

## Chapter 2

# Systematic Designs

**Abstract** A successful systematic design is extremely important for wireless power transfer. It helps to clarify the features that are the most important and that can be given up. It also helps to develop antennas and circuits techniques for the system. In this chapter, we focus on the system level design of the wireless power transfer for biomedical applications. Although biomedical applications may be variable, we try to model, extract, and discuss the common features for their power transfers. First, the basic working principle of the inductive coupling is briefly depicted. Second, a unified systematic model is proposed for the transfers. Three types of the system components, including the power antennas, the power converters, and the power management are to be described. Third, typical challenges in the systematic design are to be summed up. The most challenging part is to trade off among various characteristics. At last, the electromagnetic exposure to human body is discussed, which is a necessary consideration in the systematic design.

### 2.1 Fundamentals

Before designing systems, we introduce the fundamental working principles of the wireless power transfer. As introduced in the [Chap. 1](#), there are many types of the wireless power transfers. According to the demand for biomedical applications, stronger penetrability, higher power efficiency, and safer performance are the most critical features. As a consequence, the inductive coupling is the best choice for the biomedical applications. Therefore, the fundamentals discussed in this section are all based on the inductive coupling. These fundamentals mainly include the basic concepts of the time-varying Electromagnetic field, like the Ampere's circuital law [1], the Biot-Savart law [1], and the Faraday's law of induction [1]. Understanding these fundamental working principles is important for further discussion later.

### 2.1.1 Basic Laws

Considering the inductive coupling is the most frequently adopted transfer type in the biomedical applications, we don't distinguish the "wireless power transfer" and the "inductive coupling" anymore in the rest of the book.

A typical inductive coupling system consists of a primary power transmitter and a secondary power receiver. The transmitter adopts power converters to convert DC energy to AC energy and delivers the AC energy to a power transmitting antenna or coil. The receiver employs power receiving antenna or coil to pick up AC energy in space and converts the AC energy back to the DC energy. In some applications, the operating frequency of the time-varying electromagnetic field may be as low as 50–60 Hz, or as higher as 2.4 GHz. However, in the most of biomedical applications, the operating frequency is in the range from 100 kHz to 50 MHz. Comparing to the typical transmission distance in range from 1 to 10 cm in biomedical applications, the corresponding wave length of the electromagnetic field is relatively much longer. Therefore, the transfer can be viewed as a near field progress. The whole progress can be analyzed by using basic electromagnetic laws. To clearly illustrate the transfer progress, we start from the primary side by assuming there is a time-varying current in the transmitting coil.

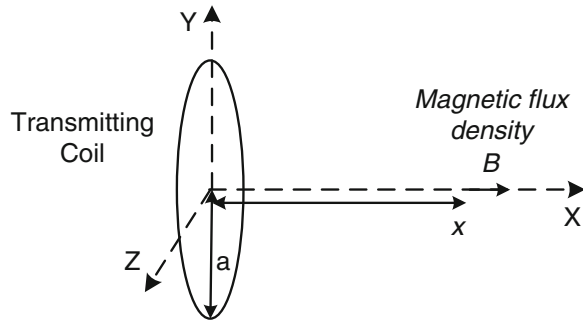
#### (a) Magnetic flux density Generated by the Primary Coil

Suppose there is a continual flow of charges which is constant in time and the charge neither accumulates nor depletes at any point, the Biot-Savart law [1] gives out the magnetic flux density generated by the flow of charges.

$$B = -\frac{\mu_0}{4\pi} \oint_l \frac{Idl \times e_r}{r^2} \quad (2.1)$$

where  $r$  is the full displacement vector from the wire element to the point, at which the field is being computed,  $e_r$  is the unit vector of  $r$ .  $Idl$  is linear-current-element in the wire, and  $\mu_0$  is the magnetic constant.

**Fig. 2.1** Magnetic field generated by a circular transmitting coil



Typically in the wireless power transfer, the transmitting coil is a circular coil as shown in the Fig. 2.1.

For the circular coil, the generated magnetic flux density  $B$  at the point  $x$  in the Fig. 2.1 can be expressed by:

$$B_x = \frac{\mu_0 N I a^2}{2(a^2 + x^2)^{3/2}} e_x \quad (2.2)$$

where  $N$  is the coil's turns,  $I$  is the current in each turn,  $a$  is the radius of the circular coil,  $x$  is the distance from the center of the coil to the point  $x$ , and  $e_x$  is the unit vector of axle  $X$ . If the current  $I$  in the transmitting coil is not constant but time-varying, the generated magnetic flux density  $B_x$  would also change over time.

#### (b) Induced voltage in the Secondary Coil

Suppose there is another circular coil in space as shown in the Fig. 2.2.

The total time-varying magnetic flux  $\Phi_m$  crossing the secondary coil can be expressed by:

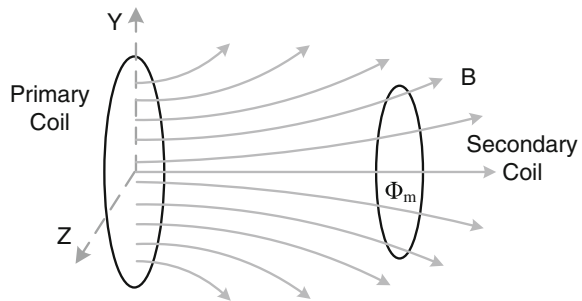
$$\Phi_m = \int_s B \cdot dS \quad (2.3)$$

where  $B$  is the magnetic flux density generated by the primary coil, and  $S$  is the surface of the secondary coil. According to the Faraday's law of induction [1], the induced voltage in the secondary coil is:

$$V(t) = -\frac{d\Phi_m(t)}{dt} \quad (2.4)$$

where  $\Phi_m(t)$  is the total time-varying magnetic flux crossing the second coil,  $V(t)$  is the induced voltage in the second coil. The voltage would cause an induced current in the secondary coil. An induced magnetic field is also generated. According to the Faraday's law [1], the polarity of the induced magnetic field is such that it produces a magnetic field opposes the change which produces it. Because the induced voltage and the current are produced at the secondary side, power is successfully transferred to the secondary side. This is the basic working principles of the wireless power transfer or the inductive coupling.

**Fig. 2.2** Magnetic field crossing the secondary coil



### 2.1.2 Transformer Basis

Another way to analyze the wireless power transfer is to use the transformer theory [2]. A transformer is a power converter that transfers AC electrical energy through inductive coupling between circuits of the transformer's primary and secondary coils.

As Fig. 2.3 shows, a transformer has a primary coil with  $N_1$  turns and a secondary coil with  $N_2$  turns.

An ideal transformer is the most basic transformer circuit. In an ideal transformer, it assumes that all magnetic flux generated by the primary coil links all the turns of every secondary coil. According to the Faraday's law [1], the voltages of the primary and secondary coils can be expressed by:

$$\begin{cases} V_1(t) = -N_1 \frac{d\Phi_1(t)}{dt} \\ V_2(t) = -N_2 \frac{d\Phi_2(t)}{dt} \end{cases} \quad (2.5)$$

where  $N_1$  and  $N_2$  are the turns of the primary and secondary coils. Due to the transformer is ideal, the magnetic flux  $\Phi_1(t)$  crossing the primary side exactly equals to the magnetic flux  $\Phi_2(t)$  crossing the secondary side.

$$\Phi_1(t) = \Phi_2(t) \quad (2.6)$$

Consequently, the voltage equation for the ideal transformer is given by:

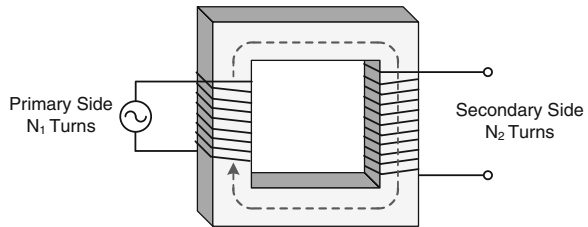
$$V_2(t) = \frac{N_2}{N_1} V_1(t) \quad (2.7)$$

Apparently, the voltages rate is only proportional to the rate of turns between the primary and the secondary sides.

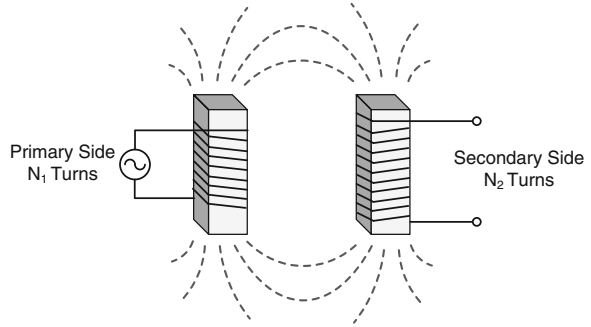
In the real wireless power transfer, the transfer medium is air or human tissue. Therefore, magnetic flux loss exists during the transfer. We next analyze imperfect transformers as shown in the Fig. 2.4. Since the primary and the secondary sides have no physical contact, it can be used in the wireless power transfer.

For imperfect transformers, the concepts of the self-inductance, mutual-inductance, and coupling factor are needed for analysis. The self-inductance  $L$  of

**Fig. 2.3** Ideal transformer



**Fig. 2.4** Non-ideal transformer



the coil is defined by dividing the total generated magnetic flux by the current in the coil as follows:

$$L = \frac{N\Phi}{I} \quad (2.8)$$

where  $N$  is the coil's turns,  $I$  is the current in the coil, and  $\Phi$  is the magnetic flux crossing each turn of the coil. By substituting the above equation to the Faraday's law [1], the following equation is given as:

$$V = L \frac{dI}{dt} \quad (2.9)$$

where  $V$  is the induced voltage in the coil,  $L$  is the self-inductance of the coil,  $I$  is the time-vary current in the coil. Suppose there is another coil in space and the magnetic field generated by the first coil crosses the second coil. Accordingly, the mutual inductance is defined by the following equations:

$$\begin{cases} M_{21} = \frac{N_2 \Phi_{21}}{I_1} \\ M_{12} = \frac{N_1 \Phi_{12}}{I_2} \end{cases} \quad (2.10)$$

where  $\Phi_{21}$  is the magnetic flux generated by the first coil and crossing the second coil, and the  $\Phi_{12}$  the magnetic flux generated by the second coil and crossing the first coil. The following equation can be proved:

$$M = M_{21} = M_{12} \quad (2.11)$$

The coupling factor  $k$  can be defined by the self and the mutual inductances as the following equation. It describes the coupling strength between the two coils.

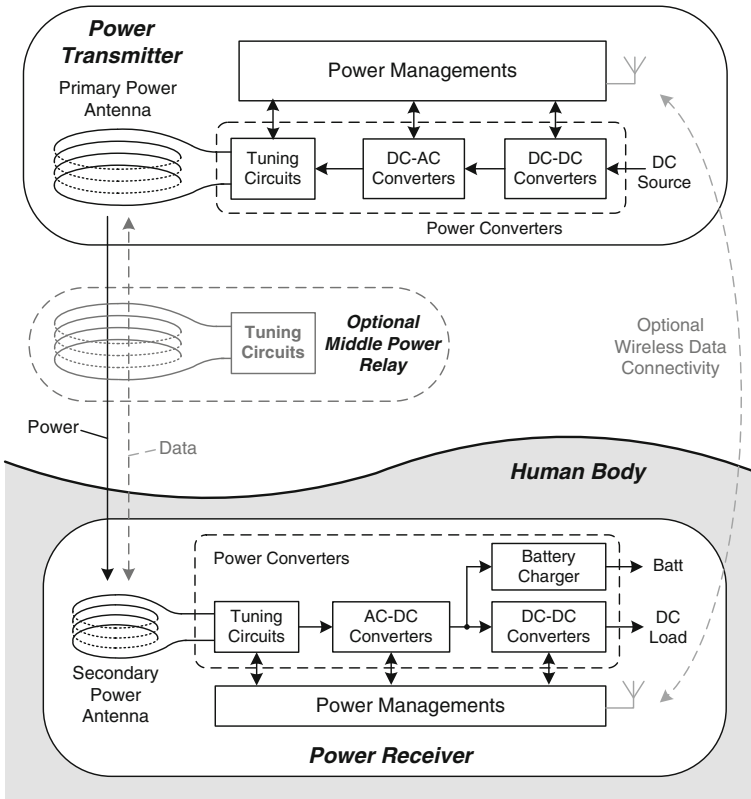
$$M = k\sqrt{L_1 L_2} \quad (2.12)$$

## 2.2 System Modeling and Components

In this section, a systematic model for the wireless power transfer for biomedical applications is to be proposed. Three types of the system components are to be introduced.

### 2.2.1 System Modeling

A wireless power transfer system for the biomedical applications is usually composed of a power transmitter outside of the human body and a power receiver inside of the body or patched on the human skin. Some complex wireless power transfer systems may employ a middle power relay as the third parts to help delivering power to farer place. Figure 2.5 shows the proposed model with a power transmitter, a power receiver, and a middle power relay.



**Fig. 2.5** A model of a wireless power transfer system for biomedical microsystems

### 1. *Power Transmitter:*

The basic function of the power transmitter is to emit wireless power into space. Further functions may include regulating the transferred power level to ensure that recovered power is stable, adaptively changing the operating frequency so that the coupling efficiency is optimized, smartly stopping the transfer when the recharging is over, and so on. The transmitter can be worn on human body, or placed in a room as a location fixed equipment.

Figure 2.5 shows a typical wireless power transmitter. The transmitter is composed of a primary power antenna [3–7], a corresponding tuning circuit [8], a DC–AC converter [9–11], a DC–DC converter [12, 13], and a power management circuit [14]. The DC energy source of the transmitter can be a group of batteries or a city power adapter. The DC–DC converter is responsible to convert the DC energy source to another designed DC voltage for the DC–AC converters and the power management circuits. The DC–DC converter can be fulfilled by linear regulators [15] or switch-mode DC–DC converters [13]. The DC–AC converter in the Fig. 2.5 is the core of the wireless power transmitter. It converts DC energy to AC energy at a specified operating frequency. The DC–AC converter is also called the power inverter [9–11]. The power efficiency of the transmitting side is essentially decided by the efficiency of the inverter. Tuning circuit is necessary to be adopted to allow the antenna to resonant at the designed operating frequency. The power management circuit is used to control the whole transmitter. Typical task includes adjusting the operating frequency and the transferred power level. It may also have wireless data connectivity with the power receiver. The data connectivity can be used to send command to the receiver. It can be also designed to feedback power information from the receiver to the transmitter, so a close-loop power control can be set up.

### 2. *Optional Middle Power Relay:*

The function of the middle power relay is to resonate at the operating frequency and help to deliver wireless power to farer place. The middle power relay is not a necessary part. It is usually adopted when the power transmitter is not placed near the human body but positioned over a distance from the human body. In this case, the middle power relay worn on the human can be very useful to help the transfer. Typical middle power relays are realized by the LC resonators [16] or the helical antennas [17].

### 3. *Power Receiver:*

The function of the receiver is to receive the wireless power and provide stable energy to the load or charge the energy into a battery. Further functions of the receiver may include feeding back power information to transmitter so that the transfer power can be regulated, smartly changing the power consumption of the load so that it can adapt to the recovered power, and so on. The receiver may

be implanted into the human body, swallowed into the digestive track, or patched on the skin.

As Fig. 2.5 shows, the receiver is composed of a secondary power antenna, a corresponding tuning circuit, an AC–DC converter [18–21], a DC–DC converter [13], a battery charger [22–25], and a power management unit [14]. The tuning circuit makes sure the secondary antenna resonate at the operating frequency. The AC–DC converter converts the AC energy back to DC power. The AC–DC converter can be also called rectifier [18–21], which maybe is a full-wave rectifier [26], a half-wave rectifier [27], a switch-mode rectifier [20], or any other type of rectifiers. The rectifier is definitely the most important circuit in the power receiver. The power receiving efficiency is essentially determined by the rectification efficiency. Because the output of the rectifier is unregulated DC power, DC–DC converter is adopted in the receiving side to provide regulated and stable DC power for the load. The load is actually an application circuit or a rechargeable battery. The power management circuit in the Fig. 2.5 is employed to control the whole receiver. It may be used to monitor the recovered power level and send the power information back to the transmitter using wireless data connectivity.

According to the introduction above, the wireless power transfer for biomedical applications is composed of many modules. Actually, these modules can be classified into three types of system components. They are the power antennas, the power converters, and the power management circuits. Next, we give a brief introduction to the three components. The three components correspond to Chaps. 3, 4, and 5 respectively.

### 2.2.2 Component Type I: Power Antennas

The power antennas are widely adopted in the wireless power transmitters, receivers, and middle power relays. As shown in the Fig. 2.5, the power antenna in the transmitter excite near-field magnetic field in space. It converts electrical power in circuit to magnetic power in space. The antenna in the middle power relay resonates with the magnetic field, so the magnetic flux density nearby is enhanced. At last, the power antenna in the receiver produces induced voltage and current, which recovers the magnetic power back to the electrical power in circuit.

The power antennas actually play an essential role in the wireless power transfer. The total power transfer efficiency is determined by two efficiencies. One is the coupling efficiency in space. The other is power conversion efficiency in circuits. Generally speaking, the coupling efficiency in the space is much lower than the power conversion efficiency in the circuit. Besides the efficiency, there are other considerations for the power antennas, for example the power level, the size limitation, the quality factor, the medium loss, and so on. Accordingly, the design of power antennas is a quite a comprehensive task.

Typically, the power antennas are loop coils. Tuning capacitor would be adopted to form a LC resonant circuit. At present, many biomedical microsystems are



employing this type of power antennas for its decent coupling performance over short distance [4, 19, 20]. To further improve the coupling performance, kinds of new antenna techniques and transfer structure were proposed in recent years. Some of these antennas emphasize to enhance the power efficiency [7, 28], while some emphasize to reduce antenna size [8], realize full directionality [29], and so on.

The details of the power antennas are to be introduced in Chap. 3.

### ***2.2.3 Component Type II: Power Converters***

Both the wireless power transmitter and the receiver need power converters. As shown in the Fig. 2.5, the power converters in the transmitter include at least a DC–DC converter and a DC–AC converter. At the receiving side, the power converters include at least an AC–DC converter and a DC–DC converter. The battery recharging circuit [22–25] in the receiver is also a kind of power converter. All these converters may need other auxiliary circuits, like a Bandgap [30, 31] to provide a reference voltage, a bias circuit [32] to provide a bias current, an oscillator [33, 34] to provide a clock, and so on.

The power converters are significantly important in the system. Researchers try to design power converters with higher power conversion efficiency. For example, conventional rectifiers use diodes or Schottky diodes to recover AC power. However, the dropout voltages of diodes or Schottky diodes are too large for low-voltage low-power applications. Accordingly, many efficiency-enhanced rectifiers are proposed for the wireless power transfers, like the comparator based rectifier [20, 35–37], the rectifier with ZCP prediction [38], and so on. There are so many other state-of-the-art power converters.

The details of the power converters are to be described in Chap. 4.

### ***2.2.4 Component Type III: Power Management***

For relatively simple biomedical applications, the power management circuit may not be adopted. For those complex applications, both the power transmitter and the receiver may employ power management. The power management is a relatively vague concept. It may have many functions and it can be viewed as a central controller for the transmitter or the receiver. As shown in the Fig. 2.5, the power management circuits have connections to all power converters. Typically functions include determining the operating frequency, determining the transmitting power level, adjusting the power consumption of the load, and so on. The power management may also act like a power monitor in the receiver. When the voltage, current, or temperature is out of normal range, the power management could trigger an alarm. It can also be used for other special functions.

The details of the power management are to be illustrated in Chap. 5.

## 2.3 Design Challenges

As introduced above, the wireless power transfer is a promising way to offer energy for biomedical microsystems. However, the transfer still suffers from some problems including the unsatisfied power efficiency, the limited transfer distance, the unpredictable reliability, the thermal issues and other problems. Therefore, this section investigates in-depth the design challenges of the wireless power transfer in biomedical applications. First, we introduce the overall systematic design challenges. Then, both the design challenges at the transmitter and the receiver sides are to be discussed respectively.

### 2.3.1 Systematic Challenges

Generally speaking, there are five systematic design challenges. They are the transmitter's and receiver's sizes, the transfer distance, the transfer medium, the lateral and angle misalignments, and the required power level.

- Systematic Challenge I: Transmitter's and Receiver's Sizes

In typical biomedical applications, the wireless power transmitter is placed out of human body and the power receiver is located inside of the body or patched on the skin. Accordingly, the receivers usually have much smaller size than the transmitters. For example, the size of a hearing aid [39, 40] is usually only several millimeters, and the size of a pacemaker [41, 42] is limited to several centimeters. On the contrary, because the power transmitter is outside of human body, their size can be much larger. At present, one of the developing trends of the biomedical microsystems is miniaturization. It's a huge challenge for the designers. The decrease of the size would degrade the antenna's quality factor, decrease the coupling factors between the transmitter and the receiver, and force to increase the operating frequency and the energy loss in human tissue.

- Systematic Challenge II: Transfer distance

One of the most critical parameters in the wireless power transfer is the transfer distance. The ratio of the transfer distance and the transmitter's and the receiver's sizes is the key parameter. When the antenna's size is very small and the transfer distance is much longer, the coupling factor would become very small. Transferring power efficiently would become a huge challenge. For instance, the endoscopic capsule [43] is in diameter of around 1 cm, and the required transfer distance is in range from 1 to 10 cm. Consequently, the power transfer efficiency is only 0.3 % [43] in the worst case.

- Systematic Challenge III: Transfer medium

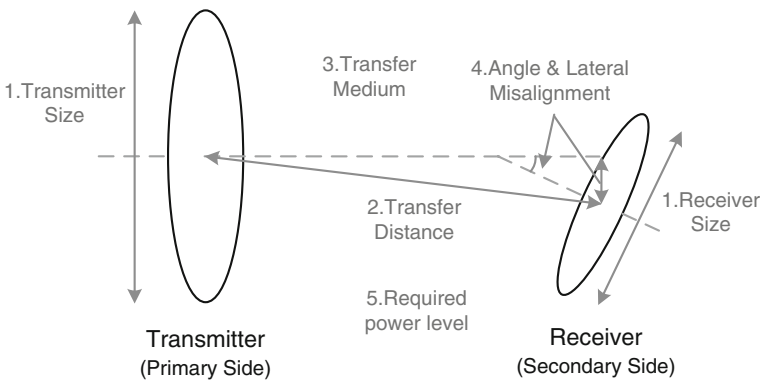
The transfer medium significantly affects the performance of the wireless power transfer. Biomedical applications involve three medium types. They are the air, the human tissue, and the metals. The air has the minimum absorption of electromagnetic field. The human tissue would absorb certain electromagnetic energy according to the operating frequency and the transferred power level. The absorbed energy would cause heat or even get patients hurt. Because some implantable devices use metal shell to protect the internal circuits, the electromagnetic phenomenon of eddy effect [2] appears in the metals. Accordingly, energy is wasted in the metal shell. The antenna in the shell might only receive little energy.

- Systematic Challenge IV: Lateral and angle misalignments

During the use of the wireless power transfer system, there might be lateral and angle misalignments between the power transmitter and the receiver. The definitions of the lateral and angle misalignments are depicted in the Fig. 2.6. The two misalignments cause the degradation of the coupling factor between the transmitter and the receiver. As a result, the transfer efficiency decreases. Making sure the transfer system could work under certain misalignments is very necessary. For some implantable devices like the endoscopy capsule [43], it randomly rotates in the digestive track. Accordingly, special antennas and circuits should be considered.

- Systematic Challenge V: Required Power Level

The required power level is the last systematic design challenge. Satisfying the power demand of the power receiver is the core task of the transmitter. Implantable microsystems like the hearing aid [41, 42], the signal recorder [20], and the nerve stimulator [44] consume tiny energy, typically less than 10 mA. For those low-power applications, how to increase the power transfer efficiency is a design



**Fig. 2.6** Overall transfer design challenges

challenge because the power efficiency typically decreases when the power level decreases. To the contrary, for those high-power applications, like the artificial heart [45], how to avoid thermal issue at the transmitter side and how to keep the electromagnetic energy absorbed by patients as low as possible are the key challenges.

### 2.3.2 Challenges at the Transmitter Side

To design a successful wireless power transfer system, it is necessary to understand all detailed challenges at the both transmitter and receiver sides. We firstly investigate the design challenges in the transmitter side. Although some applications have special design challenges, there are five common challenges for the transmitter. They are the peak transfer power, the power dynamic range, the power conversion efficiency, the transmitter size and weight, and the safety issue. Figure 2.7 shows the challenges.

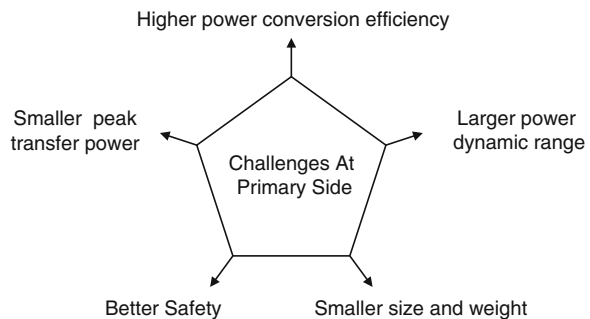
#### Transmitter challenge I: Peak transfer power

The responsibility of the wireless power transmitter is to satisfy the power demand of the receiver at anytime. For example, a typical wirelessly powered endoscopic capsule consumes the power of 10–30 mW [43]. In the worst case, the transfer efficiency is only around 0.3 % [43]. Consequently, the power transfer is required to offer the peak power of at least 10 W. Although it's quite difficult to know the exact power transfer efficiency before the antennas and circuits are designed, it's still very necessary to predict the peak power for the transmitter before detail designs. It helps to estimate the transmitters' thermal and safety issues.

#### Transmitter challenge II: Power dynamic range

In some wireless power transfers, the coupling efficiency may change in a wide range. For example, the highest power efficiency of the wirelessly powered capsule endoscopy reaches 5.2 % [43]. However, in the worst case, the efficiency falls to merely 0.3 % [43]. In order to save power and minimize the harmful electromagnetic radiation for the patients, some systems dynamically adjust the

**Fig. 2.7** The five design challenges in the transmitter



transmitting power to adapt to the changing coupling efficiency or the changing power consumption of the receiver. As a result, the power transmitter needs to adjust the transferred power level in a broad dynamic range. It's one of the design challenges.

#### Transmitter challenge III: Peak Conversion Efficiency

The power conversion efficiency of the transmitter is dominant by the DC-AC converters, which are typical realized by Class D or Class E power amplifiers. The Class D amplifier is more commonly used since it's insensitivity to the change of output power or the operating frequency. In the transmitter, the power conversion efficiency is significantly affected by the operating frequency. The efficiency goes down when the frequency increases. Designers have to face the design challenge of trading off between the high operating frequency and the high conversion efficiency. Actually, the selection of the operating frequency has to consider much more factors. The factors include at least the antenna's size, and the specific absorption rate [46], and the power conversion efficiency at the receiver side. It makes the selection of the operating frequency much more complicated. Once the frequency is determined, designers may take the advantage of circuit techniques to improve the power conversion efficiency.

#### Transmitter challenge IV: Transmitter's Size and Weight

Although the size and weight limitation on the power transmitter is not as critical as the limitation on the power receiver, some applications still have size or weight requirement on the transmitter. For example, the conventional power transmitter for the batteryless capsule endoscopy connects to the city power by using long power cables, which makes patient's movement very inconvenient. To avoid the power cable and allow patients to walk freely, the new transmitter is supposed to use portable batteries as the power source. For the patient's convenience, the transmitter is supposed to be as small and light as possible.

#### Transmitter challenge V: Better Safety

For the transmitter, two safety issues have to be concerned. One is the thermal problem. The other is the electromagnetic safety issue.

Because the power level at the transmitter side is much higher than the receiver side, the transmitter produces much more heat. The heat is mainly generated by the power transistors in the DC-AC converter and by the conductor resistance of the transmitting antenna. When the power level or the operating frequency increases, the thermal problem becomes serious. Heat sinks and fans can be used. For those high power applications, like the artificial heart [45], the thermal issue at the receiver side should be also concerned.

The other safety issue is the harmful electromagnetic radiation. First, the radiation may interference the normal work of other implanted electronics like the pacemaker [41, 42]. Second, the human expose to electromagnetic radiation may cause risks and hazards. The exposure to electromagnetic fields at frequency above about 100 kHz can lead to significant absorption of energy and temperature

increases [47]. Although there are still no authoritative standard dedicated for the electromagnetic radiation caused by wireless power transfer for medical usages, designers could take two famous international electromagnetic standards as references. One is the IEEE Standard C95.1 [48]. The other is the ICNIRP Guidelines [47]. A lower operating frequency may be considered to reduce the heat and the radiation.

Summarizing the above concerns at the transmitter side, the key question is how to build a wireless power transmitter that has large peak power, wide power dynamic range, high power conversion efficiency, small size and light weight, little heat, and little radiation for the patients.

2.3.3 Challenges at the Receiver Side

At the secondary side, there are also five challenges. They are the power demand, the supply voltage, the power conversion efficiency, the power reliability, and the receiver size. Figure 2.8 shows the challenges.

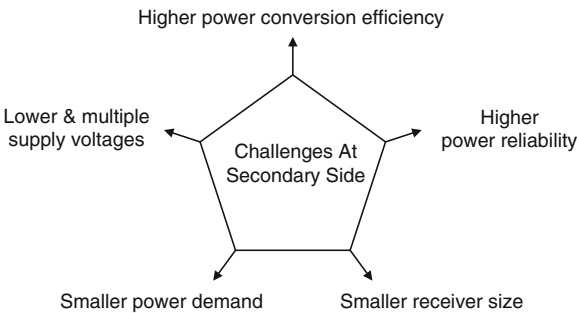
Receiver challenge I: Power Demand

The power demand of the wireless power receivers differs from applications. For example, the nerve stimulator and the capsule endoscopy usually consume the power of 10–30 mW [43, 44]. However, the wirelessly powered artificial heart consumes a lot more power, like up to 15 W [45]. How to meet the peak power demand of the application circuits is always the first concern in the wireless power receiver’s design.

Receiver challenge II: Supply voltages

The load of the power receiver is actually applications circuits. They usually have specific requirement on the supply power voltage. For example, if the load is a digital circuit, it may require a power supply voltage like 1.8 or 3.3 V. Because the AC-DC converter in the receiver outputs unregulated DC voltage, DC–DC converters have to be used to generate well-regulated voltage for the loads. A special problem is that the rectified DC voltage varies with the transfer distance and the

Fig. 2.8 The five design challenges in the receiver



relative orientation between the transmitter and the receiver. As a consequence, the rectifier output is likely lower or higher than the required voltages by the load. Special circuit techniques are needed to solve this problem.

#### Receiver challenge III: Power conversion efficiency

The power conversion efficiency is definitely one of the most important concerns in the design of the wireless power receiver. According to existing wireless power receiver designs [8, 18–21, 38], the power conversion efficiency unavoidably goes down when the operating frequency increases or the transfer power decreases. As a result, it is a big challenge to design a low-power but high-efficiency power receiver, especially when the operating frequency is very high. For example, the power efficiency of a rectifier working at 900 MHz with output power of only 140  $\mu$ W is no more than 65 % [8]. To the contrary, to transfer large power at a low operating frequency can be much more energy-efficient, like 93.6 % [38]. Since the power level is determined by the load, the designer's only choice is the operating frequency.

#### Receiver challenge IV: Power reliability

Comparing to a power cable, the wireless power system is much more unstable. The unstable factors arise because the separate distance between the transmitter and the receiver may suddenly changes, the relative orientation between the transmitter and the receivers may also alters, and the magnetic field may be affected by other unexpected devices. Consequently, the reliability of the wireless power receiver becomes unpredictable for the load. Designers should clarify all unstable factors in systems. For example, how can we ensure the application circuit could successfully start up when the wireless power is transmitted at the very beginning? What if the receiver suddenly rotates? If the power recovered by the receiver falls slowly, what is the response of the application circuits? Would it trigger any error operation? It is a challenge to answer these questions. Power management may be adopted for the promotion of the power reliability.

#### Receiver challenge V: Receiver's Size

Receiver's size is another problem we have to consider, especially for those ultra small size implantable biomedical devices. For example, researchers have pronounced the mm-sized wirelessly powered system [8]. The receiver's size is determined by the receiving antenna's size and the circuit's size. As to the antenna, it can be significantly decreased by using higher operating frequency. However, as mentioned, the power conversion efficiency goes down when the operating frequency increases. As to the circuit, the circuit's size is actually decided by the passive components employed in the circuits. For example, rectifiers need decoupling capacitors at the output terminal. Linear regulators require decoupling capacitors at input and output terminals. DC–DC converters need off-chip inductors. In most of time, the sizes of these passive components are too large to be integrated into microchip. Consequently, they are the main contributions to the circuit's size. How to design a small size receiver is a challenge.

Summarizing the above concerns at the receiver side, the key question is how to build a wireless power receiver that has wide input voltage, small size, high power reliability, and high power conversion efficiency in the low-power high-frequency condition.

## 2.4 Electromagnetic Safety

Comparing to regular cable power systems, the wireless power transfer suffers from unique safety issues. One of the concerns is the risk caused by the exposure to the electromagnetic radiation. Exposure to low-frequency electric and magnetic fields normally results in negligible energy absorption and no measurable temperature rise in the body [47]. However, exposure to electromagnetic fields at frequency above about 100 kHz can lead to significant absorption of energy and temperature increases [47]. Accordingly, understanding and considering the radiation safety issues are very necessary. In this section, we firstly introduce two international electromagnetic safety standards. Secondly, we present several clinical experiences as references for the systematic design.

### 2.4.1 Safety Standards

Although there are still no authoritative international standard dedicated for the wirelessly power transfer for biomedical systems, there are two international electromagnetic standards for public safety that we could take as references. One is the “IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Field” [48] from the Institute of Electrical and Electronics Engineers (IEEE). The other is the “ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, magnetic, and Electromagnetic Fields” [47] from the International Commission on Non-Ionizing Radiation Protection (ICRIRP).

1. IEEE Standard [48]: The Institute of Electrical and Electronics Engineers is founded in 1884 and is the world’s largest technical professional society. The international committee on Electromagnetic Safety (ICES) develops standards for the safe use of electromagnetic energy. The ICES is sponsored by IEEE. In 1960, IEEE and U.S. Navy co-sponsored the development of the first US national RF standard (C95.1-1966). Later, ICES published a group of standards including C95.6-2002 “IEEE Stand for Safety Levels with Reset to Human Exposure to Electromagnetic Field, 0–3 kHz” and C95.1 “Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz–300 GHz”. Due to most wireless power transfers work at the operating frequency in range from 100 K to 50 MHz, we introduce the standard of IEEE C95.1 but not the C95.6.



2. ICRIRP Guideline [47]: In 1974, the International Radiation Protection Association (IRPA) formed a working group on non-ionizing radiation. At the IRPA congress in Paris in 1977, this working group became the International Non-Ionizing Radiation Committee (INIRC). In cooperation with Environmental Health Division of the World Health Organization (WHO), the INIRC developed a number of health criteria documents. In 1992, a new independent scientific organization,—the International Commission on Non-Ionizing Radiation Protection (ICNIRP) was established as a successor to the INIRC. The functions of the Commission are to investigate the hazards that may be associated with different forms of NIR, develop international guidelines on NIR exposure limits, and deal with all aspects of NIR protection. Its publication “ICRIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields” is right such a document.

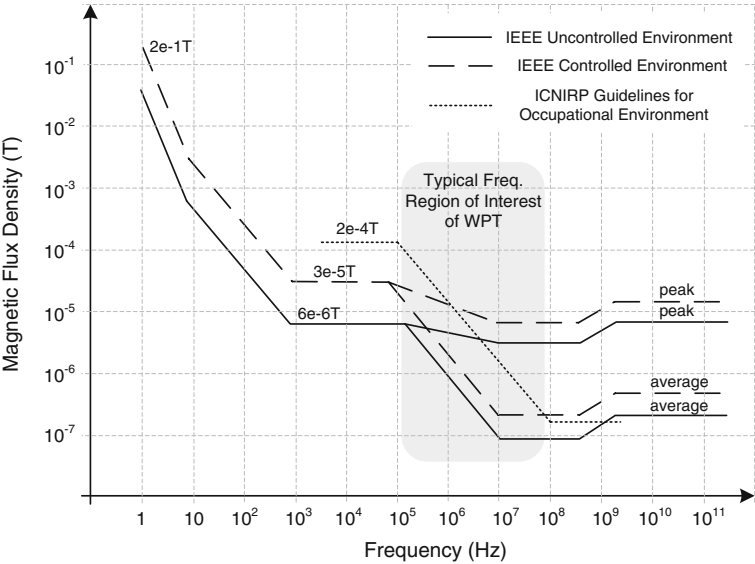
Both the IEEE standard and the ICNIRP guideline give the maximum permissible exposure. The IEEE standard covers the frequency in range from 1 Hz to 300 GHz. The ICNIRP guideline applies to frequency in range from 3 kHz to 300 GHz. Both of them cover the typical operating frequency range in the wireless power transfer, which is from 0.1 to 100 MHz. The given permissible exposure is ruled the maximum magnetic flux density and the maximum electrical field strength.

(a) Maximum magnetic flux density:

A magnetic field can be specified in two ways, the magnetic flux density  $B$  expressed in Tesla (T), or the magnetic field strength  $H$  expressed in ampere per meter (A/m). Figure 2.9 shows the maximum permissible exposure of time-varying magnetic field expressed in Tesla (T) ruled by the two documents.

As Fig. 2.9 shows, the maximum permissible exposure magnetic field decreases when the operating frequency increases. It is noted that there are two environments in each documents. In the ICNIRP guideline, the two environments are called the “occupational” and the “general public”. In the IEEE standard, the two environments are the “controlled” and the “uncontrolled”. Both the occupational and the controlled environments mean locations where there is exposure that is incurred by persons who are aware of the potential for exposure as a concomitant as a concomitant of employment. Both the general public and the uncontrolled mean where there is the exposure of individuals who have no knowledge or control of their exposure. Accordingly, the maximum permissible expose in the occupational and controlled environments are much higher than the general public and the uncontrolled environments. The detail limits in the two documents in the interesting frequency range for wireless power transfer are summarized in the following Table 2.1.

According to the definitions of the “occupational” or the “controlled” environments, we suggest the maximum permissible exposure caused by the wireless power transfer for biomedical purposes could be larger than the current



**Fig. 2.9** Maximum permissible exposure of time-varying magnetic field suggested by the IEEE standard and the ICNIRP guideline

**Table 2.1** Maximum permissible exposure of time-varying magnetic field suggested by the IEEE standard and the ICNIRP guideline

Frequency range $f$ in MHz	IEEE controlled environment ( $\mu\text{T}$ )	IEEE uncontrolled environment ( $\mu\text{T}$ )	ICNIRP occupational environment ( $\mu\text{T}$ )	ICNIRP general public environment ( $\mu\text{T}$ )
0.1–0.15	$20.4/f$	$20.4/f$	$2.0/f$	6.25
0.15–1				$0.92/f$
1–10				
10–30			0.2	0.092
30–100		$199/(f^{1.668})$		

*Note* The expose values in terms of magnetic field strengths are the mean values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body

permissible exposure for “occupational” environments. It is because the two documents deal with generally healthy people. But, the wireless power transfer for biomedical applications deals with people in risk of diseases or even death. The wirelessly powered systems may save the patient’s life.

Can the wireless power transfer comply with the permissible magnetic flux density? The magnetic field generated by typical low-power transfers like the percutaneous transfer [8] could comply with the documents. However, for those high-power systems that transfer dozens of watts, the magnetic flux density may reach 1.25–10  $\mu\text{T}$  [3] when the limitation is about 2  $\mu\text{T}$  at 10 MHz in the IEEE

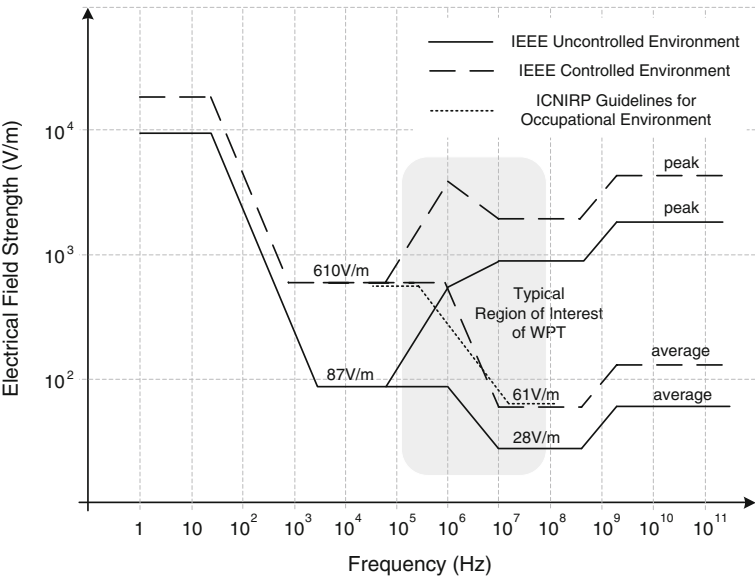
standard. As a reference, the Magnetic Resonance Imaging (MRI) produces a much larger magnetic flux density in range from 500,000 to 1500,000  $\mu\text{T}$  in strength [49].

(b) Maximum Electric Field Strength:

Not only the magnetic field strength is ruled, but also the maximum electric field strength is limited. An electric field,  $E$ , exerts forces on an electric charge and is expressed in volt per meter (V/m). The Fig. 2.10 shows the maximum permissible exposure of time-varying electric field expressed in volt per meter (V/m) regulated by the two documents. It's clear that the maximum permissible exposure electric field decreases when the operating frequency increases. The detail limits in the two documents in the frequency range for the wireless power transfer are summarized in the Table 2.2.

Can the wireless power transfer comply with the permissible electric field? Actually, for those high-power wireless power transfers, they may easily exceed the limitation. For instance, to transfer 60 W over 2 m, previous research produced an electrical field in range from 210 V/m to 1.4 kV/m in the frequency of 9.9 MHz [3]. The suggested maximal electric field is only 61 V/m for the occupational environment in the ICNIRP guideline.

For both electric and magnetic fields, the maximum peak permissible value and the maximum average permissible value are different. The average values are



**Fig. 2.10** Maximum permissible exposure of time-varying electrical field suggested by the IEEE standard and the ICNIRP guideline

**Table 2.2** Maximum permissible exposure of time-varying electric field suggested by the IEEE Standard and the ICNIRP guideline

Frequency range f in MHz	IEEE controlled environment (V/m)	IEEE uncontrolled environment (V/m)	ICNIRP occupational environment (V/m)	ICNIRP general public environment (V/m)
0.1–1.34	614	614	610	87
1.34–3		823/f	610/f	87/f <sup>0.5</sup>
3–10	1842/f			
10–30		27.5	61	28
30–100	61.4			

*Note* The expose values in terms of electric field strengths are the mean values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body

usually measured based on any 6-min period [47], and the peak value is suggested about 20 times of the average value.

2.4.2 Clinical Experiences

Both the IEEE standard and the ICNIRP guideline are based on clinical literatures and experiences on the biological effects and potential health effects of electromagnetic fields. Learning these clinical literatures and experiences helps us understanding the effects caused by the wireless power transfer. Meanwhile, because some wireless power transfers for the biomedical microsystems may exceed the suggested maximum permissible expose in two above documents, it is necessary for us to know the consequence of over-exposing. According to the ICNIRP guidelines [47], there are following clinical experiences.

(a) Reproductive and Cancer Studies:

According to the statement of ICNIRP guidelines [47], only a limited number of studies have been conducted on reproductive effects and cancer risks in individuals exposed to electromagnetic radiation. For example, two extensive studies on woman treated with microwave diathermy to relieve the pain of uterine contractions during labor found no evidence for adverse effects on the fetus [50]. In the studies of female plastic welders and physiotherapists working with shortwave diathermy device, there were no statistically significant effects on rate of abortion or fetal malformation [51]. Overall, the studies on reproductive outcomes suffer from poor assessment of exposure and small numbers of subjects. It is difficult to draw firm conclusions on reproductive risk without more assessment [47]. The cancer studies also have little quantitative assessment. Overall speaking, the results of the small number of reproductive and cancer studies are inconclusive.

**Table 2.3** A summary of existing experimented exposes in terms of SAR and their corresponding clinical adverse effects

SAR (W/kg)	Experiment subject	Corresponding effects
100–140	Rabbit	Cataracts in eye [54]
7–15	Mice	Slight heating [56]
4	Volunteer	Increased body core temperature of less than 1 °C [55]
1–3	Rat and Monkey	Decreased task performance [57, 58]

*Note* The safety SAR limited by ICNIRP is 0.4 W/kg, which is much lower than the values of the SAR in these experiments

(b) Volunteer and Animal Studies:

According to previous studies [52], as the frequency increases from 100 kHz to 10 MHz, the dominant effect of exposure to a high-intensity electromagnetic field changes from nerve and muscle stimulation to heating. At 100 kHz the primary sensation was one of nerve tingling, while at 10 MHz it was one of warmth on the skin. In this frequency range, therefore, basic health protection criteria should be such as to avoid stimulation of excitable tissues and heating effects. For example, there have been several studies of thermoregulatory response of testing volunteers exposed to electric magnetic field in magnetic resonance imaging systems [47]. In general, these have demonstrated that exposure for up to 30 min, under conditions in which whole-body Specific Energy Absorption (SAR) was less than 4 W/kg, caused an increase in the body core temperature of less than 1 °C [47]. There are numerous reports on the behavioral and physiological response of laboratory animals, including rodents, dogs, and non-human primates [47]. Previous studies [53] shows exposure of laboratory animals to electric magnetic field producing absorption in excess of approximately 4 W/kg has revealed a characteristic pattern of thermoregulatory response in which body temperature initially rises and then stabilizes following the activation of thermoregulatory mechanisms. Meanwhile, decreased task performance by rats and monkeys has been observed at SAR values in range 1–3 W/kg. Microwave exposure of 2–3 h duration has produced cataracts in rabbits’ eye at SAR values from 100 to 140 W/kg, which produced lenticular temperature of 41–43 °C [54].

(c) Summary and Conclusions:

We summarized the existing experience in Table 2.3. It sums up the clinical experiences when the SAR is increased from 1 to 140 W/kg.

To conclude, the exposure for approximately 30 min to electric magnetic field producing a whole-body SAR between 1 and 4 W/Kg results in body temperature increase of less than 1 °C [55]. Even the most sensitive tissues can handle the exposure greater than 4 W/kg [47], which can be used as the safety threshold for wireless power transfer systems for biomedical microsystems.

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