Chapter 10
Wireless Communications and Powering of Implants

Abstract Communication and powering facilities augment the capabilities of the implants by providing remote monitoring of therapy and charging of implant batteries to avoid replacement by surgery. At short distances in the range of a few centimeters, inductive links are used. The transference of data and power pose conflicting requirements. These requirements are sometimes fulfilled by using separate coils. The cost is a larger footprint and increased electromagnetic interference. Load-shift keying (LSK) technique is applied for uplink data transmission. Downlink data transmission is implemented by one of the three techniques: binary amplitude-shift keying (BASK), binary frequency-shift keying (BFSK), or binary phase-shift keying (BPSK), with BASK representing the plainest approach. Long-distance telemetry >2 m is restricted to the agreed 402–405 MHz band for therapeutic implants or the industrial, technical, and medicinal/curative radio bands: 902–928 MHz, 2.4–2.4835 GHz, and 5.725–5.875 GHz frequency bands with transmission range up to 10 m.

Keywords Inductive charging • Resonance charging • Radio charging • Biotelemetry • ASK • FSK • PSK • LSK • AC-LSK • Adaptive LSK • PPSK • PHM

10.1 Introduction

After implantation of the electronic device in the human body, two basic concerns are: (1) to feed power to the implant for its uninterrupted operation, and (2) to maintain unidirectional/bidirectional exchange of data amidst the implant and the outside world. Power- and information-carrying signals often pose oppositely directed requirements. A rigorous study of power and information transmission is therefore useful to appreciate their roles. It also helps to optimize their respective operations, thus improving the performance of the medical implant as a whole.

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Table 10.1 Methods of powering implants

Sl. No.	Through percutaneous leads	Wireless charging
1.	Disagreeable and embarrassing to the patient	More acceptable and convenient to the patient
2.	Totally restricts patient's movement	Restricts movement within limited area
3.	Chances of infection	No such chances
4..	More energy efficient	Less efficient
5.	Less resistive heating	Increased resistive heating
6.	Faster charging	Slower charging due to lower efficiency
7.	Less complex and less costly	More complex and expensive as it requires drive electronics and coils in both external part and implant

10.2 Powering the Implant

Powering of the implant is the process of supplying energy to the implant. By receiving energy, it can function properly in the desired manner. As implants cannot derive energy from body heat or nutrients in the blood, they must be supplied energy from a source either outside the body or placed internally (Table 10.1).

10.2.1 Through Percutaneous Leads

The easiest conceivable, though most inconvenient, way to power the implant is by connecting a wire passing from the external device percutaneously (across the skin of the patient) to the implant. It impairs the mobility and freedom of the patient. The tethered patient feels uncomfortable and tied up due to restrictions on movements. Moreover, there is risk of infection at the site where the wire is inserted. So, breaching the skin is unsafe for the patient as well as the implant [1]. On these grounds, it is long given up except for temporary testing.

10.2.2 Wireless Charging

Many applications require more ampere-hours than a single battery can provide. Using a larger number of batteries in the implant is not possible. There are two underlying reasons. Firstly, only a limited space is available in the implant. Secondly, extra weight unduly burdens the patient. Hence, it is an unaffordable solution and outright rejected. In place of percutaneous charging, the concept of "wireless charging" of the implant battery has gained acceptance. This charging is done by a wireless process. The wireless process is based on electromagnetic induction across the skin instead of a wire penetrating through the skin [2]. Without harming the skin, the battery can draw power from the external source. Obviously, wireless charging is less efficient. It is also slower than charging through wires because of the energy lost in the intervening medium. But wireless power transfer can provide power for indefinite periods. Also, there is no risk of infection associated with a percutaneous lead.

Wireless charging is not a new idea. In 1831, Michael Faraday discovered electromagnetic induction. He demonstrated that electromagnetic energy can propagate through space. Afterwards, in the late eighteenth century and early nineteenth century, Nikola Tesla conducted experiments on wireless transmission of power. Wireless charging is subdivided into three classes (Table 10.2): (1) inductive charging, (2) resonance charging, and (3) radio charging. Of these, only the first two are of wide interest in implantable electronics. The third class uses higher frequencies. The higher frequencies may be associated with injurious biological effects. Notwithstanding, depending on the application chosen and communication distance, several different frequencies are used in medical electronics and implantable electronics. They range from kHz to MHz range.

Table 10.2 Three types of wireless charging

Sl. No.	Inductive charging	Resonance charging	Radio charging
1.	Based on magnetic induction	Works on resonance-enhanced magnetic induction	Radio waves received through an antenna are used for the charging process
2.	Uses an induction coil in the external part to produce an electromagnetic field, which is alternating in polarity. Another induction coil is placed inside the implanted medical device. This coil draws power from the alternating electromagnetic field of the external part and transforms it into an electrical current. The current thus created charges the battery of the implant. The implant works with this battery as a source of energy	Uses an inductance-capacitance tuned circuit for resonance coupling. By doing so, the coils in the transmitter coil (located externally) and receiver coil (placed inside the implant) undergo oscillations at the resonant frequency. Through these coupled oscillations, power is transferred from the external to the internal part, wherein it is used for battery charging. This battery is the source of energy for the implant	Uses an inductance-capacitance tuned circuit for resonance coupling (like resonance charging) whereby the transmitter and receiver coils oscillate at the same frequency. The power transferred from the transmitter coil of the external part to the receiver coil of the internal part inside the implanted medical device is used for charging the battery of the implant. The charged battery feeds the implant
3.	Uses sub-radio frequency or the lower frequencies in radio-frequency band of the spectrum of electromagnetic waves	Uses sub-radio frequency or the lower frequencies in radio-frequency band of the electromagnetic wave spectrum	Uses radio-frequency waves
4.	An electrical transformer is formed by the two induction coils in proximity	Resonant-coupled transformer	Radio transmitter/receiver

(continued)

Table 10.2 (continued)

Sl. No.	Inductive charging	Resonance charging	Radio charging
5.	Less efficiency	Highest efficiency	Least efficiency
6.	Near-field effect	Near-field effect	Far-field effect
7.	Typical charging distance ~5 to 7 mm	Typical charging distance ~7 to 40 mm	Typical charging distance ~2 to 10 m
8.	Less spatial freedom. The patient cannot move around easily while charging	More spatial freedom	Largest spatial freedom
9.	Useful for shallow implants	Useful for shallow/ deeper implants	Useful for shallow/deeper implants
10.	No electromagnetic pollution	No electromagnetic pollution	Creates electromagnetic pollution
11.	Less harmful to the body	Less harmful to the body	Harmful to the body

10.3 Inductive Charging

As opposed to conductive charging using a conductor for transferring power, inductive charging represents a technique of repositioning power across a short distance wirelessly [3]. It involves the use of a pair of induction coils. One of the coils is placed in the implanted device in the human body (receiver coil). The other coil is placed in the external device located outside the body (sender coil). Commonly, solenoidal coils are used, but for systems resting over the brain, planar spiral "pancake" coils are more suitable [4].

The two induction coils, not connected to each other, serve as the loosely coupled coils of a transformer. The coil in the implanted device is the secondary or pickup coil, while that in the external device is the primary coil. When the externally located primary coil is energized by passing an alternating current through it at the appropriate frequency, an electromagnetic field is set up surrounding this coil. This field also embraces the close-lying secondary coil inside the body. Hence, it can capture a shared segment of the embracing field, which causes a current to flow through it. This current is amplified and rectified to charge the battery.

10.3.1 Frequencies Used

Inductive charging is done at frequencies below radio frequencies or in the low radio-frequency range. Radio-frequency band stretches from 3 kHz to 300 GHz. AM radio broadcasts within 535 kHz–1700 kHz and FM radio between 88 and 108 MHz. As the frequencies used for inductive charging lie in the low radio-frequency range, therefore it does not produce any electromagnetic interference in electronic devices. It is a near-field magnetic field-based system. Further, inductive charging involves magnetic field phenomena. Since magnetic fields interact weakly with living organisms, it is biologically safe.

At 125 kHz, the skin depth in titanium, the widely used housing material for implants, is 0.9 mm. Therefore, at an operating frequency of 125 kHz, the coupling is effective up to 1 mm thick titanium [5]. Typically, the distance separating the participating coils is <3 cm. The coefficient of coupling is ~0.1 to 0.3 [6]. Around 175 kHz, the bandwidth is 50 kbps and the range is 8 cm [7].

10.3.2 Coupling and Loading Variations

Depending on coil displacements, the coupling is not constant. Also, the loading power within the implant varies with stimulation data changes [8]. Coupling and loading variations may lead to excessive implant heating. The heating effect may injure the adjoining tissues. Inadequate power transmission due to coupling/loading variations may cause diminution in implant voltage or current supply. This decrease is followed by implant malfunctioning and shutdown. To take care of these variations, more power may be needed, which is a power loss. Also, power fluctuations expose the tissues unnecessarily to strong electrical and magnetic fields.

10.3.3 Design Considerations

The inductive link is basically an air-core transformer. After making a beginner's diagram for the equivalent circuit of the inductive linkage, the coil geometry, dimensions, number of turns, wire type, etc., are decided. Quality factors (Q-factors) of the coils and the coefficient of mutual induction between them are vital bounds in the design of inductive link. To enhance the coupling between the coils, planar circular coils are more favored than solenoids. As compared to class A, B, or C amplifiers, the amplifiers of class E category display comparatively higher efficiency. These are highly efficient switching power amplifiers. In these amplifiers, the transistor works as an on/off switch. The waveforms are shaped to avoid simultaneous existence of high voltages and currents in the transistor.

Realization of the ideal, theoretical 100 % efficiency is possible because of the mutual displacement between the voltage and current transitions on the time scale. At an instant at which voltage is high, the current is low. Further, at a low voltage, current becomes high. Thus the voltage and current are never high or low at the same instant. This non-overlap of voltage and current in time or their nonsimultaneous acquisition of maximum or minimum values together helps to decrease the power dissipation. Power dissipation is minimized specially during the switching changes.

10.3.4 Applications

This method is widely practiced in medical implants because interaction between the two coils can take place through biological tissues like fat, muscle, bone, or blood. Besides implantable devices, many commonly used electrical appliances such as electrical toothbrushes and mobile phones avail of inductive charging method.

10.4 Resonance Charging

This method involves resonance coupling of coils. The two coils, sending coil connected to the power source and the receiving coil in the implant, are tuned to the same resonance frequency. This tuning enables energy transfer from the former to the latter at small distances of several inches or more. The power is not picked up by neighboring objects unless they are tuned to the same frequency. In comparison to conventional magnetic charging, resonance charging allows higher charge transfer rates. Additionally, resonance charging allows more flexibility in the charger location or configuration outside the body. To give an example, the charger for an eye implant can be mounted on the spectacles. The charger for the ear implant can be placed below the pillow. Also, the charging can be made more effective on an implant placed deeper inside the body.

10.5 Radio Charging

10.5.1 Similarity to Radio Transmission and Reception

Similar to a radio transmitter, in this method a radio source sends radio waves at 915 MHz. The waves are captured by the receiver in the implanted device. Thereafter, they are demodulated to recover the transmitted signal and charge the battery after suitable processing. Due to the weaker capturing rate, low power devices within a range of 10 m from the transmitter can use this facility for battery charging. In the 402–405 MHz band, the bandwidth is 250 Kbps and read range is 2–5 m [7]. But the method spreads electromagnetic pollution.

10.5.2 Safety Limits

According to human safety standards, the power transmitted to the body must be less than 10 mW/cm^2. Hence, there are restrictions on the carrier frequency to transfer power safely through the living tissue. If the frequency of electromagnetic waves is very high and in the range of radio frequencies from 3 kHz to 300 GHz, rapid heating of the tissues occurs. This heating is very much like the cooking of food in a microwave oven. For RF waves at high RF power densities ~100 mW/cm^2, considerable heating of tissues takes place. The body is not able to dissipate the large quantity of heat away. The rate of absorption by the human body has the maximum value at 80–100 MHz. Delicate regions like the eyes and testis need special care.

With reference to IEEE standards [9], below 100 kHz, the RF waves produce electrostimulation. Above 100 kHz, RF waves cause a sensation of heating. The 100 kHz frequency represents the frequency of thermal crossover. At frequencies <100 kHz, electrostimulation effects dominate. On the opposite side, at frequencies >100 kHz, temperature effects are predominant in the event of uninterrupted exposure to waves. In case of waveforms shaped in the form of pulses and having a small duty cycle, the frequency of thermal crossover can lie in the megahertz region.

Many global standards for electromagnetic protection have laid down the confinement ranges for power that can be dissipated safely inside the human body without producing unpleasant effects at frequencies >100 kHz. The limits have been prescribed with reference to the parameter known as specific absorption rate (SAR). The SAR is defined as the amount of power which is dissipated per unit mass of tissue. It is expressed in W/kg. Another defining parameter is the upper limit of allowable exposure (MPE) for current and fields [10]. Generally, at frequencies >100 kHz and <6 GHz, SAR limits are articulated with regard to two SAR parameters: (1) SAR, which has been determined as a mean or midline value considering any 1 g of tissue shaped as a cube, and also (2) the SAR averaged over the full body. For the general people, the IEEE standard decrees a tolerable ceiling value of 1 g average SAR = 1.6 W/kg. For SAR determination in the human body, numerical analysis and approximations or investigational methods based on experiments and phantoms (models of the human body) are applied. An utmost diffused numerical method to perform the above evaluation is the finite-difference time-domain (FDTD) technique. Over the past 15 years, this method has found widespread usage for several dosimetric assessments. Mathematical models or replicas of the body, as obtained by MRI scanning of patients offering their voluntary services, are employed for calculations along with FDTD method.

High frequencies are despised because they are harmful to the human body. Another adverse effect of high frequency is that a large portion of the transmitted power is lost by virtue of thermal losses in heating the tissues. Therefore, an unjustifiable drain of power takes place. As an outcome, the efficiency of the system decreases. Hence, besides the electromagnetic fields set up in the human body, the induced current in the implanted coil can dissipate substantial power within the coil itself. The finite resistivity of the coil is the underlying cause of this dissipation. This power wasted in the coil in turn raises the temperature in the surrounding tissues. Application of numerical or experimental methods helps in answering this query.

Apart from the power losses through thermal effects, at high frequencies, power-conditioning circuits in the implant as well as in the external transmitter consume more power. Necessarily, the power transmission efficiency decreases.

10.6 Biotelemetry

Telemetry is the transmission of measured parameters of the patient to the external device and vice versa.

10.6.1 Active Telemetry

Active telemetry systems make available comparatively effective data transfer in both directions over long distances using on-board battery [11]. Naturally, these systems offer increased size and decreased life. They are actually radio transmitters employing analog or digital modulation over a carrier signal. The carrier signal is amplified and transmitted from the transmitter to the receiver antenna [12]. Aboard signal processing circuits for amplification, mixing, information superimposition on the carrier signal by modulation and its extraction, and various other operations on signals are assimilated into the implant. For power supply, these systems depend on batteries, especially for long-term use. Hence, their regular maintenance becomes unavoidable. Overall system cost is increased by the added cost of the battery and signal processing circuitry. A further expenditure is incurred in the assembly of the different components. Moreover, prevention of heating of the tissues proximate to implants becomes troublesome. This happens owing to the lossy characteristics of the active systems.

10.6.2 Passive Telemetry

Passive telemetry decreases the distance up to which communication is effective. But it permits battery-free operation providing unrestricted time of operation. No on-board batteries are needed. Battery-less operation increases the autonomous life expectancy of the system. It also decreases the occupied space significantly. This is because the battery is a major contributor to the volume of the system. Absence of the hulking batteries makes passive systems ideal candidates for biomedical implants that have uncompromising size constraints. Passive wireless systems usually include less on-chip signal processing. So, the device size is eventually smaller. By discarding the batteries and a larger fraction of on-chip signal processing, the size and the final cost of the device decrease. A comparative study between the active and passive systems is made in Table 10.3.

Table 10.3 Active and passive telemetry [13, 14]

Sl. No.	Active telemetry	Passive telemetry
1.	The implant has a local oscillator producing radio-frequency waves that carry data	The implant does not produce radio-frequency waves itself. Instead, it receives energy by engaging in mutual interaction with the waves produced by the outside part. The same energy is used for data transference
2.	Power attenuation is less and smaller antennas suffice	Power is significantly reduced leading to high attenuation, and therefore large antennas are required
3.	Useful for smaller implants located deeper inside the body	Usually used in larger implants and placed underneath the skin
4.	Higher power consumption	Lower power consumption
5.	Used when a huge amount of data is to be transmitted at a fast speed. Disfavored whenever lower data rates are acceptable due to power consumption and space required by antenna and circuitry	Favored for low data rate transmission, e.g., when a small quantity of data is to be conveyed at a slow pace

10.7 Data Telemetry Uplink: From the Implanted Medical Device to its External Part

Telemetry uplink involves the contactless transmission of patient's vital data to the external device.

10.7.1 Digital Modulation Techniques: A Quick Relook

In binary amplitude-shift keying (BASK) (Fig. 10.1), the amplitude A of the carrier signal is altered in concurrence with the information-containing modulating signal. However, its frequency and phase are kept constant. As an example, transmission of 0 is done using one particular value of amplitude A_1 of the carrier. Transmission of 1 is done by using another amplitude value A_2. If one amplitude value A_1 or A_2 is taken as zero, the transmission takes place through the presence or absence of the carrier. This is a particular form of BASK called on/off keying (OOK).

In binary frequency-shift keying (BFSK), Fig. 10.2, the frequency f of the carrier signal is altered in response to the modulating signal. Its amplitude and phase are kept constant. One particular frequency f_1 represents 0. Another frequency f_2 denotes 0.

In binary phase-shift keying (BPSK), Fig. 10.3, the phase ϕ of the carrier signal is shifted to indicate information. Its amplitude and frequency are kept constant. Phase is the starting angle of the sinusoidal waveform. Thus one phase value may correspond to $\phi_1 = 0$. The other phase value may correspond to $\phi_2 = 180°$.

Table 10.4 displays the characteristics of BASK, BFSK, and BPSK.

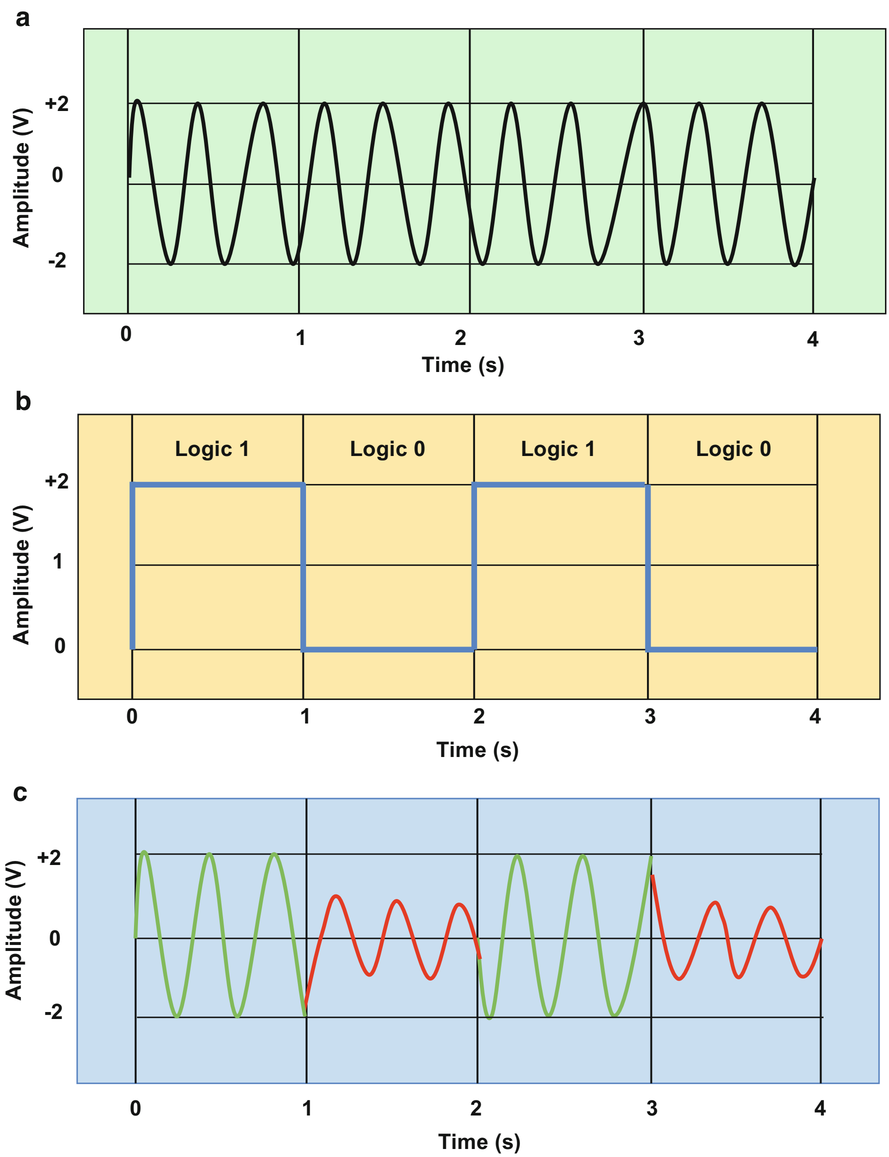

Fig. 10.1 Amplitude-shift keying (ASK): (**a**) sine wave carrier, (**b**) modulating digital signal, and (**c**) modulated wave

Reader's attention is drawn to the prefix "binary" before ASK, FSK, and PSK. This prefix signifies two amplitudes, two frequencies, and two phases, respectively. Note that in BASK, BFSK, and BPSK, each symbol represents one bit. To increase the bandwidth over that achievable with BASK, BFSK, and BPSK, multi-level or *M*-level ($M = 2^N = 2^2, 2^3, 2^4, 2^5, \ldots$.) modulation schemes are used. In these

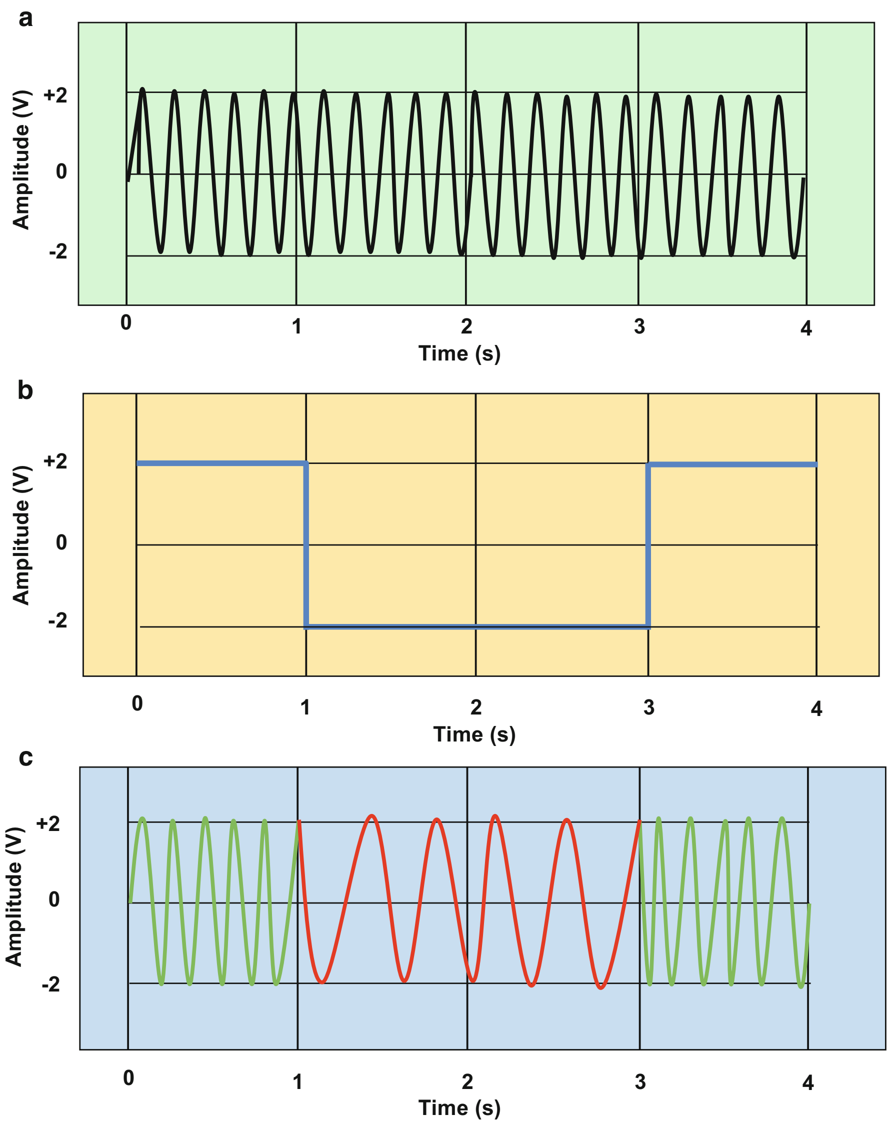

Fig. 10.2 Frequency-shift keying (ASK): (**a**) sine wave carrier, (**b**) modulating digital signal, and (**c**) modulated wave

schemes, each symbol represents *N* bits. These are called *M*-ary ASK, *M*-ary-FSK, and *M*-ary PSK modulation schemes, respectively. As an example, an *M*-ary ASK scheme uses *M* amplitudes in place of 2 amplitudes in BASK. *M*-ary FSK and *M*-ary PSK have similar meanings.

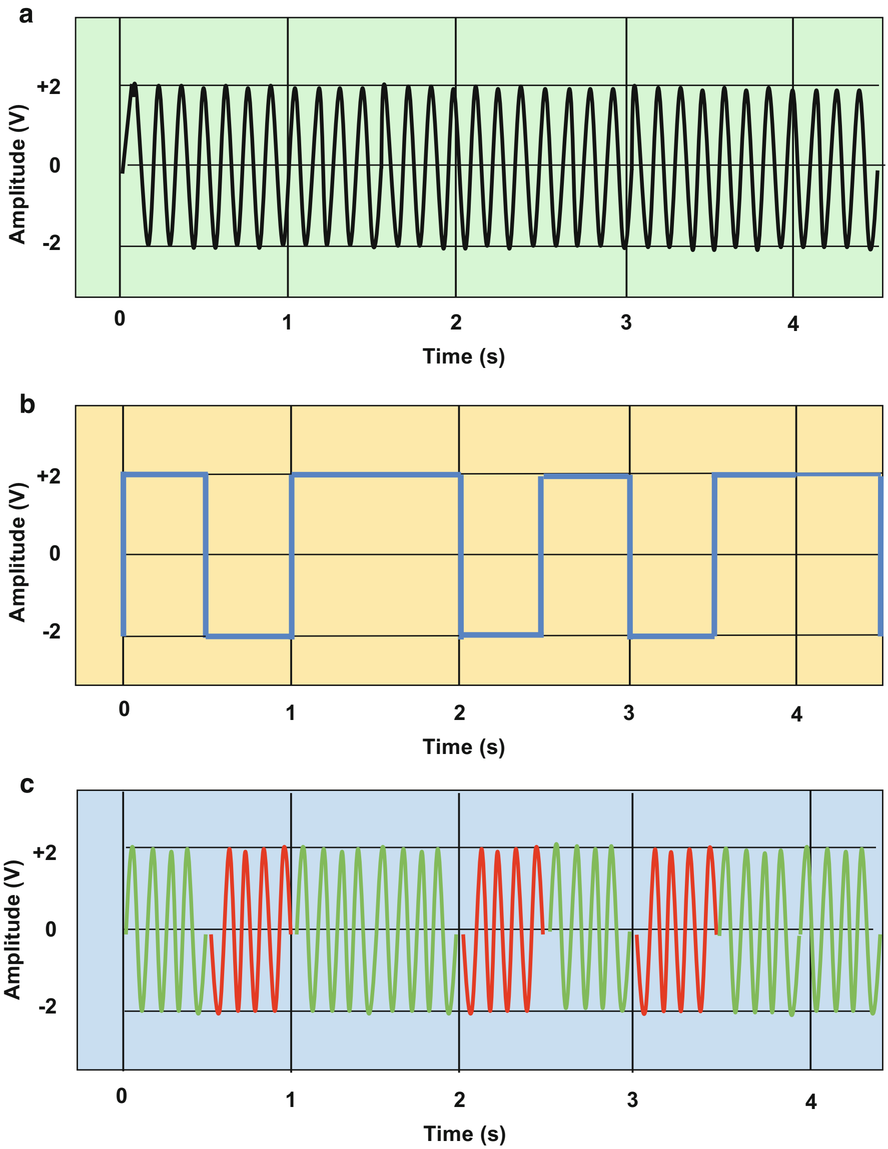

Fig. 10.3 Phase-shift keying (ASK): (**a**) sine wave carrier, (**b**) modulating digital signal, and (**c**) modulated wave

10.7.2 Load-Shift Keying and Multilevel Load-Shift Keying

For data transmission from the medical implant to the exterior device, load-shift keying (LSK) is used. LSK is a special form of amplitude-shift keying (ASK). Also called "reflectance modulation," it is a communication arrangement. It allows simultaneous transference of power and data on the same inductive linkage

Table 10.4 Digital modulation schemes at a glance

Sl. No.	BASK	BFSK	BPSK
1.	Uses two different amplitudes to represent 0 and 1	Uses two different frequencies near the carrier frequency for representing 0 and 1	Uses two different phases separated by 180° to represent binary digits 0 and 1
2.	Simple	More complex than ASK	More complicated process of detecting and recovering signal than either in ASK or FSK
3.	Performs poorly. It is profoundly influenced by noise and interference effects	Better than ASK but less than PSK	Superior in performance in comparison to both ASK and FSK
4.	Low bandwidth	FSK spectrum is 2 × ASK spectrum	Needs or extends over similar bandwidth as ASK. Possible to achieve more efficient bandwidth utilization and obtain higher rate of data transfer, as compared with FSK
5.	Sensitive to interference	Less susceptible to errors than ASK	Less susceptible to errors than ASK
6.	Used to transmit up to 1200 bps on voice grade lines and very high-speed digital data over optical fiber	Used to transmit up to 1200 bps on voice grade lines, for 3–30 MHz RF range and at even higher frequencies on local area networks with coaxial cable	Used in satellite communication systems, being a robust mode

(Fig. 10.4). LSK is based on variation of loading of the secondary coil in accordance with the serialized stream of data. The secondary coil is heavily loaded when logic "high" is to be sent and kept unloaded for sending a logic "low" state. By mutual inductance of the coils, any variation in the load of the secondary coil is reflected as a change in impedance of the primary coil. If this impedance change is resistive, amplitude-shift keying of the backscattered signal results. If it is capacitive, phase-shift keying takes place.

In a typical implementation, the binary data stream short-circuits the implant-side coil. The alteration in impedance is reflected in the transmitter. This is because the load due to the implant is much larger than the resistance offered to current flow by the switching transistor during its on-state. For a system using only two coils for both power and data, there is a risk of discontinuation in power supply if the short-circuiting of the implant-side coil is done for too long a period. An optimization of the characteristics of the link ought to be done to obtain maximum transference of power under the condition when communication is inoperative.

The main shortcoming of LSK is the sizeable deviation created by it in the voltage induced in the secondary coil with respect to its normal value. Due to this disturbance, difficulty is experienced in voltage regulation to provide a dependable

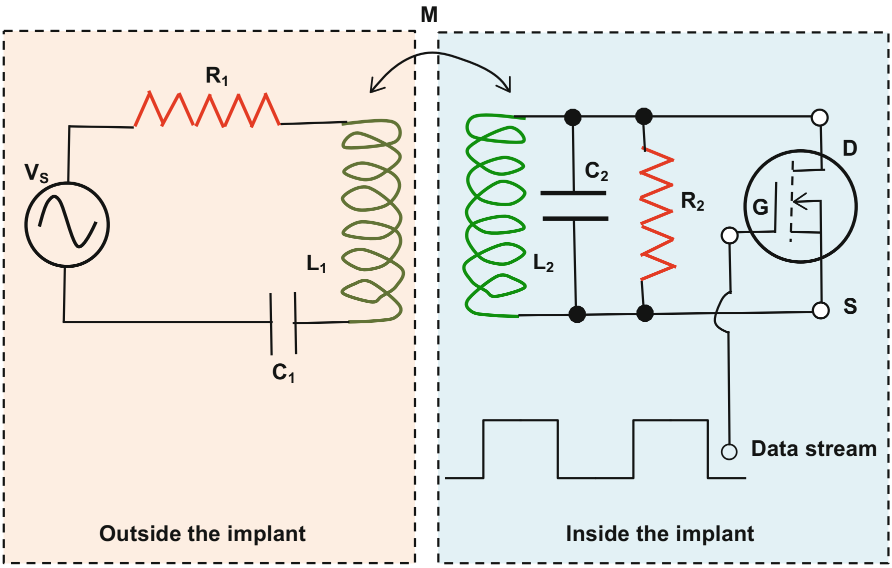

Fig. 10.4 LSK modulation principle

Table 10.5 Bilevel and multilevel LSK [16]

Sl. No.	Bilevel LSK	Multilevel LSK
1.	In essence, opens or short-circuits the secondary coil located on the side of the implant	Creates >2 different backscattering patterns whose properties are varied by multibit/symbol of data transmitted
2.	Provides back telemetry at a limited rate of data transfer	Provides back telemetry at a high rate of data transmission

source voltage. The bandwidth of LSK is held back by the coefficient of coupling, the coil parameters, and the transitory behavior of the inductive link. The bandwidth limit of the inductive link due to the quality factors of the coils fixes the maximum data rate. A large value of Q assists efficiency of transferring power but restrains the rate of data transport [15].

For data rate enhancement, multilevel LSK is preferred, as demonstrated in [16] with discrete components. Herein, 2× improvement in data rate was indicated for a back telemetry system based on passive LSK and comprising four levels in comparison with usual back telemetry of bilevel type (Table 10.5).

10.7.3 Auxiliary-Carrier Load-Shift Keying

To overcome the deficiencies of LSK for reverse data telemetry from the medical implant to the exterior environment, auxiliary-carrier load-shift keying employs two carriers. These carriers are called the main carrier and the auxiliary carrier. They are given the responsibilities of power transfer from the exterior device to the medical implant and data telemetry from the medical implant to the exterior device, respectively [17]. The need for two carriers arises because power transference is more efficient at low frequencies at which a smaller bandwidth suffices. Contrariwise, data telemetering efficiency increases with increasing bandwidth. The large bandwidth is available at the higher frequencies. So, a single frequency cannot meet both the requirements. If a single-carrier frequency is used, efficiency of one function is maximized at the sacrifice of efficiency of the other function due to their opposing frequency dependences. The two carrier waveforms are superimposed on each other. A dual-frequency resonant inductive link has therefore to be set up between the external device and the implant. This link has two resonant frequencies, one resonant frequency to carry out the function of transmission of power (f_M) and another resonant frequency for the role of transmission of data (f_A). The principle of auxiliary-carrier-LSK is illustrated in Fig. 10.5.

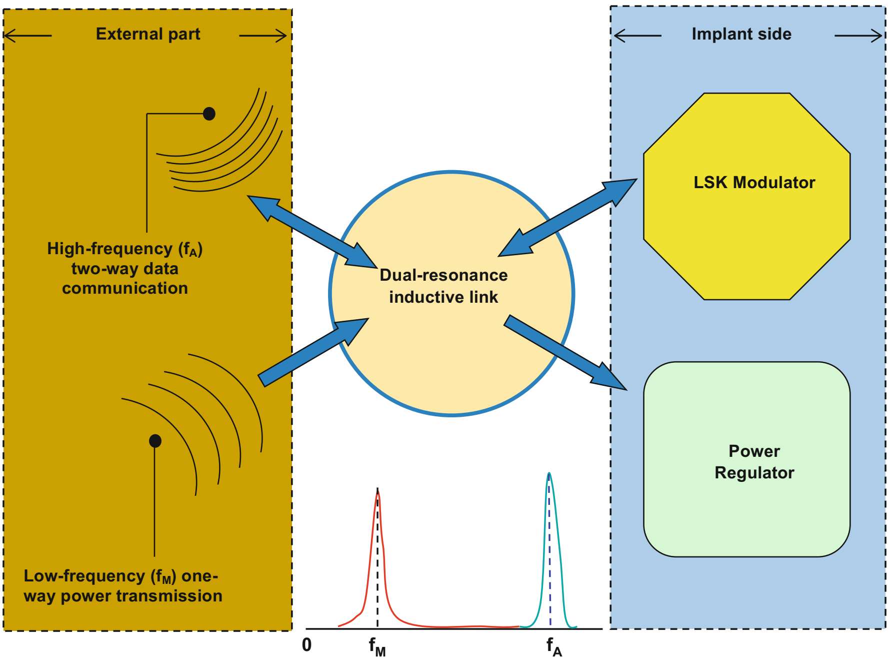

Fig. 10.5 Auxiliary-carrier load-shift keying approach

Table 10.6 Conventional and auxiliary-carrier LSK [17]

Sl. No.	Conventional LSK	Auxiliary-carrier LSK
1.	Uses single-carrier link	Uses dual-carrier link
2.	Uses one single carrier for telemetry of both power and data	Uses two carriers: main carrier for power and an auxiliary carrier for data telemetry
3.	Restriction on the choice of frequency for data	No such restriction because power and data are handled by different carriers
4.	Suffers from low data transfer rates	Since frequency for carrier telemetry can be chosen to be much higher than one used for power telemetry, high data rates are achievable
5.	Degradation in power transferred to the medical implant	No conspicuous deprivation in power

Auxiliary-carrier LSK (AC-LSK) is very beneficial for power retrieval on the implant side as compared to simple LSK. The simple LSK shows degradation in quality, as pointed out above. Thus continuous transfer of power can take place without any disturbance from reverse data telemetry. In the system developed by Karimi et al. [17], carrier frequencies of 1 MHz and 10 MHz were selected for telemetry of power and data, respectively. Similarly, depending on particular applications and keeping the human safety considerations in view, one lower and one upper frequency can be selected for building the auxiliary-carrier LSK system. This gives more freedom to the implant system designer. The auxiliary-carrier LSK technique introduces no difficulties with the coil designs for the inductive link. In the opposite way, some complexities in power amplification as well as matching and reverse data telemetry circuits are unavoidable. Table 10.6 compares AC-LSK with the conventional LSK.

10.7.4 Adaptive Control Load-Shift Keying

In an ordinary LSK-based system, large power fluctuations are induced by displacements in coil positions, loading changes, or both. To take care of all possible situations, excess power must be supplied to the implant. This unduly lowers the power efficiency. Wang et al. (2005) [8] designed and implemented an adaptive control LSK system for a retinal prosthetic device. The proposed system removes power fluctuations induced by coupling coefficient or loading variabilities (Table 10.7). The system is a dual band telemetry link using a lower frequency for transmission of power and a higher frequency for transfer of data. Information regarding the power reaching the implant side is sent back to the external device in a closed-loop network. This information flow enables the feeding of the exact amount of power needed by the medical implant from the exterior device. Up to 250 mW of power could be supplied over a coil distance from 0.7 to 1.5 cm. The data transfer rate from the medical implant to the external humankind was 3.3 kbps.

Table 10.7 Conventional and adaptive LSK

Sl. No.	Conventional LSK	Adaptive LSK
1.	Large fluctuations occur in the power transferred to implant with coil displacements, load variations, etc.	Mitigates such fluctuations
2.	Gives low power efficiency because excessive power is supplied to overcome worst-case situations	Provides improved power efficiency
3.	Involves undesirable exposure of tissues to high power	Unwanted exposure of tissues to harmful power levels is avoided

10.7.5 Passive Phase-Shift Keying

The passive phase-shift keying [18], with acronym PPSK, utilizes the transitory response of the inductive linkage caused by the switching of the load and maneuvering of power. By opening or closing a switch at regular intervals, data from the implant are transmitted to the exterior device. Using a carrier frequency of 4 MHz, data transmission rates up to 222 kbps could be achieved. A monolithic PPSK modulator [15] for telemetry by inductive coupling was fabricated using CMOS technology with gate length of 0.6 μm. It used a solitary set of coils to execute both the activities of transference of data and supply of power. For a carrier frequency of 13.56 MHz, it was found to transmit up to 847.5 kbps (1/16 of the carrier) along with power transfer. It recorded the speediest rate of data transmission reached by a single inductively coupled wireless link applied concurrently for delivery of power and conveyance of data in medical implants. Contrasting with LSK, in PPSK, the switch across the secondary coil (Fig. 10.6) shuts up in synchrony with the carrier for half the carrier cycle. The momentary response in the primary coil current is perceived as a logic “1” signal.

10.7.6 Pulse Harmonic Modulation

Hitherto described modulation techniques for inductive telemetry links were carrier-based. These carrier-based methods were used in the early implants. So, the carrier waveform of low frequency employed for data transfer could also be utilized for implant powering. In high-performance, wider bandwidth implants, on the other hand, the carrier wave for power was estranged from that for data. This separation was done because the frequency of the power carrier could not be increased due to the losses in the biological tissue at high frequencies. The deployment of data carrier waves of high frequency for broadband communication in the implants requires the undesirably complicated RF circuits for stabilizing the frequency. An example is provided by the phase-locked loops (PLLs). The RF circuits are more power hungry.

For obtaining lower power consumption and higher data rates in near-field telemetry links, a pulse-based data transmission technique has been devised [19]. It is called pulse harmonic modulation (PHM). The transceiver for PHM employs two

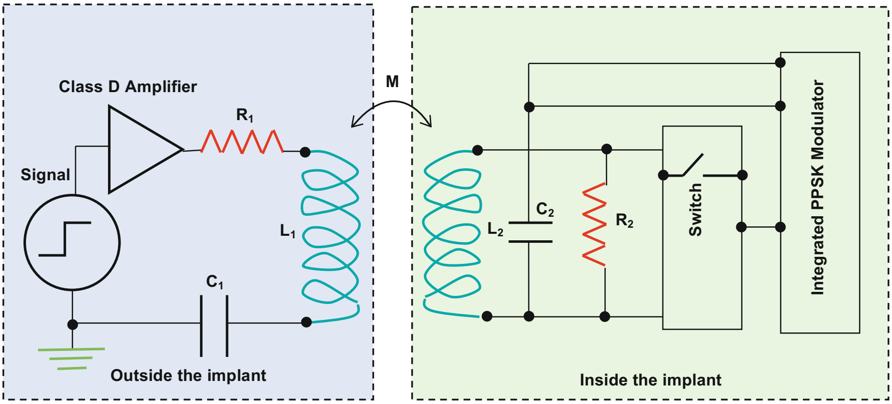

Fig. 10.6 PPSK modulation system

constricted pulses of particular amplitudes and timings at the transmitter section. This is required to smother intersymbol interference at the *LC* tank circuit of high-quality factor at the receiver segment. The interference is repressed for achieving high rates of data transfer without decreasing the *Q*-factor of the inductive link to enlarge the bandwidth. Consequently, better range and selectivity are achievable with the link. The PHM receiver architecture utilizes a pulse-based automatic gain control circuit. This circuit appreciably lessens the power consumption and inter-symbol interference at short coupling distances. By using the PHM technique and carefully designing the transceiver, high data rates of 20 Mb/s could be attained across a 1 cm inductive link with a carrier frequency of 66.7 MHz.

Pulse harmonic modulation represents a high-speed data transmission technique for inductive links. But the drawback is the requirement of a separate link for its implementation because the method is carrier less.

10.8 Data Telemetry Downlink: From the External Part to the Implanted Medical Device

Telemetry downlink is the transmission of information from the external device to the patient.

10.8.1 Amplitude-Shift Keying

Due to the inherent simplicity of designing the modulator at the external device and the demodulator at the implant, amplitude-shift keying was the first preferred technique used for data transmission. But the data transmission rates were exceedingly low. The bit rates are generally limited to 1/10th of the carrier frequency. An ASK demodulator for implantable electronic devices [20] energized through an inductive link was tested with carrier frequencies in the 1–15 MHz range. Data rates up to several 100 kbit/s could be supported. Several ASK-based systems have been reported [21, 22].

The main limitations of ASK-based methods are:

1. In applications requiring high-bandwidth data transmission, it is not possible to integrate the large-value capacitors of high-order filters. These filters are necessary to obtain spiky cutoff frequencies in the low radio-frequency part of the spectrum.
2. The voltage induced between the terminals of receiver coil varies inversely as the third power of the distance separating the coils, presupposing that all other parameters are constant. The implication is that the amplitude of the induced signal, which is the entity entrusted with the responsibility of carrying information in ASK, is exceptionally susceptible to the relative distance changes in implants. Such amplitude fluctuations are very infuriating.
3. The signal is impaired even when the relative distance is fixed. This impairment takes place because a constant power is received. Any alterations in the current consumed by wireless chip, as caused by current impulses of the digital circuits induce changes in the envelope voltage of the carrier signal received. Hence, the quality of the ASK signal is degraded.

10.8.2 Frequency-Shift Keying

The superior immunity of FSK over ASK against noise sources and interference is well known. This ruggedness of FSK becomes further apparent in inductively coupled devices. These devices obtain both data and power from the same carrier wave. Unlike amplitude in ASK, the relative distance or changes in current do not influence the frequency of the induced signal in FSK schemes. The modus operandi of FSK modulation and demodulation is utilized to propel data to inductively power wireless medical implants at rates of data transfer >1 Mbps. The carrier frequencies used are on a par with those used in ASK [23]. This FSK demodulator was checked by experimentation up to 2.5 Mbps. The bit error rate was 10^{-5}. This testing was done at the same time as receiving an FSK carrier signal of 5 or 10 MHz frequency.

BFSK enables a higher ratio of data rate to carrier frequency than BASK. Notwithstanding, the need of a broad passband in the inductive linkage to permit the copious frequencies imposes restriction on transference of power.

10.8.3 Phase-Shift Keying

PSK is a more appropriate communication procedure for data exchange and power transfer than either ASK or FSK. This suitability is because the amplitude and frequency are constant. Moreover, a carrier signal of constant amplitude ensures steady transfer of power with high efficiency. Antennas of a fixed size can be used because the carrier frequency is constant. These antennas are easily designed. The objective of design is to optimize the transference of power and data. Thus BPSK provides stable and efficient power transfer. The shortcoming of BPSK is the complexity of demodulator using commonly a Costas loop [24].

In the prototype of a demodulator architecture employing binary phase-shift keying (BPSK) [25], the highest data rate of the demodulator, found by derivation to be 1/8th of the frequency of carrier wave used, viz., 13.56 MHz, was 1695 kbs.

10.9 Discussion and Conclusions

While laying down specification of implantable devices, many parameters have to be dealt with in design and for satisfactory implementation. A few such parameters are power requirement, communication range (long-range or short-range), bandwidth, the location and environment of the medical device inside the human body, data transfer rate, frequency, authoritarian standards, and operating life of implants. These parameters guide towards the strategy to be planned for choosing uplink and downlink power and data telemetry schemes and for building the hardware/software for realization (Fig. 10.7).

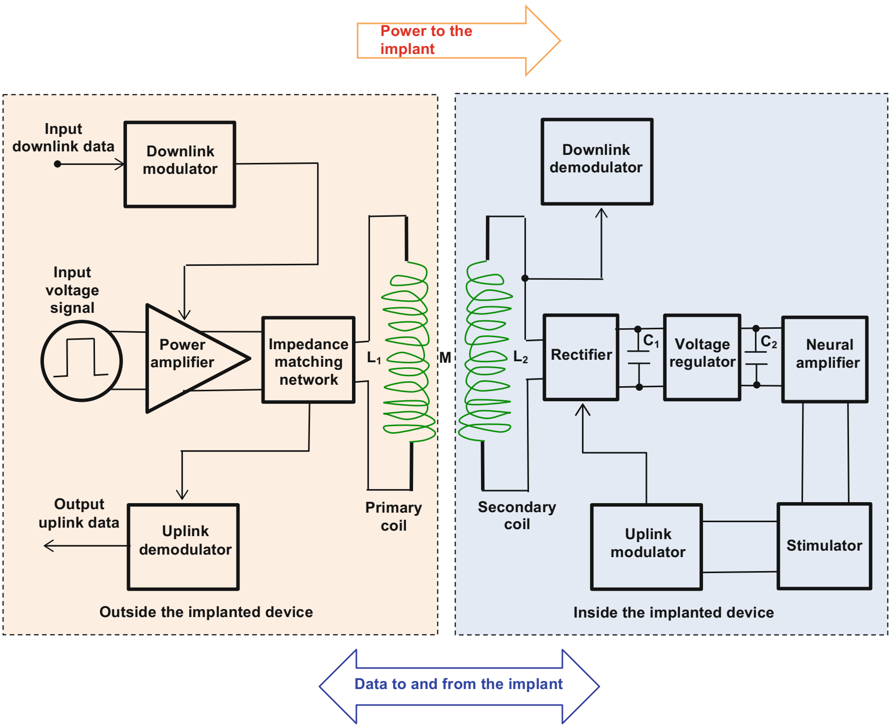

Fig. 10.7 Organization of a wireless biotelemetry system for transmission of power to an implant and data to and from the implant via an inductive link

Review Exercises

10.1 After a medical device has been implanted in the human body, what are the two main needs that must be fulfilled?

10.2 Prepare a table bringing out the main advantages and disadvantages of supplying power to an implanted device through percutaneous leads and by the wireless method.

10.3 Name the three types of wireless charging techniques. Which of these techniques are widely used in implantable electronics?

10.4 During inductive charging of an implanted device, what shape of coils is generally used? What shape is preferred for systems placed over the head?

10.5 How does magnetic induction used in inductive charging differ from resonance-enhanced magnetic induction used in resonance charging?

10.6 Arrange in ascending order of efficiency: resonance charging, inductive charging, and radio charging.

10.7 Arrange in descending order of charging distance: inductive charging, radio charging, resonance charging.

10.8 Arrange in ascending order of frequencies used: resonance charging, radio charging, and inductive charging.

10.9 Comment on the statement, "Theoretically, 100 % efficiency is achievable with inductive link."

10.10 Why is the use of high frequencies disfavored for implantable devices?

10.11 Define specific absorption rate (SAR) of tissue. How are SAR limits expressed?

10.12 Which telemetry system, active or passive, produces radio waves?

10.13 Which telemetry system, active or passive, requires larger antennas?

10.14 In a medical implant, a large capacity of data is to be conveyed at a high transference rate. Which telemetry system, active or passive, will be suitable?

10.15 Arrange in ascending order of complexity: BPSK, BASK, and BFSK.

10.16 Which of the following modulation schemes is most vulnerable to noise: BPSK, BFSK, or BASK?

10.17 State whether true or false: BPSK requires the same bandwidth as BASK?

10.18 Which modulation method is most susceptible to interference: BPSK, BASK, or BFSK?

10.19 What is the common name of reflectance modulation?

10.20 In LSK, how is the secondary coil loaded for sending "logic high signal"? How is it loaded for transmitting "logic low signal"?

10.21 What are the limitations of bilevel LSK? How are they overcome?

10.22 Decide whether the following statement is true or false: multilevel LSK provides limited data rate of back telemetry.

(continued)

(continued)

10.23 What is the main carrier used in auxiliary-carrier LSK? What is the role of auxiliary carrier?

10.24 Point out whether true or false: auxiliary-carrier LSK suffers from restriction on choice of frequency for data.

10.25 In which of the two schemes, LSK or auxiliary-carrier LSK, high data transfer rates are not attained?

10.26 Which of the two schemes, conventional or adaptive LSK, suffers from the problem of large fluctuations in power transferred to the implant? Which of the two gives low power efficiency? Which one produces overexposure of tissues?

10.27 What is the principle of PPSK? How does it differ from LSK?

10.28 Name a modulation scheme which is not carrier-based. What is its advantage? What is the shortcoming?

10.29 For data telemetry downlink, what was the first preferred technique? What were the problems faced with this technique?

10.30 Discuss the relative merits and demerits of the following for data telemetry downlink: ASK, FSK, and PSK.

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