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Excerpt
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Part I

Basics of Wireless Energy Harvesting and Transfer Technology

1 Basics of Wireless Energy Harvesting and Transfer

Dusit Niyato, Ekram Hossain, and Xiao Lu

1.1 Introduction

Energy harvesting is an important aspect of green communication that provides self-sustainable operation of wireless communications systems and networks. Energy harvesting has been adopted in low-power communication devices and sensors. There are different forms of energy harvesting suitable for different applications. Table 1.1 shows the summary of different energy harvesting technologies.

- Photovoltaic technology has been developed over decades, and it is one of the most commonly used energy harvesting techniques. A solar panel which is composed of multiple solar cells converts sunlight into a flow of electrons based on the photovoltaic effect. The effect describes the phenomenon that the light excites electrons into a higher state of energy. The electrons then can act as charge carriers for electric current. A solar cell contains a photovoltaic material, e.g., monocrystalline silicon, polycrystalline silicon, amorphous silicon, and copper indium gallium selenide/sulfide. The efficiency of a solar cell can be up to 43.5%, while the average efficiency of a commercial solar cell is 12%–18%. Photovoltaic technology has been adopted in many applications, including rooftop and building integrated systems, power stations, rural electrification, and telecommunication. However, photovoltaic systems need a large area and cannot supply energy during the night. Moreover, their efficiency depends on the orientation of the solar panel, which can be complicated to optimize. Photovoltaic systems are suitable for static data communication units, e.g., a base station and access point, while their applicability to mobile units, e.g., user equipment, is limited.
- Thermal energy or heat can be converted to electricity using a thermoelectric generator based on the Seebeck effect or Thomson effect. The effect describes the conversion of temperature difference and electricity in thermoelectric devices. While thermoelectric devices are typically used for measuring temperature, recently they have been developed to serve as energy sources. The devices can produce 20–16 μW/cm^2 with the human body as a heat source at room temperature. The benefit of thermoelectric devices is the capability of generating

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Table 1.1. Different wireless energy transfer techniques [1]

	Power density	Output voltage	Availability	Circuit weight
Solar [2]	100 mW/cm^2	0.5 V (single Si cell), 1.0 V (single a-Si cell)	Daytime only	5–10 g
Thermal [3]	60 μW/cm^2	N/A	Anytime	10–20 g
Ambient RF	Up to 1 μW/cm^2	3–4 V	Anytime	2–3 g
Vibration [4]	20 μW/cm^3	10–25 V	Activity dependent	2–10 g
Push button (piezoelectric) [5]	50 μJ/N	100–10000 V	Activity dependent	1–2 g

energy as long as there is a temperature difference or a heat flow. Additionally, since they do not have any moving parts, they have high reliability. However, the devices are bulky and heavy. Also, they can supply only a small amount of energy, with typical efficiencies of approximately 5%–8%.

- Vibration can cause mechanical strains that can be converted into electricity through the piezoelectric effect. Piezoelectric devices can continuously generate electricity as long as there is some vibration, e.g., from noise and wind. Human movement can let the piezoelectric devices generate electricity intermittently, e.g., arm motion and shoe impacts. It is also possible to harvest energy from blood pressure that can be delivered to implantable or wearable sensors. The output power in such a case has a density of around 250 μW/cm^3. Although the harvesting circuit has a light weight, it needs a large area and the output energy can vary drastically. A push button energy generation circuit has light weight and its size is relatively small. However, the conversion efficiency can be low.

Wireless energy harvesting is different from other forms of energy harvesting, e.g., solar, wind, and vibration. Firstly, energy sources for wireless energy harvesting can support regular and controllable energy supply with high efficiency for near-field energy transfer and over distance for far-field energy harvesting. Secondly, if energy harvesting nodes are fixed, usually their wireless energy supply will be relatively predictable since the efficiency depends on the distance. However, since the efficiency depends on the distance, the energy supply among nodes at different locations can be non-uniform. Thus, the capability of each node can be different, which makes the network operation more challenging.

Figure 1.1 shows a generic block diagram of a wireless sensor device. The device is typically composed of three major components.

- *Energy sources*. An energy harvester can harvest and generate electricity from energy sources. As shown in Table 1.1, different energy sources can be used for different applications depending on the amount of energy, size, weight, etc.
- *Power supply unit*. This is responsible for regulating incoming electricity and storing it in an energy storage device such as a battery and capacitor. The power

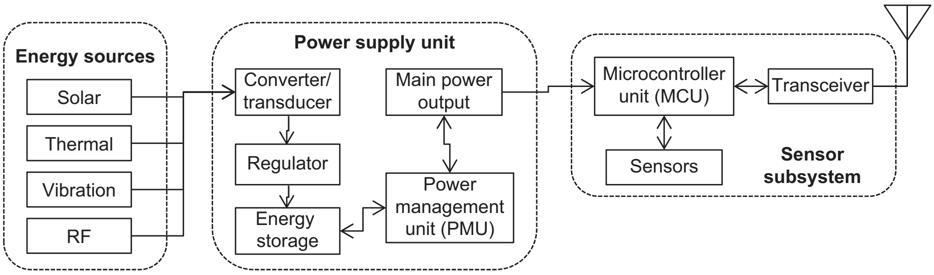

Figure 1.1 A generic model of an energy harvesting sensor device [1].

management unit (PMU) is designed to transfer energy from the energy storage to the sensor subsystem. The PMU may decide to switch on or switch off the sensor subsystem, e.g., when there is enough and not enough energy, respectively.

- *The sensor subsystem* is controlled by the microcontroller unit (MCU). The MCU interfaces with the sensors. Depending on the application, for example, the sensors can be a motion detector or video camera for surveillance. The MCU packetizes and transfers the data collected from the sensors to the transceiver. The transceiver transmits a data packet to a receiver. Moreover, the transceiver also receives a packet, e.g., a control signal, to adjust the operations accordingly.

1.2 History of Wireless Energy Harvesting and Transfer Technology

The history of wireless energy harvesting and transfer can be traced back to 1819. Hans Christian Oersted performed an experiment and observed that a compass needle can be made to deviate from magnetic north because of the change of current from a battery. He found that electric current can induce a magnetic field around the wire that the current flows through. Thus, he established the relationship between electricity and magnetism. This finding served as a basis for André-Marie Ampère to develop mathematical models to capture and explain the relationship between electricity and magnetism. Ampère found that two parallel wires can repel or attract each other depending on the directions of electric currents. He then proposed Ampère's law, which states that the force between two wires with currents passing through them is proportional to the lengths of the wires and the amounts of the currents.

The later major developments following on from Ampère include the Biot–Savart law, Gauss's law for magnetism, and Faraday's law. The Biot–Savart law models the magnetic field generated by an electric current. The law describes the relationship among magnitude, direction, length, and proximity of the electric current and the intensity of the magnetic field. Gauss's law for magnetism is related to the zero divergence of a magnetic field. Faraday's law describes the phenomenon that a change of magnetic flux can induce an electromotive force in a circuit. The amount of force is a function of the rate of change.

James Clerk Maxwell established a set of partial differential equations, called Maxwell's equations, that characterize the effect of electric and magnetic fields generated and varied by each other. They are related to the change of currents. In 1873, he published a book titled *A Treatise on Electricity and Magnetism* [6] that momentously lays down the fundamentals of electricity and magnetism. The aforementioned discoveries and theories established the modern theoretical foundation of electromagnetism that has found numerous applications in electronics, telecommunications, and electrical power engineering.

In the context of wireless energy transfer, Heinrich Rudolf Hertz postulated the existence of electromagnetic waves. He experimented and demonstrated their existence by using an oscillator connected to induction coils. These coils radiated electric and magnetic fields as transverse waves. The detector designed as a ring was able to measure the magnitude and direction of the waves as well as their polarity and reflection. This was the first experiment to show that electricity can be transmitted through the air.

The remarkable development of wireless energy transfer technology was achieved by Nikola Tesla, the founder of alternating current electricity. He was the first to experiment on wireless power transfer using microwave technology in the period 1891–1904. He demonstrated a system of inductive and capacitive coupling to transmit energy wirelessly. The system is based on spark-excited radio-frequency (RF) resonant transformers. The transformers are currently known as Tesla coils. The system is able to show the wireless energy transfer capability to illuminate light bulbs a short distance away. Later, he tried to increase the distance. The method used was based on resonance inductive coupling. However, the distance is still within 100 m. To increase the transmission range further, Tesla considered the RF energy transfer technique. He constructed the Wardenclyffe Tower, which is a large high-voltage coil infrastructure. The purpose was to demonstrate his vision of a "World Wireless System." Although the construction was never finished, it can be considered as the first attempt to achieve long-range RF wireless energy transfer technology.

In 1964, William C. Brown developed a rectenna to convert microwaves to electricity. Brown demonstrated the applications of such a concept by developing a model helicopter powered wirelessly. In 1975, Brown managed in an experiment to transfer 30 kW of power over a distance of 1 mile with 84% efficiency. A similar idea was adopted in a solar power satellite introduced in 1968. The idea is to place a large solar power satellite in geostationary Earth orbit. The satellite receives sunlight and converts it into electricity before transmitting the energy back to the Earth using microwaves.

It is only recently that research and development in wireless charging have received tremendous momentum. With regard to applications to supply and recharge portable electronic devices, many manufacturers now see the commercial potential of the technology, e.g., [7]. In 2007, WiTricity technology was introduced. In experiments, this mid-range non-radiative wireless charging based on near-field resonant inductive coupling can supply energy to a 60 W light bulb. An efficiency of 45% and 90% is achieved at a distance of 7 and 3 feet, respectively. The experimental system is based on two five-turn copper coils with 60 cm diameter. An efficiency of 45% was achieved. The coils, arranged to be on the same axis, resonate at 9.9 MHz. The Cota system (www.ossiainc.com), PRIMOVE (primove.bombardier.com), and Powercast wireless rechargeable sensor system (www.powercastco.com) use similar technology. Powercast is based on RF energy harvesting that can receive energy from a dedicated or ambient RF source. The devices are designed to support battery charging and capacitor charging in battery-free devices. The frequency of energy harvesting is 850–950 MHz, and it is able to work with 50 Ω antennas. The output voltage is configured to be 4.2 V and 5.25 V. It is claimed that a conversion efficiency of 70% can be achieved. Combined with an advanced antenna system, magnetic MIMO was designed to support multi-antenna beamforming for magnetic waves of wireless energy transfer.

The major standardization organizations for wireless energy transfer are the Wireless Power Consortium (www.wirelesspowerconsortium.com), Power Matters Alliance (www.powermatters.org), and Alliance for Wireless Power (www.rezence.com). Different producers adopt different standards; however, technology convergence is expected in the future.

1.3 Wireless Energy Harvesting and Transfer Technology

Wireless technologies can be broadly classified into two major types, i.e., non-radiative coupling-based charging and radiative RF-based charging [8] as shown in Figure 1.2. The former is mostly used for near-field charging, while the latter is suitable for far-field charging. Non-radiative coupling-based charging can be divided into inductive coupling [9], magnetic resonance coupling [10], and capacitive coupling [11]. They are based on using magnetic flux to carry energy from a transmitter to a receiver. The attenuation of the magnetic field is a cube of the reciprocal of the distance. The absorption of the magnetic field affects the transmitter, e.g., the current. Alternatively, radiative RF-based charging can be classified into directive and non-directive RF power transfer [12]. They are based on using an RF signal and beam to transfer energy from a transmitter to receivers. The attenuation of the RF signal depends on the reciprocal of the distance, and the absorption of the RF signal does not impact the transmitter. Table 1.2 summarizes and compares different wireless energy transfer techniques [13].

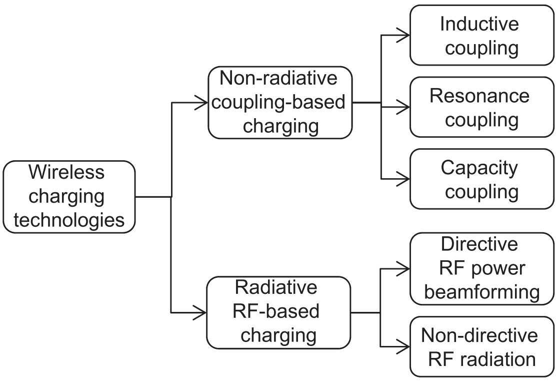

Figure 1.2 Classification of wireless charging technologies.

Table 1.2. Different wireless energy transfer techniques [13]

Techniques	Effective distance	Efficiency	Applications
RF energy transfer (far field, radiative)	A few centimeters to hundreds of meters	0.4%, above 18.2%, and over 50% at −40 dBm, −20 dBm and −5 dBm input power, respectively [14]	Wireless sensor network [15], wireless body network [16]
Resonant inductive coupling (near-field, non-radiative)	A few millimeters to a few centimeters	From 5.81% to 57.2% for frequency 16.2–508 kHz [17]	RFID tags, contactless smart cards, phone charging
Magnetic resonance coupling (near-field, non-radiative)	A few centimeters to a few meters	From 90% to 30% for distance 0.75–2.25 m [10]	PHEV charging, phone charging

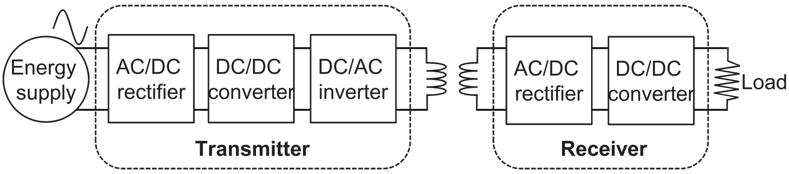

Figure 1.3 Major components of a non-radiative wireless energy transfer system [8].

1.3.1 Non-Radiative Wireless Energy Transfer

Figure 1.3 shows a general block diagram of a non-radiative wireless charging system [8]. The transmitter receives energy in a form of alternating current (AC) with a frequency of 50–60 Hz. However, this frequency is too low to be used for induction. Thus, the AC is converted to direct current (DC) using an AC/DC rectifier. The DC will be converted by the DC/DC converter to increase the voltage. The DC/AC inverter changes DC to AC with higher frequency and passes it to the transmit coil. The coil generates a magnetic field. At the receiver, which is separated from the transmitter by an air gap, the receive coil is induced by the magnetic field from the transmitter. The converts the AC to DC. The DC/DC converter adjusts the voltage to make it suitable for the load.

In the following, we give an overview of two major non-radiative wireless energy transfer technologies, i.e., inductive coupling and magnetic resonance coupling.

1.3.1.1 Inductive Coupling

Magnetic inductive coupling uses magnetic field induction as a means to transfer energy between two coils (Figure 1.4). A primary coil is used as a transmitter, while a secondary coil is used as a receiver. The primary coil, which is made of a conductive material such as copper, is connected with an AC power source. The current flow from the source generates an oscillating magnetic field. The field propagates to the secondary coil, which

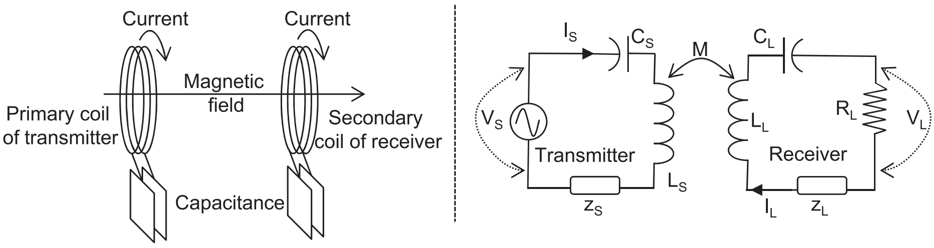

Figure 1.4 Inductive coupling.

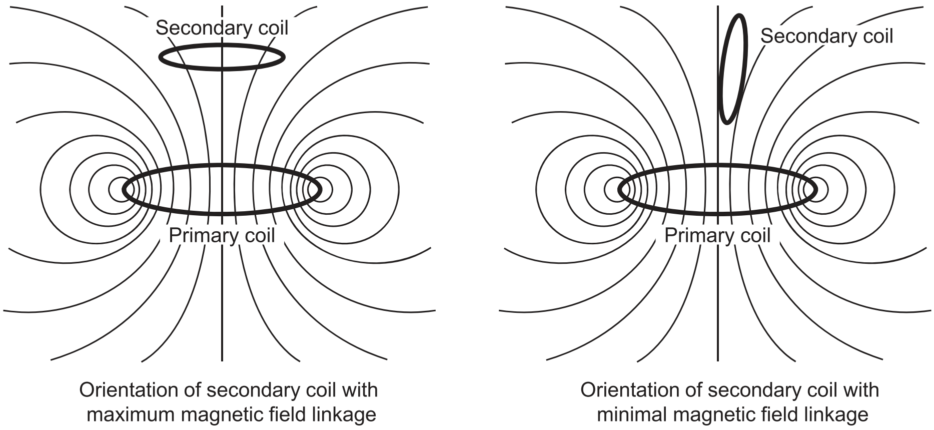

Figure 1.5 Orientation of the secondary coil.

is called the conducting coil. For effective energy transfer, the distance between the two coils is usually less than a wavelength of the frequency used for inductive coupling, which is in the range of kHz. At the secondary coil, the varying magnetic field induces an electric current for the receiver. Then, the current can be used to supply the load or it can be stored in an energy storage device such as a capacitor or a battery. The effective charging distance for the inductive coupling is within 20 cm, i.e., typically less than the diameter of the coils).

The orientation of the secondary coil has a significant impact on the energy reception. Figure 1.5 shows the orientations that result in maximum and minimal magnetic linkage and thus induction. In the first scenario, the primary and secondary coils are aligned in such a way that a large amount of magnetic field passes through the secondary coil. This will result in high energy transfer efficiency. By contrast, in the second scenario, the secondary coil is aligned such that minimal magnetic field passes through, leading to low energy transfer efficiency.

In general, the magnetic inductive coupling is easy to implement, flexible to operate, of high efficiency (for short-distance energy transfer), and of low cost. Therefore, it is suitable for commercial products such as radio-frequency identification (RFID) tags and mobile phone chargers. Table 1.3 shows a summary of some existing hardware implementations of inductive coupling.

Table 1.3. Comparison among hardware Implementations of inductive coupling

References	Technique	Output	Maximum charging efficiency	Maximum charging distance	Frequency
[19] (2010)	0.18 μm CMOS	1.8 V	54.9%	10 mm	13.56 MHz
[20] (2012)	0.5 μm CMOS	3.1 V	77%	80 mm	13.56 MHz
[21] (2013)	0.18 μm CMOS	3 V	87%	20 mm	13.56 MHz
[22] (2013)	0.18 μm CMOS	1.5 V	82%	11.35 mm	100–150 kHz
[23] (2014)	0.13 μm CMOS	3.6 V	65%	20 mm	40.68 MHz

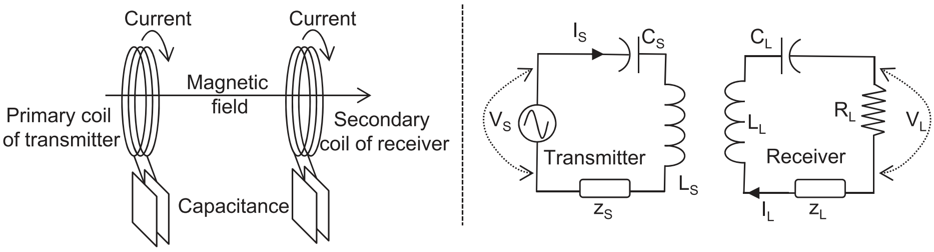

Figure 1.6 Magnetic resonance coupling.

Inductive coupling systems can be designed based on one of the four basic topologies, i.e., series–series, series–parallel, parallel–series, and parallel–parallel [18]. The series–series and series–parallel topologies are more commonly adopted. In contrast, parallel–series and parallel–parallel topologies can yield better performance. However, they require sophisticated circuit design and performance tuning.

1.3.1.2 Magnetic Resonance Coupling

Magnetic resonance coupling was developed to improve the energy transfer. It is based on evanescent wave coupling. As in inductive coupling, there are two coils, i.e., primary and secondary coils. However, the magnetic field is oscillating, and capacitances are added to the transmitter and receiver circuits (Figure 1.6). The oscillation is at the same frequency, typically in the MHz range, for the transmitter and receiver. Magnetic resonance coupling can achieve a higher efficiency and a longer charging distance than is possible with inductive coupling. Additionally, magnetic resonance coupling allows simultaneous charging of multiple devices which are tuned to the same frequency. Nonetheless, interference among coils can occur, meaning that optimal performance adjustment is required.

With the setting of the magnetic resonance coupling system shown in Figure 1.6, the relationship among the transmitter current I_S, the receiver current I_L, and the mutual inductance M between the two circuits can be expressed as follows:

$$I_L\left(R_L + j\omega L_L + \frac{1}{j\omega C_L} + z_L\right) = j\omega M I_S, \tag{1.1}$$

where R_L is the resistance of the receiver, L_L is the inductance, C_L is the capacitance, and z_L is the complex impedance. ω is the resonance angular frequency of the system, which is obtained from

$$\omega = \frac{1}{\sqrt{L_S C_S}} = \frac{1}{\sqrt{L_L C_L}}. \tag{1.2}$$

In coupling systems, not only is the receiver induced by the magnetic field from the transmitter, but also the transmitter is affected by the receiver. In this case, the voltage on the transmitter can be expressed as follows:

$$V_S = I_S\left(j\omega L_S + \frac{1}{j\omega C_S} + z_S + R_T\right) - j\omega M I_L, \tag{1.3}$$

where I_S is the current on the transmitter circuit, L_S is the resistance of the transmitter, C_S is the capacitance, and z_S is the complex impedance. R_T is the resistance of the transmitter.

Notably, a magnetic resonance coupling system usually operates at the same resonance frequency. This can cancel the terms $j\omega L_L$ and $1/(j\omega C_L)$ for the receiver and the terms $j\omega L_S$ and $1/(j\omega C_S)$ for the transmitter. The receive power at the load of the receiver can be obtained from [24]

$$P_R = P_T Q_T Q_R \eta_T \eta_R k^2(d), \tag{1.4}$$

where P_T is the transmit power. η_T and η_R are the efficiencies of the transmitter and receiver, respectively. The efficiencies are obtained from

$$\eta_T = \frac{z_S}{R_T + z_S}, \quad \eta_R = \frac{z_L}{R_R + z_L}, \tag{1.5}$$

where Q_T and Q_R are the quality factors of the transmitter and receiver, respectively. R_R is the resistance of the receiver. The quality factors are obtained from

$$Q_T = \frac{\omega L_S}{R_T + z_S}, \quad Q_R = \frac{\omega L_L}{R_R + z_L}. \tag{1.6}$$

$k^2(d)$ is the coupling coefficient between the transmit and receive coils as a function of distance d. It can be expressed as follows [25, 26]:

$$k^2(d) = \frac{r_T^3 r_R^3 \pi^2}{(d^2 + r_T^2)^3}, \tag{1.7}$$

where r_T and r_R are the radii of the transmit and receive coils, respectively.

The resonance coupling system shown in Figure 1.6 is based on a single-input, single-output (SISO) configuration. It is possible to implement multiple coils at the transmitter and receiver, which are referred to as multiple-input, single-output (MISO) and single-input, multiple-output (SIMO), respectively.

Figure 1.7 shows a resonance coupling system with the MISO configuration with N_T transmit coils. The receive power at the receiver from the transmit coil n can be obtained from [27]

$$P_R^n = P_T^n Q_T^n Q_R \eta_T^n \eta_R k_n^2(d_n), \tag{1.8}$$