8

Power Amplifiers for Electronic Bio-Implants

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1. Introduction

Healthcare systems face continual challenges in meeting their aims to provide quality care to their citizens within tight budgets. Ageing populations in the developed world are perhaps one of the greatest concerns in providing quality healthcare in the future. Figure 1 shows projections from the United Nations, indicating that the median age of citizens in economically developed regions is set to approach 40 years by the year 2050, and reach as high as 55 years in Japan. This trend is likely to lead to strained economies caused by less revenue raised by smaller workforces. Another effect of ageing populations is the need of further care in order to remain healthy. This care varies from frequent check-ups to condition monitoring, compensation for organ malfunction and serious surgical operations. As a result of these trends, healthcare systems will face the task of servicing more people with more serious and expensive health services, all using less available funds. Effort is being focused on running cheaper and more effective healthcare systems and the development of technology to assist in this process is a natural research priority.

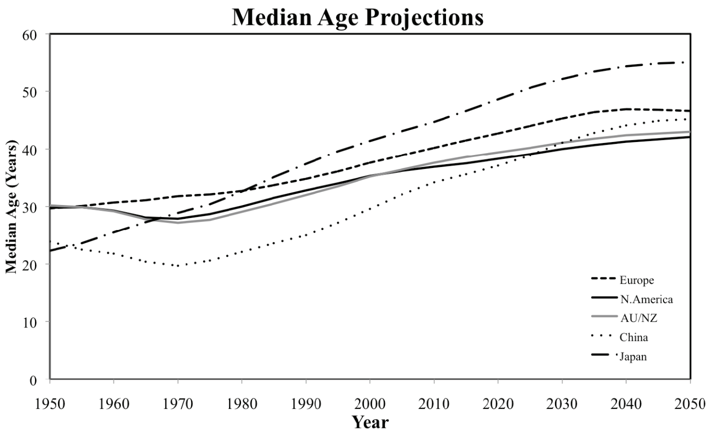

Fig. 1. UN Median Age Statistics (UN, 2010)

1.1 Technology in medicine

Archaeological evidence shows the application of technology to medicine for rehabilitative, functional and aesthetic purposes as far back as 5000 years ago in ancient Egypt, where

prosthetic devices were designed engineered and constructed with basic materials such as leather and wood. The earliest written evidence exists from ancient India, mentioning a prosthetic iron leg (Thurston, 2007). These materials formed the basics of prosthetics until recently, the only variations being in manufacturing techniques.
The application of titanium alloys to medicine was a significant advance due to their ability to form biological bonds with human tissue (Long and Rack, 1998). Developments in polymer technology led to biocompatible polymers, allowing more precise, detailed and finer implants to be made such as blood vessel reinforcements (Ramakrishna et al., 2001). The latest developments in biomaterial research is in fact designing polymers to allow the body to heal itself (Hench and Polak, 2002).

1.2 Electrical and electronic technology

The field of electronics has been a relatively recent technological advance in history, and it has seen an escalating rate of sophistication. After the renaissance, serious curiosity in the phenomenon of electrical charge developed, and several fundamental developments were made such as the discovery in 1791 by Galvani, that electricity was the medium through which information was passed to muscles in the body. The voltaic pile was developed in 1800 by Volta, which provided the first reliable source of electrical energy, and other major developments happened such as the recognition of electromagnetism by Orsted and Ampere, and Faraday's electric motor.
Tesla's achievements in the transmission of low frequency wireless power were significant. He proposed to apply the concept of resonance to electrical energy in order to transmit energy wirelessly. Hertz used spark gaps to generate high frequency power and detect it at a receiving end, using parabolic reflectors at the transmitting and receiving ends. These developments were further built upon in the late 1930s with the availability of higher energy microwave power generators. Developments in microwave power transmission escalated during the 20th century due to World War II and the Cold War, resulting in sophisticated satellite communication technologies (Brown, 1984).
The development of quantum theory and semiconductor electronics laid the foundations for rapid technological development in what is now being called `The Age of Silicon' (Jenkins, 2005). They allowed for the rapid development of integrated circuit technology characterised by Moore's Law, which states that the number of transistors in a given surface area increases exponentially with time (Łukasiak and Jakubowski).
Computer networks developed in the 1970s and led to the eventual creation of internet (Kleinrock, 2008). This has led to a technological and sociological revolution characterising the 21st century as `The Information Age’, with omnipresent networks, small sensors, constant and cheap access to information on increasingly intelligent personal devices that are modestly called `phones’.

1.3 Electronics in medicine

Galvani's frog experiment showed biology as one of the original phenomena through which human understanding of electricity was developed. Interestingly, knowledge in the field of electronic engineering has since advanced to a stage where it is being used to understand, monitor and even treat biological and medical systems.
Medical imaging is fundamental to the understanding of the human body and diagnosing medical problems. X-Ray technology is widely used to capture two-dimensional details for

orthopaedic applications. The rays are created by rapidly decelerating electrons to produce high frequency electromagnetic radiation, which is diffracted and penetrated differently by bones and flesh, allowing the resultant radiation to be recorded on X-ray sensitive polymers to show internal details of the body. Ultrasound is commonly use to provide a real-time image of the body's internal operations, being a popular and safe technology in monitoring various stages of pregnancy. Computed Tomography (CT) scanning and Magnetic Resonance Imaging (MRI) provide three-dimensional images of the body's internal organs, allowing fine differentiation between different types of body tissue. Such types of scans involve powerful computing capability to reconstruct models of internal organs, and have been invaluable to the understanding of the human body in a non-destructive way (Seligman, 1982).

Robotics in medicine has become another exciting field in which the application of intelligent electronics is contributing greatly, to the point where they are used to conduct complex surgery, which is remotely controlled by surgeons. Their ability to move accurately without shaking hands or unstable movements allows minute and delicate operations to take place, while still being controlled by a doctor. The application of robotics to medical prosthesis is another significant advance since the first pneumatically powered hand in 1915 (Childress, 1985). So advanced is this field, that robotic prosthetic arms are being developed and controlled by electrical signals sent by the brain through the body's nervous system.

The cardiac pacemaker is the oldest and perhaps best known implantable prosthetic electronic device. It was first used externally on a patient in 1952 and as the first semiconductor transistors were developed, the possibility to implant led to the first human implant in 1960 (Greatbatch and Holmes, 1991). This was the beginning of several exciting developments in the area of medical prosthetics.

Cochlear implants, popularly termed `Bionic Ears' were a major breakthrough in medical prosthesis. The Cochlea is a part of the ear that converts sound vibrations to electrical signals that are sent via the audio nerve to the brain where they are interpreted. In deaf patients where the Cochlea does not operate properly and the auditory nerve does, cochlear implants are possible. A system was designed and created to replace the Cochlea with an electronic prosthetic device, such that the sound recorded by a microphone is processed by an implanted device and sent to the brain on the audio nerve.

Retinal prostheses, popularly termed 'Bionic Eyes' have been the focus of much research. The concept is similar to Cochlear prosthesis, however this electronic prosthetic device aims to substitute the retina, which is the part of the eye which converts light to electrical signals and sent to the brain via the optic nerve. For patients that have suffered blindness due to macular degeneration, this prosthetic device has the potential to re-introduce sight.

Patient monitoring is an important part of medicine in that it assists doctors in understanding the condition of their patients, be it for known issues or as a means of diagnosis. Condition monitoring of patients is also conducted after serious surgical operations, in order to ensure that no complications arise. This is often a major reason for a patient's long stay in hospital after an operation.

Prevention is preferable to treatment, and the ability to monitor vital health indicators such as the electrocardiogram (ECG), body temperature and blood pressure information via medical telemetry may offer adequate tools to view logged or real time data for vulnerable patients, especially the elderly. Growing telecommunications infrastructure with increasing sophistication is opening the possibilities with regards to medical telemetry, making it theoretically possible for patients to carry out their daily tasks while being monitored remotely by doctors. Implantable medical telemetry is in fact becoming an increasingly important field of research, with the potential to reduce medical risks, lower medical costs and cater for ageing populations.

2. Telemetry

Telemetry is a significant element of health care, involving the measurement and communication of a patient's biological information for interpretation by medical professionals. It is mostly conducted by external medical equipment, however medical telemetry is making its way into the body in the form of implantable monitoring devices, which will potentially be able to measure very detailed body signals. Figure 2 shows a general block diagram of most implantable telemetry systems.

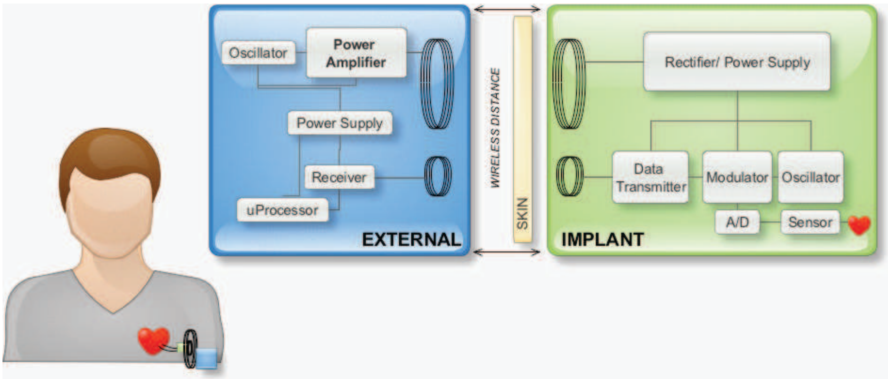

Fig. 2. General architecture of telemetry systems

One important factor to consider when dealing with implantable devices is the supply of power. In order to send power to implantable devices, wireless links are usually employed in the form of inductive links. Inductive power transfer is more efficient at lower frequencies (Vaillancourt et al., 1997). However, lower transmission frequencies use larger circuit components, especially transmission coils. From the perspective of implantable devices, space is important and this has led to a need to design highly efficient transmission circuits at higher frequencies.

Switching power amplifiers have been a popular choice for the transmission of wireless power (Raab et al., 2002). While the most popular choice has been the Class-E amplifier, it is also useful to gain an understanding of other power amplifiers, Class-F and Class-D.

3. Class-F amplifier

The Class-F power amplifier may be seen as a development from the Class-A and Class-B power amplifier, with a 50% conduction time and the use of harmonic resonators on the load network (Reynaert and Steyaert, 2006). An example of the Class-F amplifier is shown in Figure 3 comprising a transistor, choke inductor and an input source.

The network attached to the output of the transistor is manipulated by harmonics such that the voltage and current are manipulated. The voltage is shaped by odd harmonics of the fundamental frequency such that the voltage appears as a square-wave. The current is 180^0 out of phase and shaped to appear as a half sine-wave (Raab, 1997).

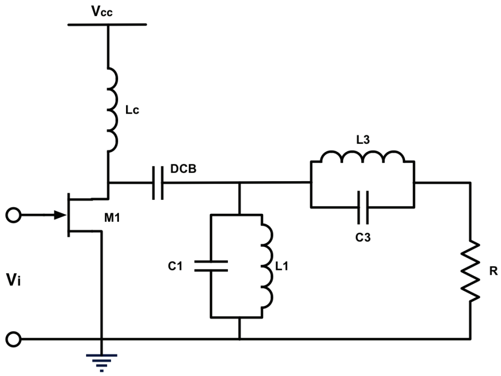

Fig. 3. Class-F Amplifier

The more harmonic frequencies are used to shape the voltage and current curves, the higher the efficiency of the Class-F amplifier. The theoretical efficiency of the amplifier with the use of third harmonics is 88.4%, while the additional use of fifth harmonic resonators produces an efficiency of 92% (Reynaert and Steyaert, 2006).
Inverse Class-F amplifiers also exist where the current curve is shaped to be a square-wave, while the voltage is shaped as a half sine-wave (Young, 2006).

4. Class-D amplifier

Like the Class-F power amplifier, the Class-D power amplifier is a non-linear amplifier in that the transistors of the amplifier behave as switches such that the output of the transistors is related to the supply or reference voltage, depending on which transistor is turned on at the time. The fact that the output signal of the amplifier is determined by the switching of the amplifier's transistors means that the Class-D power amplifier may be described as a switching power amplifier (Reynaert and Steyaert, 2006).

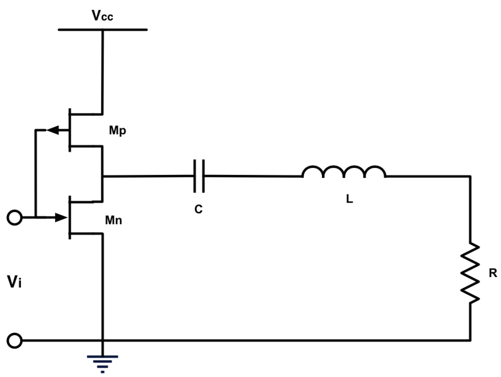

Fig. 4. The Class-D amplifier

Figure 4 shows an example of a Class-D switching power amplifier. It comprises an inverter, which switches two transistors on and off alternatively to generate a square wave. The output of the inverter is connected to a series RLC network as shown in Figure 4, which is resonant at the fundamental frequency of the square-wave, producing a sinusoidal signal at this frequency. Assuming that the series L and C network only allows sinusoidal current to reach the load R, the theoretical efficiency of the Class-D amplifier is 100%.

In reality, circuit elements are not ideal and several losses have been analysed with a focus on parasitic drain-source capacitance in each of the transistors, which becomes significant in higher frequency RF designs. The drain-source capacitance, C_{ds} actually introduces a capacitor where an open circuit should ideally exist. At high frequencies, typical capacitor values are in the order of pico Farads, which means that parasitic capacitance C_{ds} becomes a significant circuit element, which dissipates energy during switching cycles thus decreasing the amplifier's efficiency (El-Hamamsy, 1994, Kiri et al., 2009, Raab et al., 2002).

5. Class-E amplifier

The Class-E power amplifier was introduced by Sokal et al., shown in Figure 5 (Sokal and Sokal, 1975). Like the Class-D amplifier it is also a switching power amplifier driven by a square-wave input, however rather than two transistors it comprises one transistor and a choke inductor. As a result the signal seen by the load is not hard-switched.

Similar to the Class-D amplifier, the series LC network of the Class-E amplifier only allows a sinusoidal voltage and current to pass to the load. The Class-E amplifier also includes a capacitor C_1 across the transistor terminals and forms a key component of the circuit's high efficiency operation at high frequencies as well as absorbing C_{ds}. The amplifier's high efficiency operation lies in the shape of the voltage across C_1. Circuit elements are chosen such that the voltage at this point is zero when the transistor is switched on such that no stored energy is dissipated from the capacitor. The voltage is shaped such that the rate of change of voltage (dv_{C1}/dt) across this point is also zero. This feature enables robustness to phase or frequency irregularities in practice.

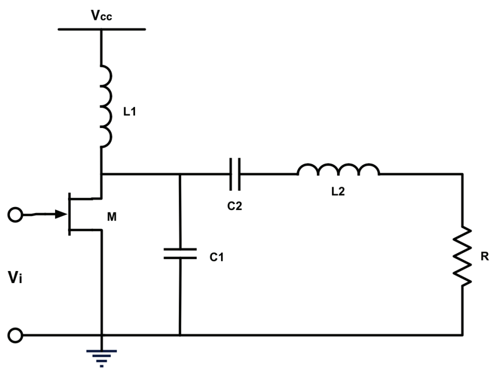

Fig. 5. The Class-E amplifier

Since the amplifier's introduction several analyses have been presented to enhance the design processes of the Class-E amplifier such that it includes more practical considerations. One of the original assumptions of the Class-E amplifier design process was that it has an

infinitely loaded quality factor (Q). Kazimierczuk et al. presented a design procedure in which the amplifier can be designed at a specific Q and switch duty cycle (Kazimierczuk and Puczko, 1987). Suetsugu et al. presented a design procedure to handle off-nominal operation where the voltage across C_1 is zero but its derivative is not, concluding that a higher C_1 capacitance is required for such conditions (Suetsugu and Kazimierczuk, 2006).
The Class-E amplifier has been applied to a number of applications, however its relevance to biomedical engineering came to light with Troyk et al.'s proposal to use the Class-E amplifier as a transmitter to transfer inductive power and data for micro implants, with L_2 representing the primary inductive coil (Troyk and Schwan, 1992).
A number of design procedures have been presented in literature, however it is interesting to consider the amplifier in the frequency domain. Given that L_1 is considered to be large, the transfer function for the output voltage (across R) is given by (1). This transfer function is a second order system, which implies that it has a resonant frequency ω, damping factor ζ and Q factor, indicated in (2)-(4).

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{g_m R C_2}{s^2 L_2 C_1 C_2 + sRC_1C_2 + C_1 + C_2} \tag{1}$$

$$\omega = \frac{1}{\sqrt{L_2 C_1 || C_2}} \tag{2}$$

$$\zeta = \frac{R}{2}\sqrt{\frac{C_1 || C_2}{L_2}} \tag{3}$$

$$Q = \frac{1}{2\zeta} \tag{4}$$

If a Class-E amplifier design was to be conducted for a practical application where the inductive coil's properties (L_2) are known as is the load R and resonant frequency ω, equations (2)-(4) can be re-arranged to select the unknown parameters. Combining (2) and (3) gives (5) and (6).

$$\zeta = \frac{R}{2\omega L_2} \tag{5}$$

$$C_1 || C_2 = \frac{2\zeta}{R\omega} \tag{6}$$

Where:

$$C_1 || C_2 = \frac{C_1 C_2}{C_1 + C_2} \tag{7}$$

The damping factor ζ (and therefore Q) is determined in the first step by substituting the known values of R, L_2 and ω into (5). This essentially implies that the quality factor of the amplifier is highly dependant on the coil inductor's quality factor. The ζ value is then used in (6), along with R and ω, which determines the capacitor combination $C_1 || C_2$.

Determining the individual capacitor values C_1 and C_2 is the more complicated step and requires care, given that the voltage between the two capacitors is vital to the circuit's Class-E operation. Generally speaking, if C_1 is smaller than C_2, charge across C_1 is dissipated quickly into C_2 prior to the transistor's next half-cycle switch. This implies that the voltage and voltage derivative of the capacitor junction is zero during switching.

6. Oscillators

Power amplifiers require square-wave clock signal inputs, so while they are known to operate efficiently at high frequencies they require a high frequency square-wave input in order to operate effectively, which is often not included in the determination of the efficiency of the amplifiers. These input signals are produced by oscillator circuits.

Oscillators are frequently used to generate high frequency signals, using resonant elements and a form of feedback. The Colpitts oscillator is a popular oscillator topology, which involves an LC network with feedback to a transistor. Other oscillators use crystals as the resonant feedback network rather than inductors and capacitors.

The idea of feeding an oscillated output signal back to the input of the amplifier implies that the circuit becomes self-oscillating- similar to the Colpitts oscillator- while operating with zero switching conditions. This is the concept behind the Class-E Oscillator shown in Figure 6 (Ebert and Kazimierczuk, 1981).

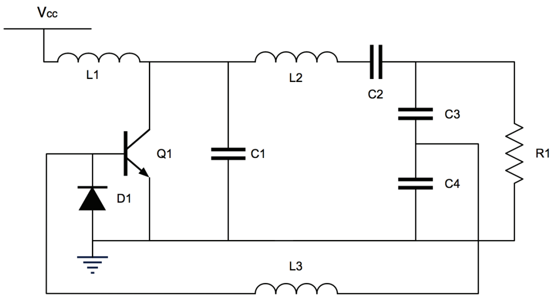

Fig. 6. Class-E Oscillator (Ebert and Kazimierczuk, 1981).

Additional circuit elements are added to form the Class-E oscillator, namely feedback elements C_3, C_4 and L_3. It was designed by Ebert et al. to constructively shift the phase of the feedback point of the oscillator. The diode D_1 is placed at the input of the transistor in order to clip the input signal such that it appears as a square wave, satisfying the requirement of the Class-E circuit to have a square-wave input.

Given that low power consumption is advantageous in biomedical systems, it is useful to consider a self-oscillating Class-E oscillator as a wireless power transmitter rather than a Class-E power amplifier. Similar to the power amplifier, the oscillator would transmit energy through L_2. This idea is currently being explored.

7. Wireless power links

The next module of an implanted telemetry system is the wireless power link. As previously mentioned, inductive power transfer has been the most popular means to transfer power wirelessly to implants. Inductive power transfer may be understood by considering two inductive coils L_1 and L_2 shown as the power transmission coils in Figure 2. A time-varying current i_1 in L_1 produces a linearly proportional magnetic flux, which passes through L_2 inducing an e.m.f. v_2 in that coil as shown in (8). The symbol M is a combination of the magnetic flux flowing between the two inductors and proportional to the number of turns in L_1 and L_2, and is referred to as the mutual inductance between the coils. A pair of inductors is considered to be strongly coupled if the mutual inductance between them is high in comparison to the respective inductances, as shown in (9), where k is referred to as the coupling coefficient.

$$v_2(t) = M\frac{di_1(t)}{dt} \tag{8}$$

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{9}$$

In the application of inductively powering implantable medical devices, one inductor of the power transmitter circuit forms the primary coil, and a receiving inductor implanted in the body forms the secondary coil. This essentially describes a weakly coupled transformer, the core of which is a combination of air and the layers of human tissue that exist between the two coils (Schuylenbergh and Puers, 2009). Typical coupling coefficients for power transfer in air are 0.17 (Ghovanloo and Atluri, 2007).

It is more efficient to transmit wireless power at lower frequencies (Vaillancourt et al., 1997), and as the complexity of implants increases, data rates are also required to increase. Wang et al. proposed the advantages of biomedical implants operating in dual frequency bands to send power and data, and it has since been the basis of further work in the area (Wang et al., 2006).

Transmission coils are an obvious point of focus, as their design holds the key to how well power is transmitted from the external device and received by the implant. Many biomedical implants employ traditional wire-wound cylindrical inductors for the power transmitting and receiving coils. In some scenarios such as retinal prosthesis wire-wound coils are preferred. Best results are usually obtained with the use of Litz wire, which reduces eddy currents caused by the skin-effect (Yang et al., 2007).

In situations such as pre-clinical monitoring, the issues related to wireless power transfer for implanted devices become more difficult to manage, mainly due to random movement by the subject of the implant. A common pre-clinical scenario involves an enclosure in which the subject is free to move. Zimmerman et al. (Zimmerman et al., 2006) investigated the optimisation of wireless power transfer in such a situation, monitoring the overall transfer efficiency by varying transmission frequency and the number of turns on the secondary coil, which was a distance of 1cm from the primary coil. The system produced 3V at 1.3mA in the implant itself, accounting for a tilting angle of 600. The primary coil was a cylindrical wire-wound coil, wrapped around the circumference of the base of the enclosure.

Zeirhofer et al. (Zierhofer and Hochmair, 1996) investigated the enhancement of magnetic coupling between coils using a geometric approach. It was concluded that coupling is enhanced when turns of the coil are distributed across the radii rather than concentrating them at the outer radius of the inductors. A number of subsequent papers have been presented analysing and using planar spiral coils for implantable applications (Harrison, 2007, Jow and Ghovanloo, 2010, Silay et al., 2008, Simons et al., 2004). The theory used to design planar spiral coils is quite involved, with most designers opting for simplified and sometimes empirically derived equations such as (10), where L is the inductance calculated by the surface area A of a square spiral and the number of turns n within the area (Liao, 1987, Wadell, 1991).

$$L = 8.5\sqrt{A}n^{5/3} \tag{10}$$

Work is being implemented in the use of stacked spiral coils for use in implantable devices. Stacking spiral coils together allows the advantages of spiral shapes to be combined with space efficiency. An increase in coil capacitance also reduces the self-resonant frequency of these coils making them compact and optimised for lower frequency transmission, which is advantageous for the inductive transfer of power (Laskovski et al., 2009).

8. Data carrier generation

Implantable biomedical telemetry schemes are moving towards a dual-band approach, meaning that power and data are sent at different frequencies, power at a lower frequency and data at a higher frequency. There are several methods used to generate data carrier frequencies for implantable devices.

Many systems involve the generation of data carrier signals on the external side of the system, leaving only the data recovery, modulation and transmission to the implantable circuitry (Mandal and Sarpeshkar, 2008, Zhou et al., 2006). Ziaie et al. presented a dual band implantable neuromuscular stimulator, the 2MHz data clock of which is recovered from 2MHz power supply (Ziaie et al., 1997), while Wise et al. operated at 4MHz (Wise et al., 2004) as did Sauer et al.'s (Sauer et al., 2005). Generating data carrier signals external to the implanted device allows for the reduction of device complexity and power consumption, however such a system requires a synchronised send/receive protocol as well as an accurate data recovery block.

The other option popularly used is to generate a data carrier frequency from within the implantable device itself. Kocer et al. presented an on-chip LC oscillator for general non-implantable non-medical telemetry, and other options for implantable devices involve ring oscillators (Ghovanloo and Najafi, 2004).

One idea currently being developed for implantable involves the generation of a data carrier signal within the implant. However, this signal is generated without the use of a dedicated oscillator block. It is generated by using an inverter to turn the incoming power signal into a non-sinusoidal square-wave signal in order to generate harmonics. One of these harmonics is then filtered and used to transmit data (Laskovski and Yuce, 2008).

9. Modulation techniques

The majority of modulation techniques used to encode biological signals are digital in that the signals are digitised within the implants. Some common forms of modulation include Frequency Shift Keying (FSK), Load Shift Keying (LSK), Amplitude Shift Keying (ASK), Phase Shift Keying (PSK).

FSK involves allocating different frequencies for different bit values. For example, binary FSK translates to bit `0' transmitting at a frequency $f_1$ and bit `1' transmitting at a different frequency f_2. Modulating a signal using FSK involves a switch and the generation of two

different carrier frequencies, and bits are usually decoded by bandpass filters (Ghovanloo and Najafi, 2004).
Impedance modulation or LSK involves altering a load in the transmitting circuit according to digital information. Since it usually involves switching one part of the load on and off, the frequency of transmission is varied with each bit, making this scheme very similar to FSK. A number of medical devices make use of this scheme (Chaimanonart and Young, 2006, Mandal and Sarpeshkar, 2008, Wang et al., 2005).
Shifting a carrier frequency's phase occurs to achieve PSK. Depending on the number of symbols in the scheme, the phase shift varies. A popular PSK scheme is Binary PSK (BPSK), where a 180^0 phase shift is implemented in order to indicate a particular bit. A number of biomedical and non-biomedical telemetry systems use this scheme (Kocer and Flynn, 2006, Zhou et al., 2006)
ASK modulation is achieved by producing a different amplitude for different bits. A typical and simple example of ASK is called On-Off Keying (OOK), where bits are distinguished by either sending data at a carrier frequency to represent bit `1', or no no signal to represent bit `0'. This type of modulation is very straightforward to implement, being as simple as implementing a data controlled switch in series with an RF transmitter. It can be decoded by rectification and/or a lowpass filter (Ziaie et al., 1997). For low-power implantable circuits, OOK is a simple and space efficient method of modulation.

10. Conclusion

This chapter provided a broad background in the development of biomedical engineering, and the recent contribution of electronics to this field. The role of power amplifiers was explained in the form of three switching power amplifiers, specifically the Class-E amplifier, which included a simple design process. A new idea to use Class-E oscillators was highlighted and is being developed. Basic theory of wireless power transfer was explained and methods in data carrier generation explained. A new method of generating carrier frequencies was briefly explained, which simplifies and reduces the power use of implantable devices. The meaning behind the acronyms of major data modulation schemes were explained, with the features of each described.

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Rapid technological developments in the last century have brought the field of biomedical engineering into a totally new realm. Breakthroughs in materials science, imaging, electronics and, more recently, the information age have improved our understanding of the human body. As a result, the field of biomedical engineering is thriving, with innovations that aim to improve the quality and reduce the cost of medical care. This book is the first in a series of three that will present recent trends in biomedical engineering, with a particular focus on applications in electronics and communications. More specifically: wireless monitoring, sensors, medical imaging and the management of medical information are covered, among other subjects.

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