireless Power Consortium (www.wirelesspowerconsortium.com) was established to set the international standards for interoperable wireless charging. Member companies in the consortium include IC manufactories,

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mobile phone makers, and mobile telecom operators. These standardization efforts will help accelerate the pace of bringing WPT technologies to the market place.

In this article, we discuss three categories of WPT technologies, namely, inductive coupling, EM radiation, and magnetic resonant coupling. For each technology, we review its physical characteristics, discuss its strengths and weaknesses, and explore its suitability for WSNs. Table 1 gives a summary of the three WPT technologies.

Inductive Coupling

Inductive coupling works by magnetic field induction, i.e., an alternating current in a primary coil (connected to a source) generates a varying magnetic field that induces a voltage across the terminals of a secondary coil at the receiver. An electrical transformer is a good example of inductive coupling. Due to its simplicity, convenience, and safety, inductive coupling has been an important and popular technology to transfer power without wires. It has been successfully commercialized to a number of products, including electric toothbrush, charging pad for cell phone or laptop (Fig. 2a), and medical implants [4]. In 2010, the Wireless Power Consortium approved the world's first wireless charging standard (Qi) for low-power inductive charging (< 5W). Today, inductive coupling is considered a mature technology, and is considered a stepping stone for new WPT developments such as magnetic resonant coupling.

Under inductive coupling, power transfer falls off steeply even over a very short distance. It works best when the charging node and power receiving node are close in contact (usually less than a coil diameter, e.g., centimeter-range) and have accurate alignment in the charging direction. Due to these limitations, inductive coupling is not suitable for WSNs.

EM Radiation

EM radiation emits energy from the transmit antenna of a power source to the receive antenna via radiative EM waves. Depending on the energy-emitting direction, it can be classified into omnidirectional radiation and unidirectional radiation. For omnidirectional radiation, a transmitter broadcasts EM waves in an assigned ISM band (e.g., 850–950 MHz [5] or 902–928 MHz [6] in the U.S.,[2] both with a center frequency of 915 MHz), and a receiver (e.g, RFID tags) tunes to the same frequency band to harvest radio power (Fig. 2b). Although suitable for transferring information, omnidirectional radiation suffers from a serious efficiency problem in energy transfer since EM waves decay quickly over distance. For example, it was reported in [7] that power transfer efficiency was only about 1.5 percent when a receiver is 30 cm away from the RF transmitter. Moreover, to prevent potential health hazards to humans from EM radiation, omnidirectional radiation is only appropriate for ultra low-power sensor nodes (e.g., up to 10 mW [5, 6]) with very low sensing activities (e.g., temperature, moisture and light).

When a clear line-of-sight (LOS) path exists, unidirectional radiation can achieve high power transmission over a much longer distance (e.g., kilometer-range) by using a microwave or laser beam. For most microwave-based systems, wireless power is transmitted on microwave frequencies of either 2.45 or 5.8 GHz, both in the ISM frequency band. Laser-based systems, still considered less mature than microwave-based systems, transmit power under the visible or near infrared frequency spectrum (i.e., from several THz to several hundred THz). In the 1980s, a prototype aircraft, designed as a communications relay by Canada's Communications Research Center, could receive power beamed from a large ground-based microwave transmitter (about 80 m in diameter). A rectifying antenna, mounted on the lower body of the plane, could receive and convert microwave power (at a frequency of 2.45 GHz) to DC electricity. The unmanned plane, called the Stationary High Altitude Relay Platform (SHARP),[3] flew at an altitude of about 21 km and in circles of 1 km in radius so that it could stay in the transmission range of a ground-based transmitter (Fig. 2b). Unidirectional radiation is not suitable for a WSN due to several undesirable requirements, such as LOS, complicated tracking mechanisms, and the inherent large scale of devices.

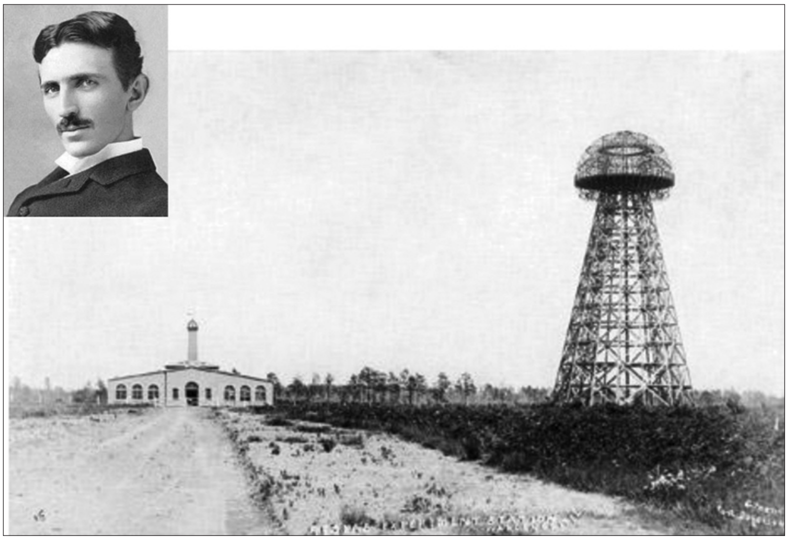

Figure 1. *Nikola Tesla and his Wardenclyffe Project in Long Island, New York in early 1900 (www.teslasociety.com).*

Magnetic Resonant Coupling

The third category of WPT technology is magnetic resonant coupling, which was developed by Kurs *et al.* [2]. This technology is based on the well-known principle of resonant coupling, i.e., by having magnetic resonant coils operate at the same resonance frequency so that they are strongly coupled via nonradiative magnetic resonance induction. Intuitively, the effect of magnetic resonance is analogous to the classical mechanical resonance, under which a string, when tuned to a certain tone, can be excited to vibration by a faraway sound generator if there is a match between their resonance frequencies.

Under resonant coupling, energy can be transferred efficiently from a source coil to a receiver coil with little loss of energy to extraneous off-resonant objects. A highlight of Kurs'

[2] *ISM bands may differ in world regions and countries.*

[3] *G. W. Jull, "An Overview of SHARP," July 1997, URL: http://www.friendsofcrc.ca/Projects/SHARP/sharp.html.*

WPT technologies		Strengths	Weaknesses	Example applications
Inductive Coupling		Simple, high power transfer efficiency in centimeter range	Short charging distance, requiring accurate alignment in charging direction	Electric toothbrush, charging pad for cell phones and laptops
EM radiation	Omnidirectional	Tiny receiver size	Rapid drop of power transfer efficiency over distance, ultra low-power reception	Charging a WSN for environmental monitoring (temperature, moisture, light, etc.)
	Unidirectional (microwave/ laser)	Effective power transmission over long distance (kilometer-range)	Requiring LOS and complicated tracking mechanisms, inherently large scale of devices	SHARP unmanned plane
Magnetic resonant coupling		High efficiency over several meters under omni-direction, not requiring LOS, and insensitive to weather conditions	High efficiency only within several-meter range	Charging mobile devices, electric vehicles, implantable devices and WSNs

Table 1. *A comparison of WPT technologies.*

experiment was to power a 60-W light bulb from a distance of 2 meters away, with about 40 percent power transfer efficiency (Fig. 3),[4] which significantly differs from inductive coupling that was limited to very close range, or EM radiation that was restricted to low-power (~mW) energy transfer. The diameter of both source and receiving coils was 0.5 m, which means that the charging distance can be 4 times the coil diameter.

At first glance, this technology reminds us of inductive coupling, and in some sense, it can be considered a special case of inductive coupling where the primary and secondary coils are tuned in resonance by adding compensation capacitors. Nevertheless, there are some fundamental advances with magnetic resonant coupling. Compared to inductive coupling, magnetic resonant coupling can achieve higher transfer efficiency while significantly extending the charging distance from a very close range (i.e., distance less than the coil diameter, usually several centimeters) to several times the coil diameter (e.g., 2 meters in Kurs' experiments). Compared to EM radiation, magnetic resonant coupling has the advantages of offering a much higher power transfer efficiency even under omni-direction, and not requiring LOS.

Although preliminary experiments by Kurs *et al.* showed the great potential of magnetic resonant coupling, a number of technical challenges (such as orientation and interference) still exist before transitioning this technology to a success-

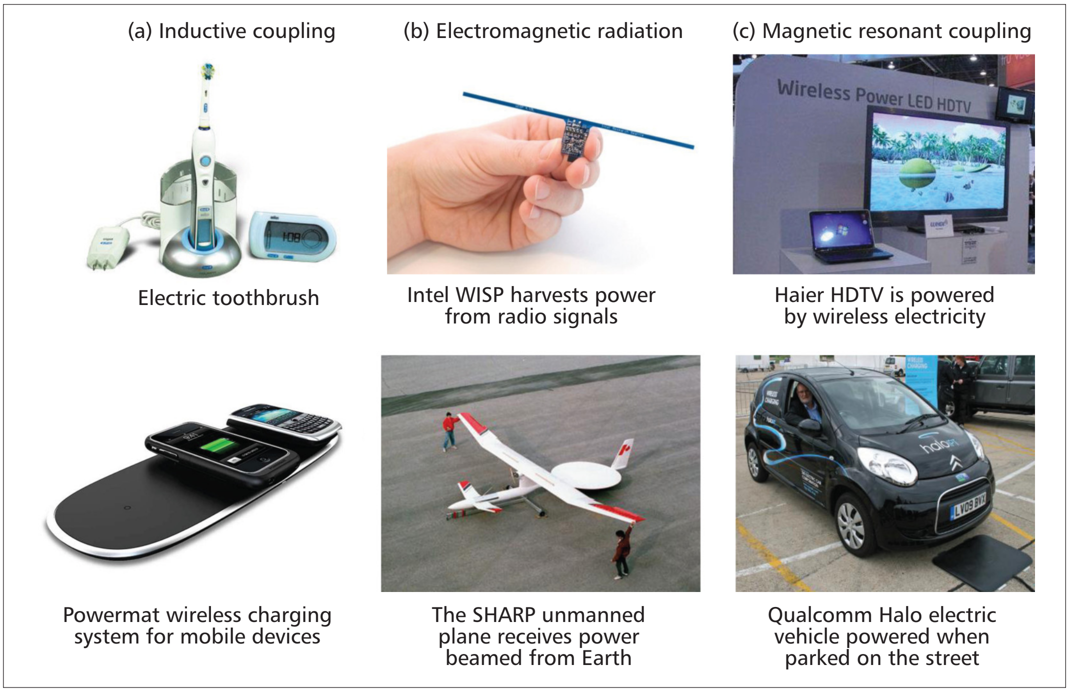

Figure 2. *Applications of three WPT technologies. URLs: a) (top) http://express.howstuffworks.com/toothbrush-autopsy.htm (bottom) http://www.powermat.com/; b) (top) http://www.intel.com (bottom) http://www.friendsofcrc.ca/Projects/SHARP/sharp.html; c) (top) http://www.pconline.com.cn/zt/ces2011/datafamily/datafamilynews/1101/2315749 2.html (bottom) http://evworld.com/news.cfm?newsid=24420.*

[4] *This efficiency between source coil and load is the most important component of the system efficiency. System efficiency also includes AC-DC conversion efficiency and other system factors (such as rectifier, drivers) [8].*

ful commercial product. First, the maximum charging distance can be achieved only when source and receiving coils are aligned coaxially (along their axis). Other alignment settings, such as a 45 degree rotation with respect to the coaxial alignment or coplanar, reduce the coupling factor between coils and thus the achievable distance [2]. Second, when the technology is extended to charge multiple devices, mutual coupling among various receiving coils and other objects may cause interference, and therefore careful tuning is necessary.

Recent Advances — Since the first demo by Kurs *et al.* in 2007, there have been some new advances in magnetic resonant coupling to make it suitable for commercial applications. In 2008 (Fig. 3), engineers at Intel demonstrated magnetic resonant coupling by using flat coils, which are easier to fit into a mobile device than the helix coils used in [2]. Kurs *et al.* launched a start-up company called Witricity Corp. (www.witricity.com), and at the TED Global 2009 conference, they demonstrated WPT for portable devices such as cell phones (Fig. 3). Further, Kurs *et al.* developed an enhanced technology (by properly tuning coupled resonators) that allows energy to be transferred to multiple receiving coils at the same time [9]. This technology allows for broader home and office applications, e.g., charging multiple mobile devices (laptops, tablets, cell phones) simultaneously.

In 2010, home appliance maker Haier exhibited an all wireless HDTV without power cords and signal cables (Fig. 2c). More recently, several leading automakers (e.g. Rolls-Royce, Audi, Nissan, Toyota, Mitsubishi) have been working to power electric or plug-in hybrid vehicles wirelessly. In 2011, Rolls-Royce unveiled an electric version of its Phantom car. The development of WPT technology allows these electric vehicles to be charged while they are parked along the street or in a garage without any power cord. This WPT technology, once fully mature, could help boost the electric car industry.

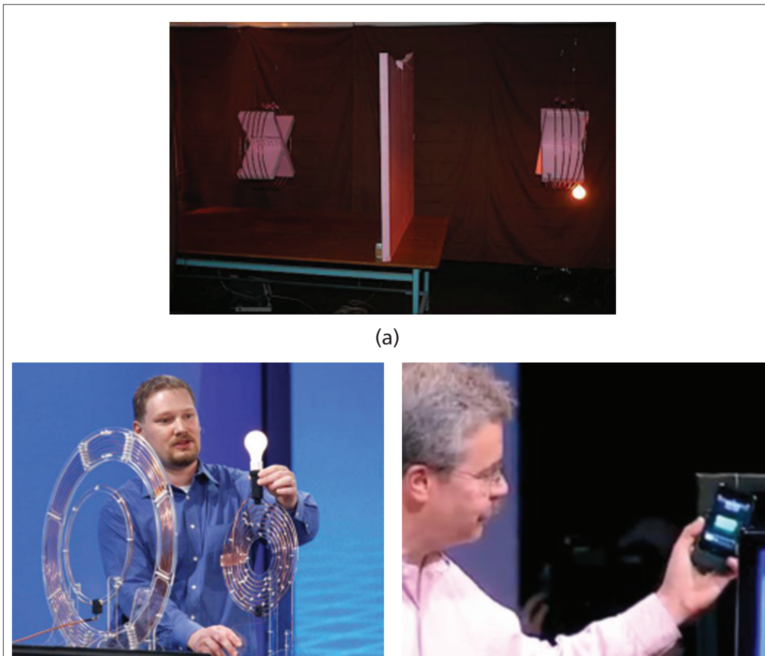
(a) (b) (c)

Figure 3. *a) Magnetic Resonant Coupling was first demonstrated by Kurs* et al. *[2]; b) Intel developed wireless power system by using flat coils (URL: http://www.intel.com); c) Witricity demonstrated this power transfer technology for cell phones (URL: http://www.witricity.com).*

Omnidirectional EM Radiation and WSNs

Omnidirectional EM radiation may be necessary in applications when the locations of sensor nodes are either unknown or uncontrollable. It has been used to harvest energy for a WSN, e.g., deploying wireless chargers [7, 10], employing a mobile robot [11], and passively harvesting from ambient radio signals [12]. In this section, we briefly describe these efforts.

In [10], Tong *et al.* conducted a preliminary experiment for charging sensor nodes via Powercast chips, which are commercially available RF-based WPT products [5]. The results showed that the power transfer efficiency for a single node is very low (less than 1 percent and 20 cm away from the energy transmitter). Based on the same WPT technology, Peng *et al.* employed a mobile robot carrying a wireless charger to charge a sensor network [11]. They studied the charging schedule problem for the mobile charger (i.e., when and how long to charge a node) to prolong network lifetime. In [11], data routing was given a priori, while data routing topology was assumed to be static. To prolong network lifetime, the authors proposed a heuristic algorithm, with a basic idea of charging nodes in the order of their expected lifetimes, with the shortest first. They conducted prototype experiments for a small-scale network and ran simulations for a large-scale network. Both experimental and simulation results showed that EM radiation could prolong network lifetime. But the low power transfer efficiency was shown to be the bottleneck.

He *et al.* [7] studied how to design an infrastructure of wireless chargers for a WSN. The authors assumed that the basic unit for deploying wireless chargers followed a triangular structure, with a wireless charger at each vertex of the triangle. The problem was to determine the side length of the triangle so that the required number of wireless chargers was minimized while the power reception rate of any sensor node in the WSN did not fall below its average energy consumption rate. They offered a solution for deployment and derived an upper bound on an asymptotic approximation ratio of the number of wireless chargers to the optimal solution. They also showed that if sensor nodes were mobile, the required number of wireless chargers could be reduced. Due to the low efficiency of WPT, the proposed solution still required dense deployment of wireless chargers (e.g., more than 100 wireless chargers over a 100 m × 100 m area).

Recently, Ajmal *et al.* [12] designed a compact RF energy harvester, which passively absorbs energy from ambient RF signals.

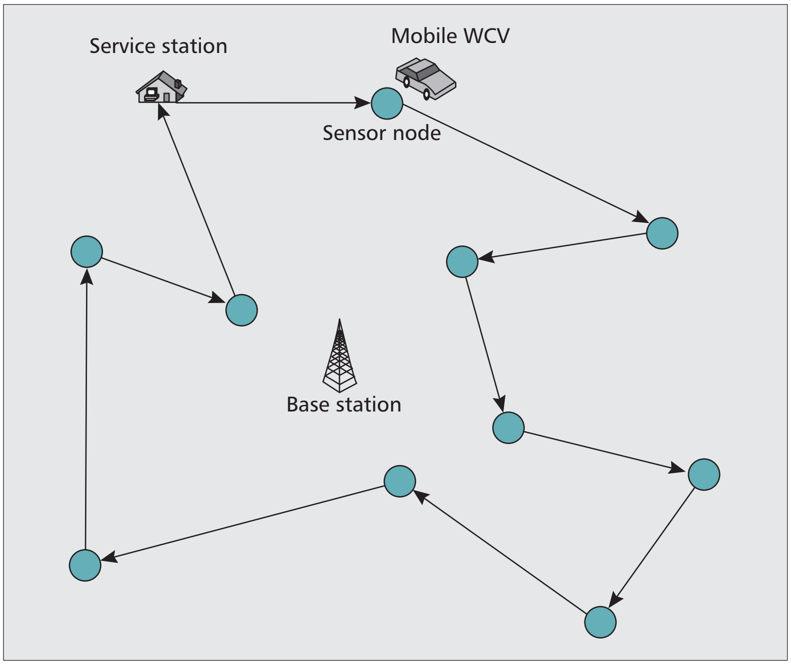

Figure 4. *A WCV periodically visits each sensor node and charges its battery via WPT based on magnetic resonant coupling [14].*

Through simulation, they showed that an ultra-low power (~ μW) node can be supported without a power outage as long as it is within the charging range of a high power transmitter (e.g., within 120 km of a 150 kW transmitter). In contrast to active power transfer [7, 10, 11], this approach has the potential to charge ultra-low power nodes located in inaccessible areas.

In summary, radiative technology has a number of limitations when applied to a WSN. First and foremost, omnidirectional radiation has very low efficiency in WPT. Second, radiative technology is sensitive to obstruction between an energy source and a receiver. Finally, active radiative technology may pose safety concern to humans. Therefore, this technology is only suitable to a WSN with ultra low-power requirements.

Recently, Zhang and Ho [13] explored using RF signals to achieve simultaneous wireless information and power transfer in a MIMO broadcasting system. Specifically, they studied a simplified three-node setup, and presented a theoretical tradeoff in designing MIMO systems for maximizing the information rate and energy transfer rate. Their work demonstrated the possibility of using multi-antenna energy beamforming to improve the power efficiency of EM radiation. This energy transfer technology is still in its infancy and further investigation is needed to understand its potential and limits.

Magnetic Resonant Coupling and WSNs

Compared to EM radiation, magnetic resonant coupling enjoys significant advantages including much higher efficiency in WPT (under omni-direction), immunity to neighboring environments, and no requirement of LOS [2, 9]. Among the WPT technologies, magnetic resonant coupling appears to be the most suitable technology for a WSN.

In [14], Xie *et al.* made the first investigation on how such WPT technology can be applied to a WSN. The authors considered the scenario of a mobile wireless charging vehicle (WCV) periodically traveling inside a WSN and charging each sensor node (Fig. 4). Upon completing each trip, the WCV returns to its home service station, takes a "vacation," and then starts out on the next trip. To ensure that the sensor nodes are always recharged in time, Xie *et al.* introduced a new concept called *renewable energy cycle* and offered both necessary and sufficient conditions. They showed that once these conditions are satisfied, a solution (including a traveling path for the WCV, a charging schedule for each sensor node, and data routing) can offer renewable energy cycles, and thus unlimited lifetime for a WSN. They further studied an optimization problem, with the objective of maximizing the ratio of the WCV's vacation time at the home service station over the cycle time. For this problem, they proved that the optimal traveling path is the shortest Hamiltonian cycle and revealed a number of interesting properties. Under the optimal traveling path, they formulated an optimization problem for joint data routing and a charging schedule for each sensor node, which is a nonlinear optimization problem. Subsequently, they developed a near-optimal solution by a piecewise linear approximation technique and proved that it can achieve near-optimality for any desired level of accuracy.

The most important finding in [14] is that once properly designed, a WPT technology, such as magnetic resonant coupling, can offer a WSN infinite lifetime. However, the WPT developed in [2] was limited to charging one node at a time and was not scalable as node density increases. So an open problem in [14] is *scalability*, i.e., how will such a WPT technology work as the WSN's node density increases?

Interestingly, Kurs *et al.* also identified this problem and developed an enhanced magnetic resonant coupling technology that allows multiple devices to be charged at the same time [9]. Motivated by this new scalable charging technology, Xie *et al.* [15] applied it to a dense WSN. They considered that a WCV follows the same periodic manner as in [14]: starting from a home service station, the WCV travels inside the network, charges sensor nodes wirelessly, and returns to the service station for a vacation. Unlike [14], the WCV is capable of charging multiple nodes at the same time, as long as these nodes are within its charging range. Based on the charging range of the WCV, they proposed a cellular structure that partitions the two-dimensional plane into adjacent hexagonal cells (similar to the cellular structure for cellular networks). Based on a general energy charging model, they studied an optimization problem by jointly optimizing the traveling path, flow routing and charging time. For this problem, they developed a provably near-optimal solution [15]. Through simulation results, they showed that their solution can indeed address the scalability problem when charging a WSN.

Conclusions

In this article, we reviewed the history of WPT and its state-of-the-art. In particular, we reviewed a number of WPT technologies over the years, pointed out their limitations, and discussed possible applications. As a focus application, we considered a WSN and discussed the suitability of each WPT technology for a WSN. We showed that omni-directional EM radiation may be applicable to a WSN with ultra-low power requirements, while magnetic resonant coupling is most promising to address the energy needs of a WSN. Clearly, the emerging WPT technologies will significantly affect our daily lives. Tesla predicted in 1906: "The transmission of power without wires will very soon create an industrial revolution and such as the world has never seen before." This pronouncement was ahead of its time then, but will soon become a reality.

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Biographies

Liguang Xie [S'08] (xie@vt.edu) is currently a Ph.D. student in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA. His research focuses on wireless power transfer for energy-constrained wireless sensor networks.

Yi Shi [S'02, M'08] (yshi@vt.edu) received his Ph.D. degree in Computer Engineering from Virginia Tech, Blacksburg, VA in 2007. He is currently an Adjunct Assistant Professor at Virginia Tech. His research focuses on optimization algorithms for wireless networks. He was a recipient of IEEE INFOCOM 2008 Best Paper Award and the only Best Paper Award Runner-Up of IEEE INFOCOM 2011.

Y. Thomas Hou [S'91, M'98, SM'04] (thou@vt.edu) received his Ph.D. degree in Electrical Engineering from Polytechnic Institute of New York University in 1998. He is currently a Professor in the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA. His research focuses on developing innovative solutions to complex problems that arise in wireless networks. He is on the editorial boards of a number of IEEE transactions. He is the Chair of the IEEE INFOCOM Steering Committee.

Wenjing Lou [S'01, M'03, SM'08] (wjlou@vt.edu) received her Ph.D. degree in Electrical and Computer Engineering from the University of Florida in 2003. She is currently an Associate Professor in the Department of Computer Science at Virginia Tech. Prior to that, she was an Associate Professor in the Department of Electrical and Computer Engineering at Worcester Polytechnic Institute. Her research interests are cyber security and wireless networks. She is on the editorial boards of a number of IEEE transactions.

Tesla predicted in 1906: "The transmission of power without wires will very soon create an industrial revolution and such as the world has never seen before." This pronouncement was ahead of its time then, but will soon become a reality.